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The dynamics of linking permit markets

Abstract

This paper presents a novel benefit of linking emission permit markets. We let countries issue permits non-cooperatively, and with endogenous technology we show there are gains from permit trade even if countries are identical. Linking the permit markets of different countries will turn permit issuance into intertemporal strategic complements. The intertemporal strategic complementarity arises because issuing fewer permits today increases investments in green energy capacity in all permit market countries, and countries with a higher green energy capacity will respond by issuing fewer permits in the future. Hence, each country faces incentives to withhold emission permits when permit markets are linked. Even though countries cannot commit to reducing their own emissions, or punish other countries that do not, the outcome is reduced emissions, higher investments, and increased welfare, compared to a benchmark with only domestic permit trade. We also show that permit market linking can arise as an equilibrium outcome.

JEL-Codes: F550, Q540.

Keywords: international agreements, permit markets, dynamic games, green technology investments.

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1 Introduction

The climate negotiations in Paris in 2015 showed that broad international participation in climate action is possible. The contributions under the agreement are determined nationally and this approach has proved more successful than earlier attempts to build an agreement top-down. In this paper, we consider a situation where countries non-cooperatively set their caps on emissions, and show that a simple linkage between the emission permit markets can reduce emissions and raise investments in green technology. This is the case even if countries are identical and no international permit trade takes place in equilibrium. We also show that such linkage can prevail as an equilibrium outcome.

The number of emission permit markets is high and increasing. According to ICAP (2018), there are now 21 international, national and regional emission trading systems (ETSs) in operation for greenhouse gases (GHGs), and the share of global emissions covered has reached almost 15%. Examples are the EU ETS, the Western Climate Initiative (WCI), the Regional Greenhouse Gas Initiative (RGGI), the Korean ETS and the recently launched national ETS in China. Both the WCI and the RGGI are examples of linked markets, and as the number of existing markets increases, so does the potential for linkages. For discussion, see, for example, Liski and Montero (2011), Grubb (2012), Ranson and Stavins (2012), Newell et al. (2013), Goulder (2013), or Ranson and Stavins (2016).

The Paris Agreement may itself motivate countries to establish trade in emission permits across borders. The agreement explicitly states that countries can agree to trade in emission allowances to reach their individual commitments (Paris Agreement, Article 6.). These individual commitments are determined nationally, without international agreement on the aggregate cap on emissions. Moreover, the individual commitments are to be updated over time. This is the same institutional setting as we assume in the basic model in this paper. The agreement also states that trade in allowances must be "voluntary and authorized by participating Parties" (Paris Agreement, Article 6.3.). This paper shows that welfare-enhancing international permit trade can indeed emerge as an equilibrium outcome.

Both the Paris Agreement and the developments in permit trade globally suggest that permit market linkages could provide an important path towards global coordination in fighting climate change. Indeed, Newell et al. (2013, p. 123) state that the "[...] dream of a top-down global design now seems far away, if not impossible. Instead, we see a multiplicity of regional, national, and even subnational markets emerging." In their Fifth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) also suggested permit market linkages as one possible form of decentralized architecture, and argue that a system of linkages is already emerging (Edenhofer et al., 2014, page 1018). But the theoretical predictions regarding the effects on emissions of such linkages are mainly negative; see, for example, Helm (2003). In contrast to this, we find that linkages can produce substantial emission reductions.

We consider the introduction of permit market linkages between countries, without assuming an agreement on the aggregate emission cap. We construct a dynamic model where a group of countries face climate change. In each country, there are energy consumers, and producers who invest in durable renewable energy production capacity. Each government non-cooperatively determines a domestic emission cap. Fossil energy consumption must be covered by tradable emission permits. When permit markets are linked, emission permits can be traded across borders. The main contribution of this paper is to show that permit market linkages will lead countries to voluntarily restrict emissions, and will thus result in higher welfare. We also show that the same benefits can be generated by linkages between renewable energy markets in different countries. Finally, we allow the linking decision itself to be endogenous and investigate under what conditions permit market linkage will prevail in equilibrium. We show that linkage between both identical and heterogeneous countries can emerge as an equilibrium outcome.

The mechanism we identify that leads to emission reductions when markets are linked can be explained in three steps. First, having fewer emission permits available in the market in any given time period gives a higher equilibrium permit price. When there is international permit trade, this price is the same in all countries. Second, a higher permit price will increase the demand for – and thus the investment in – green energy, resulting in more available production capacity in the future. Third, countries with more green energy production capacity will issue fewer permits because they put a high value on a high price. In total, these steps imply that lower permit issuance in one country in a given time period leads to lower issuance in *all* countries in future periods if the permit markets are linked. Countries will exploit this mechanism by issuing fewer permits.

A few important policy implications can be drawn from our findings. The recommendation to link markets is clear. In addition, for a country participating in international permit trade, limiting the number of permits issued has a stronger effect on emissions than previously found in much of the literature discussed below. Furthermore, our results suggest that emission caps should be reset often. This result is in contrast to the findings of Harstad (2016), who finds that because of the hold-up problem, treaties should be long-lasting, and Harstad and Eskeland (2010) who also recommend the caps be reset seldom. Finally, our results identify a novel channel through which investment in renewable energy is important through creating strategic complementarity in emission levels across countries over time.

In the literature, it is well understood that linking permit markets has benefits because marginal abatement costs are equalized (see, e.g., Flachsland et al. (2009)). Other authors who discuss the effects of permit market linkages are Mehling and Haites (2009), Green et al. (2014), Doda and Taschini (2017) and Weitzman and Holtsmark (2018). Helm (2003) and Rehdanz and Tol (2005) explicitly model the strategic incentives to alter the cap when markets are linked. Both papers find that there is no ex ante reason to expect emissions to decline following linkage. Habla and Winkler (2018) also allow for delegation of the domestic permit supply to an agent, leading to wider domestic emission caps, meaning higher emissions, when countries are linked. Lapan and Sikdar (2019) conclude that international trade in emission permits creates incentives for the individual countries to widen their national caps on emissions when pollution is only partially transboundary. There is also a numerical literature on permit market linkage, with mixed conclusions (see e.g., Carbone et al. (2009) and Holtsmark and Sommervoll (2012)). However, these papers analyze static games where the cap on emissions is set once and for all. We show that including dynamics changes the conclusions.

The failure to reach agreement in top-down international negotiations is in line with theoretical predictions from the literature; see, for example, Barrett (1994), Hoel (1992), Carraro and Siniscalco (1993), Dixit and Olson (2000), Hoel and de Zeeuw (2010) or Calvo and Rubio (2013). Moreover, a general insight from the existing literature is that free-rider problems are more severe when dynamics are taken into account (see, e.g., Hoel (1991), Fershtman and Nitzan (1991), Buchholz and Konrad (1994) and Beccherle and Tirole (2011)). We show that when permit market linking is investigated, the effect of including dynamics is the opposite.

Finally, there are also other contributions to this literature that find a positive effect of the non-contractibility of green investments. Harstad (2012) and Battaglini and Harstad (2016) demonstrate how the hold-up problem can be leveraged to produce better outcomes, by specifically allowing for renegotiation of the treaties, or exploiting the hold-up problem when punishing defecting countries.

There is also a literature that studies how cooperative behavior can be enforced by the threat of Nash reversion; see Barrett (1994), Asheim and Holtsmark (2008), Dutta and

Radner (2004), and Dutta and Radner (2009). The basic assumptions in these models are close to those in this paper. However, by restricting our attention to Markov perfect equilibria, we show that punishment schemes are not the *only* way to obtain higher welfare when policies are set non-cooperatively.

When we consider whether agreements to link permit markets will prevail in equilibrium, we build on Barrett (1994). Barrett investigates self-enforcing environmental agreements where emission levels are set to maximize the joint welfare of the coalition. He finds that either the welfare gains from cooperation are small or the number of countries participating is low (see also Barrett (2005)). Other papers, for example, Carraro et al. (2006), Hoel and de Zeeuw (2010) and Calvo and Rubio (2013), confirm these predictions when different institutional frameworks are considered, including endogenous technology investments. We show that this is not necessarily the case when we consider permit market linking.

The paper proceeds as follows: We introduce the model in Section 2, solve for the Markov perfect equilibrium and present our main results in Section 3 and conclude in Section 4. Additional discussion and several extensions to the basic model are provided in the appendix.

2 The model

Consider N countries interacting over an infinite number of time periods. In each country, there are price-taking energy consumers and renewable energy producers. All actors share the discount factor $\beta \in (0, 1)$. The representative consumer in country i derives utility $u_i(e_{it})$ from consuming e_{it} units of energy in period t. $u_i(\cdot)$ is strictly concave, twice differentiable and reaches a maximum at some finite level of energy use $\forall i$. We assume that the utility from consuming energy and a composite good taken as numeraire is separable. The same is true for energy consumption and harm from climate change. Energy is available from two sources, fossil and renewable. For simplicity, we assume that fossil energy is available for all to consume at zero price. In the appendix (Section J) we relax this assumption. Consumption of fossil energy is denoted f_{it}. Define $f_t \equiv \sum_j f_{jt}$ and let $D_i \geq 0$ represent the constant marginal damage incurred by country i per unit of fossil consumption.[1]

[1] Let S_t be the stock of GHGs in the atmosphere at t, let $S_{t+1} = \gamma(S_t + f_t)$, with $(1 - \gamma)$ as the decay rate. Each country incurs a damage from the stock, represented by the damage function $\tilde{D}_i(S_t + f_t)$. The increase in the present value of current and future damages by a marginal increase in emissions in period

In each time period, each government issues emission permits that grant the holder the right to consume fossil energy, and these permits can be traded among the country's energy consumers.[2] ω_{it} denotes the number of permits issued in country i in period t, traded at price p_{it}. If some countries link their markets, permits can be traded between all consumers in these countries, and the permit price will be equalized across the linked countries.

Consumption of renewable energy is denoted by z_{it}. The two types of energy are perfect substitutes, and total consumption is given by $e_{it} \equiv f_{it} + z_{it}$. In each period, the representative price-taking renewables producer in country i can undertake an investment, r_{it}, at a cost $c_i(r_{it})$, with $c_i(0) = 0, c_i'(\cdot) > 0, c_i''(\cdot) > 0$. The increased capacity is immediately available, and contributes to a stock of renewables production capacity denoted R_{it}. $\delta \in (0,1)$ is the survival rate and the stock develops according to

$$R_{it+1} = \delta(R_{it} + r_{it}) \quad \forall i. \tag{1}$$

There are no variable costs in supplying renewable energy from the stock. In Section H in the appendix, we relax this assumption. Domestic consumption and supply of renewables must be equal: $z_{it} = r_{it} + R_{it}$.

The welfare of country i in period t consists of utility from consumption, renewables investment costs, damage from emissions, and, if there is international permit trade with price p_t, the net cost or revenue from trading permits:

$$U_{it} = u_i(f_{it} + z_{it}) - c_i(r_{it}) + p_t \cdot (\omega_{it} - f_{it}) - D_i f_t. \tag{2}$$

We divide the dynamic game into two stages. In the first stage, analyzed in Section 3.4, countries decide simultaneously whether or not to participate in international permit trade. In the second stage, analyzed in Section 3.1 - 3.3, there is an infinite number of time periods, and within each period, the timing is as follows, regardless of whether there is international permit trade: First, the governments simultaneously issue permits. Then, the renewables producers invest, and finally, consumption is determined. The political process

t would be $D_i = \sum_{\tau=t}^{\infty}(\beta\gamma)^{(\tau-t)}\tilde{D}_i'(S_\tau)$, which for constant $\tilde{D}_i'(S) = \tilde{D}_i$, is equivalent to $D_i = \frac{\tilde{D}_i}{1-\beta\gamma}$. Golosov et al. (2014) argue that a linear damage function is perhaps not a very bad approximation, as a composition of a concave relationship between the atmospheric carbon stock and mean global temperatures and a convex relationship between temperatures and economic damage. We discuss the effect of allowing convex damages in Section I in the appendix. For an in-depth discussion on the choice of functional form for the damages, see van den Bijgaart et al. (2016).

[2] Permit holders – typically producers – are termed "consumers" to distinguish them from investors.

determining emission caps is often slow. In the EU, for example, the recent tightening of the cap followed from a long-lasting debate. Therefore, we find it reasonable to allow investors to react to changes in the permit supply within each time period, and to let energy consumers react to price changes quite quickly. These assumptions are crucial for our results.

2.1 Equilibrium consumption and investments

Let q_{it} denote the price of renewable energy. In each period, independently of whether permits are traded internationally, the representative consumer in country i solves:[3]

$$\begin{aligned} &\max_{f_{it}, z_{it}} u_i(f_{it} + z_{it}) - p_{it} f_{it} - q_{it} z_{it}, \\ \Rightarrow \quad & u_i'(f_{it} + z_{it}) = p_{it} \quad , \quad u_i'(f_{it} + z_{it}) = q_{it}. \end{aligned} \tag{3}$$

The price of renewables and permits must be equal in equilibrium, and we denote the common price p_{it}. The first-order conditions define the energy demand function, $e_{it}(p_{it})$, with $e_{it}'(p_{it}) = 1/u_i''(e_{it}) < 0$.

The representative renewables producer in each country owns a production capacity stock and takes prices as given with rational expectations. Subject to the stock transition (Equation (1)), the producers solve:

$$\begin{aligned} &\max_{r_{it}} \quad \left\{ \sum_{\tau=0}^{\infty} \beta^{\tau} p_{it+\tau} \left(R_{it+\tau} + r_{it+\tau} \right) - c_i(r_{it}) \right\}, \\ \Rightarrow \quad & c_i'(r_{it}) = \sum_{\tau=t}^{\infty} (\beta\delta)^{\tau-t} p_{i\tau} \equiv \hat{p}_{it}, \end{aligned} \tag{4}$$

defining $r_i(\hat{p}_{it})$, with $r_i'(\hat{p}_{it}) = 1/c_i''(r_{it}) > 0$. A higher price, p_{it}, results in higher investment and lower consumption, and hence lower emissions.

[3] In Section E in the appendix, we provide conditions that assure positive fossil fuel consumption $\forall i, t$, and we also show that our main results still hold when these conditions are relaxed.

2.2 First best

Aggregate welfare is defined as the sum of welfare across countries, and the first-best consumption levels and renewables investments solve:

$$W^{FB} \equiv \max_{\{\{f_{it}, z_{it}, r_{it}\}_{i=1}^{N}\}_{t=0}^{\infty}} \sum_i \sum_{t=0}^{\infty} \beta^t \Big(u_i(f_{it} + z_{it}) - c_i(r_{it}) - D_i f_t \Big),$$
$$\text{subject to} \quad z_{jt} = R_{jt} + r_{jt} \quad \forall j, t \quad \text{and} \quad R_{jt+1} = \delta(R_{jt} + r_{jt}) \quad \forall j, t.$$

The first-best allocation is characterized by the following:

$$u_i'(f_{it} + z_{it}) = \sum_j D_j \quad \forall i, t, \qquad c_i'(r_{it}) = \sum_j \frac{D_j}{1 - \beta\delta}, \quad \forall i, t.$$

Given equations (3) and (4), the first-best allocation can be implemented by a price on emissions $p_t^{FB} = \sum_j D_j, \ \forall t$.

3 Markov perfect equilibrium

We start by considering the second stage of the game, given that a set $\mathcal{M}$ consisting of M countries chose to link their markets in the first stage. We consider only Markov perfect equilibria (MPEs), and conditional on $\mathcal{M}$, the only payoff-relevant state variables are the renewables stocks. We suppress time indices unless clearly needed and next-period stocks are denoted by $^+$. The strategy of country i is a function $h : \mathbb{R}_+^N \to \mathbb{R}$. Define the initial supply of energy and permits, that is, the supply *before* the renewables producers make their investments, $s_i \equiv R_i + \omega_i$, as the choice variable of the government in country i. In Section 3.4, we consider the first stage of the game.

3.1 Autarky

First, we characterize equilibrium behavior for the $N - M$ countries that chose not to participate in international permit trade in the first stage. Market clearing in country i requires $s_i = e_i(p_i) - r_i(\hat{p}_i)$, defining the function $p_i(s_i)$. The government in country i

solves the following problem:

$$V_i^{aut}(\{R_j\}_{j=1}^N) = \max_{s_i} \Bigg\{ u_i(e_i(p_i(s_i))) - c_i(r_i(\hat{p}_i)) - D_i \sum_{j=1}^N (s_j - R_j) \\ + \beta V_i^{aut}\Big(\{\delta(R_j + r_j(\hat{p}^{\mathcal{M}}))\}_{j\in\mathcal{M}}, \{\delta(R_j + r_j(\hat{p}_j))\}_{j\notin\mathcal{M}}\Big)\Bigg\}, \quad (5)$$

subject to stock transition (Equation (1)) and the behavior of consumers and producers (Equations (3) and (4)). $p^{\mathcal{M}}$ is the permit price in the linked countries. The first-order condition becomes:

$$0 = u_i'(e_i)e_i'(p_i)p_i'(s_i) - c_i'(r_i)r_i'(\hat{p}_i)\frac{d\hat{p}_i}{ds_i} - D_i + \beta\delta r_i'(\hat{p}_i)\frac{d\hat{p}_i}{ds_i}\frac{\partial V_i^{aut}}{\partial R_i^+} \quad \forall i \notin \mathcal{M}. \quad (6)$$

The value function is linear in R_i with $\partial V_i^{aut}/\partial R_i = D_i/(1-\beta\delta)$, and the first-order condition is solved by the s_i that ensures $p_i^{aut} = D_i < p^{FB}$ and $\hat{p}_i^{aut} = D_i/(1-\beta\delta)$, $\forall i$, meaning that s_i must be constant over time $\forall i \notin \mathcal{M}$, and that ω_i is independent of the foreign renewables stocks $\forall i \notin \mathcal{M}$.

With superscript $\mathcal{M}$ denoting values in the coalition $\mathcal{M}$, the value function becomes:

$$V_i^{aut|\mathcal{M}} = \frac{1}{1-\beta}\Bigg[u_i(e_i(p_i^{aut})) - c_i(r_i(\hat{p}_i^{aut})) - D_i \sum_{j\notin\mathcal{M}} e_j(p_j^{aut}) + \frac{D_i}{1-\beta\delta}\sum_{j\notin\mathcal{M}} r_j(\hat{p}_j^{aut}) \\ - D_i \sum_{j\in\mathcal{M}} e_j(p^{\mathcal{M}}) + \frac{D_i}{1-\beta\delta}\sum_{j\in\mathcal{M}} r_j(\hat{p}^{\mathcal{M}})\Bigg] + \frac{D_i}{1-\beta\delta}\sum_{j=1}^N R_j \quad \forall i \notin \mathcal{M}. \quad (7)$$

3.2 International permit trade

For the M countries that chose to link their markets, emission permits are traded between all consumers at price p, and the governments are free to issue as many permits as they wish. Define $s \equiv \sum_{i\in\mathcal{M}} s_i$. Consumption and investment decisions are given by Equations (3) and (4), and the permit supply s is known at the investment stage. Market clearing requires that $z_j(p) = R_j + r_j(\hat{p})$ $\forall j$ and that $\sum_{j\in\mathcal{M}} f_j(p) = \sum_{j\in\mathcal{M}} \omega_j$, which gives:

$$\sum_{j\in\mathcal{M}} e_j(p) - \sum_{j\in\mathcal{M}} r_j(\hat{p}) = s. \quad (8)$$

The price prevailing in the market is thus a function of s: $p = p(s)$. We show later in this section that $p'(s) = 1/(\sum_{j\in\mathcal{M}}(e_j'(p) - r_j'(\hat{p}))) < 0$. Each government takes into account how its own permit issuance affects the equilibrium price. The reason no government will issue an infinite number of permits to raise large amounts of revenue is that doing so would drive the price to zero, and ultimately give the country zero revenue.

The government in country i chooses the action s_i to solve:

$$V_i^{\mathcal{M}}\Big(\{R_j\}_{j=1}^N\Big) = \max_{s_i} \Big\{ u_i(e_i(p(s))) + p(s)\Big(s_i + r_i(\hat{p}) - e_i(p(s))\Big) - c_i(r_i(\hat{p})) \\ - D_i \sum_{j=1}^N (s_j - R_j) + \beta V_i^{\mathcal{M}}\Big(\{\delta(R_j + r_j(\hat{p}))\}_{j\in\mathcal{M}}, \{\delta(R_j + r_j(\hat{p}_j^{aut}))\}_{j\notin\mathcal{M}}\Big)\Big\}, \tag{9}$$

subject to stock transition (Equation (1)) and the behavior of producers and consumers (Equations (3) and (4)). From the choice of s_i, the number of issued permits, ω_i, follows. The total supply, s, determines the permit price, p, through the market-clearing condition in Equation (8). The price determines $r_i(\hat{p})$ and $e_i(p)$ and the continuation values, $\forall i$. Together with the $N - M$ first-order conditions given by Equation (6), these M first-order conditions define our MPE:[4]

$$0 = p(s) + p'(s) \cdot \Big(s_i + r_i(\hat{p}) - e_i(p(s))\Big) + p'(s)e_i'(p)(u_i'(e_i) - p(s)) \\ + \frac{d\hat{p}}{ds_i} r_i'(\hat{p}) \cdot (p(s) - c_i'(r_i)) - D_i + \beta\delta \frac{d\hat{p}}{ds_i} \sum_{j\in\mathcal{M}} r_j'(\hat{p}) \frac{\partial V_i^{\mathcal{M}+}}{\partial R_j^+}, \quad \forall i \in \mathcal{M}. \tag{10}$$

The first two terms give the revenue for country i from issuing one additional permit: The direct gain $p(s)$, and the gain or loss from the resulting price decrease. The price decrease is beneficial if the country's supply, $s_i + r_i$, is smaller than its energy consumption. But this benefit from the price decrease is itself decreasing in the initial supply, s_i. If the country's supply is larger than its energy consumption, the price decrease is costly, and this cost is increasing in the initial supply. Therefore, the benefit of issuing one additional permit will eventually become negative, even if $D_i = 0$. The next two terms represent the effect of the price decrease on the country's consumers and renewables producers. The direct cost of issuing one additional permit because of higher climate damage is D_i. Finally,

[4] The first-order conditions rule out profitable one-step unilateral deviations, and the per-period utility in country i (Equation (2)) is bounded from above when s_{-i} is fixed. Then no profitable sequence of unilateral deviations exists, and our candidate Markov strategies constitute an MPE. This equilibrium is differentiable and interior, given the condition stated in Appendix E. We cannot rule out the possibility that there are other MPEs in this game. However, in Section M in the appendix, we show that this MPE is the limit of the unique subgame perfect equilibrium of the finite horizon version of the stage-two game as the number of time periods goes to infinity.

the price decrease lowers investments in renewables capacity in all countries. The reduced investments result in lower future stocks of renewables, affecting country i through the continuation value, $\partial V_i^{trade+}/\partial R_j^+$. This term makes the dynamic model fundamentally different from the static version presented in Helm (2003). Because the renewables stocks are durable, it is possible for each government to affect future behavior in *other* countries by changing their own permit issuance. By issuing *fewer* permits, the government in country i will increase the price, which will increase investments in renewables in all countries in $\mathcal{M}$, affecting future issuance there.

Differentiating the M first-order conditions with respect to the stocks, R_j, gives a system of $M \times M$ equations defining the policy responses $\partial s_i/\partial R_j$, $\forall i, j \in \mathcal{M}$, and thereby $\partial \omega_i/\partial R_j$, $\forall i, j \in \mathcal{M}$. This system can be simplified using Equations (3) and (4) and the following result states the solution, with superscript $\mathcal{M}$ denoting the MPE under international permit trade in the coalition $\mathcal{M}$:

Lemma 1.

1. *The equilibrium policy functions and permit issuance satisfy*

$$\frac{\partial s_i^{\mathcal{M}}}{\partial R_j} = 0 \;\; \forall i, j \in \mathcal{M} \qquad \Leftrightarrow \qquad \frac{\partial \omega_i^{\mathcal{M}}}{\partial R_j} = \begin{cases} -1 & \text{if } j = i \in \mathcal{M}, \\ 0 & \text{if } j \neq i, j \in \mathcal{M}. \end{cases}$$

2. *The value function is linear in the stocks, with* $\partial V_i^{\mathcal{M}}/\partial R_j = D_i/(1-\beta\delta)$, $\forall i, j \in \mathcal{M}$.

Proof. By inserting the policy response functions given in the Lemma into the value function (Equation (9)), we see that the value function becomes:

$$V_i^{\mathcal{M}} = \frac{1}{1-\beta}\Bigg[u_i(e_i(p^{\mathcal{M}})) - c_i(r_i(\hat{p}^{\mathcal{M}})) + p^{\mathcal{M}} \cdot TB_i^{\mathcal{M}} - D_i \sum_{j \notin \mathcal{M}} e_j(p_j^{aut}) \\ + \frac{D_i}{1-\beta\delta} \sum_{j \notin \mathcal{M}} r_j(\hat{p}_j^{aut}) - D_i \sum_{j \in \mathcal{M}} e_j(p^{\mathcal{M}}) + \frac{D_i}{1-\beta\delta} \sum_{j \in \mathcal{M}} r_j(\hat{p}^{\mathcal{M}})\Bigg] + \frac{D_i}{1-\beta\delta} \sum_{j=1}^{N} R_j \tag{11}$$

where $TB_i^{\mathcal{M}} \equiv s_i^{\mathcal{M}} + r_i(\hat{p}^{\mathcal{M}}) - e_i(p^{\mathcal{M}})$ is independent of R_i given the equilibrium policy functions. Differentiating the first-order conditions (Equation (10)) gives the policy response functions. □

Lemma 1.1 states that an increase in the stock of renewables in country i will lead to fewer permits issued by country i, one for one. To see why this has to be the case, consider the alternative reactions to a one-unit increase in R_i. A decrease in ω_i of less than one unit, gives price decrease *and* an increase in i's net supply. Similarly, a decrease in issuance of more than one unit would increase the price and decrease supply. In equilibrium, the initial supply, s, is unaltered, the price remains unchanged, and no other country reacts to the increased stock in country i. The only effect of an increased stock of renewables is reduced fossil energy consumption. Lemma 1.2 follows.

Given Lemma 1.1, the total supply of energy and permits is independent of the renewables stocks, meaning that the price must also be independent of the stocks, and therefore constant over time. It follows that s_τ and $\hat{p}_t$ are also independent of R_{jt} for $\tau > 0$, and therefore that $d\hat{p}/ds = p'(s)$. By differentiating the market-clearing condition (Equation (8)), we get $p'(s) = \frac{1}{\sum_{j \in \mathcal{M}}(e'_j(\cdot) - r'_j(\cdot))} < 0$. Finally, the effect on the price of an increase in the permit supply does not depend on the renewables stocks.

Proposition 1. *When the permit markets of a set of countries, $\mathcal{M}$, are linked, these countries can induce increased investments in other countries in $\mathcal{M}$ by withholding permits:* $\frac{dr_j}{dp}\frac{dp}{d\omega_i} < 0,\ \forall i, j \in \mathcal{M}$. *As a result, permit supply in the different countries become* intertemporal strategic complements*:* $\frac{d\omega_j^+}{dR_j^+}\frac{dR_j^+}{d\omega_i} > 0$, $\forall i, j \in \mathcal{M}$.[5]

Proof. Since $d\hat{p}/ds = p'(\cdot) < 0$, one fewer permit issued today will increase investment in every linked country since $r'_i(\cdot) > 0$. By Lemma 1.1, future permit issuance will then go down in every linked country since $\partial\omega_j^{\mathcal{M}}/\partial R_j = -1,\ \forall j$. □

The Proposition states that if one country in $\mathcal{M}$ issues fewer (more) permits in one period, then the other countries in $\mathcal{M}$ will issue fewer (more) permits in future periods. It is this link between issuance in each country in one time period and issuance in all other linked countries in future time periods that creates the positive welfare effects from international permit trade that we identify in this paper.

The link can be explained in the following three steps: first, the permit price increases when fewer permits are issued today. Second, renewable energy producers in every linked country respond to the increase in permit prices by increasing their investments. Third, when countries experience increased renewable energy stocks in the next period, by Lemma 1.1, they respond by issuing fewer permits. When permits are traded only domestically, countries are unable to affect the price in other countries. But under international permit trade, the price is common across countries, creating this intertemporal link. This mecha-

[5] Our definition of intertemporal strategic complementarity corresponds to the definition in both Jun and Vives (2004) and Baldursson and Fehr (2007).

nism gives all linked countries an incentive to withhold permits when there is international trade.

Lemma 2. *The equilibrium permit price is independent of time and of the stocks of renewable energy capacity, and satisfies*

$$p^{\mathcal{M}} = \overline{D}^{\mathcal{M}} \frac{1 + \Omega^{\mathcal{M}}}{1 + \frac{1}{M}\Omega^{\mathcal{M}}} > \overline{D}^{\mathcal{M}}, \tag{12}$$

where $\overline{D}^{\mathcal{M}} \equiv \sum_{j\in\mathcal{M}} D_j/M$ *is the average marginal damage from emissions across linked countries, and* $\Omega^{\mathcal{M}} \equiv \frac{\beta\delta}{1-\beta\delta} \sum_{j\in\mathcal{M}} r_j'(\hat{p})/(\sum_{j\in\mathcal{M}}(r_j'(\hat{p}) - e_j'(p))) > 0$.

Proof. Given Lemma 1, the first-order conditions (Equation (10)) can be simplified to:

$$\begin{aligned} 0 =& p(s) + p'(s)(s_i + r_i(\hat{p}) - e_i(p(s))) - p'(s)r_i'(\hat{p})(c_i'(r_i) - p(s)) \\ &- D_i + \beta\delta p'(s)\frac{D_i}{1-\beta\delta}\sum_{j\in\mathcal{M}} r_j'(\hat{p}). \end{aligned}$$

We have $c_{it}'(\hat{p}_t) - p_t(s_t) = \sum_{\tau=t+1}^{\infty}(\beta\delta)^{\tau-t}p_\tau(s_\tau)$, and we define $r'(\hat{p}) = \sum_{j\in\mathcal{M}} r_j'(\hat{p})$. Insert this into the first-order condition, sum over all i and divide by M to get

$$p_t = \frac{p_t'(s_t)r_t'(\hat{p}_t)}{M}\sum_{\tau=t+1}^{\infty}(\beta\delta)^{\tau-t}p_\tau(s_\tau) + \overline{D} - p_t'(s_t)r_t'(\hat{p}_t)\overline{D}\frac{\beta\delta}{1-\beta\delta}.$$

The initial supply, s, is independent of the renewables stocks by Lemma 1, and therefore the price is independent of state and time. Solving for a constant p gives the price as stated in the Lemma. □

In addition to M and $\overline{D}^{\mathcal{M}}$, the equilibrium price depends on the strength of the consumers' and producers' respective reactions to price changes, and on the survival rate of the production capacity and the discount factor. That is because the strength of the incentive to withhold permits facing each country is determined by these parameters. First, the magnitude of the price increase following reduced issuance in country i depends on $e'(\cdot)$. Second, $r'(\cdot)$ together with δ determines the effect on the future renewables stocks. Finally, the value that country i puts on future emission reductions depends on the discount factor β.

Because $p^{\mathcal{M}}$, as well as both p_i^{aut} and p^{FB}, are time- and stock-independent, welfare can easily be compared in all time periods, not only in steady state.

3.3 Welfare implications

The introduction of international trade in permits affects welfare in two ways. First, trade will lead to a cost-efficient distribution of abatement in the linked countries. Second, we have seen that international permit trade affects the incentives faced by countries when issuing permits, and thus aggregate emissions. The first effect is well understood, and in this paper we are mainly interested in the second. Therefore, we begin by assuming identical marginal damages across all linked countries to remove the scope for pure cost-efficiency gains. Let $V_i^{aut|\emptyset}$ represent the value function of country i given that no countries have chosen to link their markets.

Proposition 2. *Consider a set of M countries, $\mathcal{M}$, with identical marginal damage, $D_i = \overline{D}^{\mathcal{M}}, \forall i \in \mathcal{M}$. Linking the permit markets of these countries reduces emissions in every country and increases aggregate welfare by increasing investments and reducing consumption: $r_i^{\mathcal{M}} > r_i^{aut}$, $e_i^{\mathcal{M}} < e_i^{aut}$, $f_i^{\mathcal{M}} < f_i^{aut}$, $\forall i \in \mathcal{M}$, $\sum_{i \in \mathcal{M}} V_i^{\mathcal{M}} > \sum_{i \in \mathcal{M}} V_i^{aut|\emptyset}$.*

Proof. As $p^{\mathcal{M}} > \overline{D}^{\mathcal{M}}$ (Lemma 2), all consumers and producers in the linked countries experience a price increase when international trade is introduced. This price increase results in reduced consumption and increased investment in every country in $\mathcal{M}$, thus reduced emissions. As emissions in each country are inefficiently high under autarky, these emission reductions increase aggregate welfare. □

Note that if countries are completely identical, the increase in aggregate welfare means that welfare is increased in every country. But when $u_i(\cdot)$ and $c_i(\cdot)$ differ between countries, the welfare gains will not be evenly distributed because the costs of decreased consumption and increased investments will differ, and some countries may incur a net loss.

In Section F2 in the appendix, we discuss how welfare effects in individual countries depend on the country's characteristics, and we also consider further heterogeneity across countries. Here, note that the analytical results will be ambiguous if we allow for full heterogeneity. The reason is the following: in the equilibrium with international permit trade, we have $p^{\mathcal{M}} > \overline{D}^{\mathcal{M}}$, while in autarky $p_i^{aut} = D_i$. In any country with $D_i \leq \overline{D}^{\mathcal{M}}$, international trade leads to a price increase, and hence to emission reductions. This will also be the case for countries with $\overline{D}^{\mathcal{M}} < D_i < p^{\mathcal{M}}$. However, there might exist countries in $\mathcal{M}$ with $D_i > p^{\mathcal{M}}$, and consumers and producers in these countries will face a price decrease resulting in increased emissions, when the markets are linked. If countries are identical with respect to their energy demand and renewables supply, overall emissions will decrease when the markets are linked, as we show in a simplified version of the model in the appendix (Section F1). However, when $u_i(\cdot)$ and $c_i(\cdot)$ differ across countries and some countries have $D_i > p^{\mathcal{M}}$, overall emissions could increase, as is shown in a static model by Holtsmark and Sommervoll (2012).

In the following, we discuss determinants of the size of the welfare gains from linking markets.

Proposition 3. *As the number of linked countries, M, increases, the gain for the average country from linking the permit markets also increases:*

$$\frac{\partial}{\partial M}\left(\frac{1}{M}\sum_{i\in\mathcal{M}} V_i^{\mathcal{M}} - \frac{1}{M}\sum_{i\in\mathcal{M}} V_i^{aut|\emptyset}\right) > 0,$$

provided that the characteristics (R_i, D_i, $u_i(\cdot)$ and $c_i(\cdot)$) of the average country in $\mathcal{M}$ do not change.

Proof. From Lemma 2, it follows that $\partial p^{\mathcal{M}}/\partial M > 0$, while we have $\partial p_i^{aut}/\partial M = 0$. Average welfare increases with the permit price and the result follows. □

One permit withheld has a smaller effect on the international permit price when N is large. However, the effect of a given price increase on the aggregate foreign stock of renewables is larger when M is larger, because $\sum_{i\in\mathcal{M}} r_i$ is more strongly affected. The latter effect dominates and a larger M results in a stronger incentive to withhold permits and hence in a larger welfare gain when international permit trade is introduced.

Proposition 4. *The increase in the permit price following linkage of the permit markets of a set of countries, $\mathcal{M}$, is higher if the discount rate, β, and the survival rate of the renewables stocks, δ, are higher.*

Proof. From Lemma 2 we have $dp^{\mathcal{M}}/d(\beta\delta) > 0$, while p_i^{aut} is independent of $\beta\delta$ $\forall i$. □

$\beta\delta = 0$ gives $p^{\mathcal{M}} = \overline{D}^{\mathcal{M}}$ and represents the static game studied by Helm (2003). In the static game, there is no incentive to withhold permits because there is no possibility to affect the other countries. For the other extreme, $\beta\delta \to 1$, the stock of renewables would explode, there would be no fossil energy use in equilibrium, and there is no longer an international public good problem. For values of β and δ in between these two extremes, we have shown that there will be lower emissions and higher welfare under international permit trade than under no trade. The parameters β and δ can be interpreted as a representation of the length of the time periods, with Helm (2003)'s model representing the case where the cap is set once and for all. Then, our results suggest that emission caps in international permit markets should be reset often, in contrast to the conclusions from several papers in the literature. Harstad and Eskeland (2010) find that permits should be long-lasting to avoid costly signaling by firms. Harstad (2016) finds that climate agreements should be long-lasting to avoid that the costly hold-up problem appears "too often". Our conclusions are in line with Battaglini and Harstad (2016) who find that the hold-up problem can be leveraged to support equilibria with large coalitions, because we show that endogenous technology investments may lead to emission reductions.

So far, we have not considered trade in renewable energy, to focus on the effect of linking permit markets. However, the mechanism leading to welfare gains is driven by the common price of emission permits and renewables. And the common price can also be achieved by establishing trade in renewable energy, even absent international permit trade.

Proposition 5. *International trade in renewable energy alone is sufficient for the welfare effects established in earlier results to accrue. Specifically, Propositions 1, 2, 3 and 4 carry over to a setting with international trade only in renewables, provided that* $e_i(p^{\mathcal{M}}) > \omega_i^{\mathcal{M}} > 0$ *for every country* i.

Proof. Market clearing requires $f_{jt} = \omega_{jt}, \ \forall j, t$ and $\sum_{j\in\mathcal{M}} z_{jt} = \sum_{j\in\mathcal{M}}(R_{jt} + r_{jt}), \ \forall t$ when there is international trade only in renewables. This gives $\sum_{j\in\mathcal{M}} e_{jt} = \sum_{j\in\mathcal{M}}(s_{jt} + r_{jt}), \ \forall t$, the same aggregate condition as in the case with international permit trade only. As long as $e_i(p^{\mathcal{M}}) > \omega_i^{\mathcal{M}} > 0$, the equilibrium remains unchanged. This condition is trivially satisfied if countries are identical. □

The results state that the welfare gains from linking can be reaped by linking markets for permits or by linking renewables markets. However, trade in renewable energy often involves large transaction costs, so that in many cases permit trade is the simplest way to reap the gains from a common price.

3.4 Participation in international permit trade

In this section, we consider the first stage of the game, where each country decides whether or not to participate in international permit trade. In the rest of this section, we assume that $u_i(\cdot)$ and $c_i(\cdot)$ are quadratic functions, $u_i(e_i) = u_{i1}e_i - \frac{1}{2}u_{i2}e_i^2$ and $c_i(r_i) = \frac{1}{2}c_{i2}r_i^2$, $\forall i$, meaning that $e_i' = -\frac{1}{u_{i2}}$ and $r_i' = \frac{1}{c_{i2}}$ are constants $\forall i$.

First, define $\Delta_i^{\mathcal{M}}$, the value for country i of participating in a coalition $\mathcal{M}$ of countries that link their permit markets, as:

$$\Delta_i^{\mathcal{M}} \equiv (1-\beta)V_i^{\mathcal{M}} - (1-\beta)V_i^{aut|\mathcal{M}-i}.$$

$V_i^{aut|\mathcal{M}-i}$ and $V_i^{\mathcal{M}}$ and given by Equations (7) and (11). $\Delta_i^{\mathcal{M}}$ is independent of the renewables stocks and is therefore independent of time. An agreement to link markets between a set of countries, $\mathcal{M}$, is an equilibrium outcome in the dynamic game if and only if:[6]

$$\Delta_i^{\mathcal{M}} \geq 0 \quad \forall i \in \mathcal{M} \qquad \text{and} \qquad \Delta_i^{\mathcal{M}+i} \leq 0 \quad \forall i \notin \mathcal{M}.$$

It follows from the equilibrium value functions that:

$$\Delta_i^{\mathcal{M}} = -\frac{1}{2}(p^{\mathcal{M}} - D_i)^2 E_i + D_i(p^{\mathcal{M}} - p^{\mathcal{M}-i}) \sum_{j \in \mathcal{M}-i} E_j + p^{\mathcal{M}} TB_i^{\mathcal{M}} \tag{13}$$

where $E_j \equiv -e'_j + \frac{r'_j}{(1-\beta\delta)^2} > 0$, $\forall j$. The first term is the loss from participating in the common market due to the costs of the change of country i's own emission level. The second term is the gain due to decreased emissions in all other countries $j \in \mathcal{M}$. In cases where the price decreases if i participates in the common market, this term will be a loss. The third term is the trade balance of country i which can be either positive or negative.

The following parameters determine the sign of $\Delta_i^{\mathcal{M}}$: $\beta, \delta, D_i, e'_i, r'_i, \sum_{j\in\mathcal{M}-i} D_j$, $\sum_{j\in\mathcal{M}-i} e'_j, \sum_{j\in\mathcal{M}-i} r'_j$. The initial renewables stocks do not affect $\Delta_i^{\mathcal{M}}$. Whether or not a coalition $\mathcal{M}$ will link markets in equilibrium, and the largest number of countries that can link, depend on the characteristics of all N countries.

The results stated below follow from the MPE of the entire dynamic game. First, we consider identical countries and look at what determines the number of countries that will link their permit markets in equilibrium.

Lemma 3. *The largest number of identical countries that can link markets in equilibrium, M^*, is decreasing in the discount factor β, in the survival rate δ, and in the price sensitivity of the renewables producers, r'_j. It is increasing in the price sensitivity of the energy consumers, e'_j. The marginal damage from emissions, D_j, and the initial renewables capacity stocks, R_j do not affect M^*.*

[6] This is parallel to the definition of self-enforcing agreements used in Barrett (1994).

Proof. For identical countries we have $\Delta_i^{\mathcal{M}} = 0$ for $M \geq 0$ only when:

$$M^*(\Omega^{\mathcal{M}}) = -\frac{1}{2}\Omega^{\mathcal{M}} + 2 + \frac{1}{\Omega^{\mathcal{M}}} + \sqrt{\frac{1}{4}(\Omega^{\mathcal{M}})^2 + \Omega^{\mathcal{M}} + 4 + \frac{4}{\Omega^{\mathcal{M}}} + \frac{1}{(\Omega^{\mathcal{M}})^2}}, \qquad (14)$$

with $\Omega^{\mathcal{M}} = \frac{\beta\delta}{1-\beta\delta}\sum_{j\in\mathcal{M}} r'_j/(\sum_{j\in\mathcal{M}}(r'_j - e'_j))$. Furthermore, when $\Delta_i^{\mathcal{M}} = 0$ we have $\partial\Delta_i^{\mathcal{M}}/\partial M < 0$, meaning that $M^*(\Omega^{\mathcal{M}})$ gives the number of countries that will link markets in the MPE. We have $M^{*\prime}(\Omega^{\mathcal{M}}) < 0$, and the derivates of $\Omega^{\mathcal{M}}$ with respect to β, δ, r'_j and e'_j are found by differentiating $\Omega^{\mathcal{M}}$. $\Omega^{\mathcal{M}}$ does not depend on D_j or R_j for any j. □

The next result shows that there can potentially be large groups of countries with linked markets in equilibrium.

Proposition 6.

1. *For any number of identical countries, $M \leq N$, there exist parameter values such that an agreement to link permit markets between M countries will be an MPE outcome.*
2. *When countries are identical and $N \geq 3$, the number of countries that will link their markets in the MPE will be weakly larger than* 3.

Proof. We have that $\lim_{\beta\delta\to 0}\Omega^{\mathcal{M}} = 0$ and $\lim_{\beta\delta\to 1}\Omega^{\mathcal{M}} = \infty$. From Equation (14), we get $\lim_{\Omega^{\mathcal{M}}\to 0} M^*(\Omega^{\mathcal{M}}) = \infty$ and $\lim_{\Omega^{\mathcal{M}}\to\infty} M^*(\Omega^{\mathcal{M}}) = 3$ □

As an example illustrating this result, let $N \geq 10$, $D_i = 25$, $r'_i = 0.07$ and $e'_i = -1$ $\forall i$, while $\beta = \delta = 0.9$. Given these parameter values, we get $M^* = 10$, meaning that any 10 countries linking their markets is an MPE. With the initial renewables stocks $R_i = 0$ $\forall i$, the utility function parameter $u_{i1} = 500$ $\forall i$ and $N = 10$, linking would result in a 21.9% increase in welfare compared to the situation with no international trade, because of reduced emissions. For $N > 10$ the welfare gain from linking would be even larger, since even countries outside the linked market would benefit.

These results are partly in line with Barrett (1994). He considers self-enforcing environmental agreements with emission levels set to maximize the aggregate welfare of participating countries. He finds that a self-enforcing agreement can include a large number of countries, but only if the welfare gains from cooperation are relatively small. In our model, large agreements can be formed in equilibrium when $\Omega^{\mathcal{M}}$ is small. $\Omega^{\mathcal{M}}$ is small when $r'_j \to 0$ or $\beta\delta \to 0$, which both give weak incentives to withhold permits in the common market. However, this does not mean that agreements to link can be large in equilibrium only when the welfare gains are small. That is because higher marginal damage $\overline{D}$ means that welfare gains from linking are larger, while it does not affect the number of countries that will link markets in equilibrium.

As $\Omega^{\mathcal{M}} \to \infty$ the equilibrium price in the common permit market approaches the first-best price: $p^{\mathcal{M}} \to p^{FB}$. Hence, in this situation the model is close to the setup of Barrett (1994). The results are thus in line with his finding that with a linear-quadratic model, the largest self-enforcing agreement contains three countries.

Although agreements between large groups can be more difficult to form, heterogeneity does not prevent all agreements in equilibrium. In general, both the sign and the size of all derivatives of $\Delta_i^{\mathcal{M}}$ depend on the combination of all the parameters. The effect of a change in D_i on the incentives of country i to participate in the common market can serve as an example. Consider a country with $D_i = 0$. This country can never do worse by participating than it does in autarky, because it can always flood the market with permits until $p^{\mathcal{M}} = 0$. We know that this is not optimal behavior for such a country, since the equilibrium price will be higher than zero even if there exist countries in the common market with $D_i = 0$ (Lemma 2). Hence, this country can gain from participating. On the other hand, this is not necessarily the case for a country with low, but positive D_i. Such a country would incur a (potentially very large) loss from the increased emissions resulting from $p^{\mathcal{M}} = 0$. Therefore, flooding the market with permits is not necessarily a good option for this country. Finally, a country with high marginal damage, $D_i > p^{\mathcal{M}-i}$, could enter without changing its own permit issuance, resulting in $p^{\mathcal{M}} > p^{\mathcal{M}-i}$. While i would increase its emissions, the price change means higher permit issuance, but lower emissions $\forall\ j \in \mathcal{M} - i$. The change in its own emissions is costly, while the reduction in emissions in the other countries is beneficial. Depending on the exact parameters, a country with very high D_i could thus either gain or lose from participating and following this strategy. Hence, some countries with high D_i will gain from participating. In summary, an increase in D_i does not affect incentives to participate in the common market in a monotonic way or independently of the other parameters. Similar ambiguity arises for changes in all the parameters.

We discuss the effects on $\Delta_i^{\mathcal{M}}$ of changes in each of the parameters in more detail in Section G in the appendix.

Our final result tells us that it can be an equilibrium outcome that countries who care about climate change link their markets with countries who do *not* care about climate change. Such linking would result in lower aggregate emissions, including emission reductions in the country or countries that do not care.

Proposition 7. *There exist parameters such that both countries with $D_i = 0$ and $D_j > 0$ will participate together in a common international permit market in equilibrium.*

Proof. Given Equation (13), it is possible to find parameter values such that $\Delta_i^{\mathcal{M}} \geq 0$ $\forall i \in \mathcal{M}$ and $\Delta_i^{\mathcal{M}+i} \leq 0$ $\forall i \notin \mathcal{M}$ even when $\exists D_i = 0 \in \mathcal{M}$ and $\exists D_j > 0 \in \mathcal{M}$. □

A coalition of five heterogeneous countries that can form a self-enforcing agreement to link their markets is illustrated in Table 1.[7]

i	1	2	3	4	5
D_i	0	20	20	20	20
r_i'	0.2	0.2	0.2	0.2	0.2
e_i'	-1	-1	-1	-1	-1
$V_i^{aut\|\emptyset *}$	648	150	150	150	150
$V_i^{\mathcal{M}*}$	669	187	187	187	187
$\Delta_i^{\mathcal{M}*}$	2.1	0.1	0.1	0.1	0.1

* In thousands. $\beta = 0.9$, $\delta = 0.9$.
$\sum_{i=1}^{5}(V_i^{\mathcal{M}} - V_i^{aut|\emptyset})/\sum_{i=1}^{5} V_i^{aut|\emptyset}$ =0.135.

Table 1: Let $N = 10$ and let countries $6 - 10$ be identlical to countries $2 - 5$ in the table. Then, an agreement to link markets between countries $1 - 5$ is an equilibrium outcome. Country 1 does not care about climate change, but is willing to enter the common market and will reduce its emissions in the MPE compared to autarky. Countries $2 - 5$ care about climate change, but are despite this willing to link markets with country 1. The agreement gives a 13.5 % increase in welfare for the linked countries in total.

Countries that do not care about climate change cannot be expected to join international cooperation to reduce emissions. However, our results show that such countries can gain from reducing emissions if they participate in international permit trade. Moreover, countries with $D_i > 0$ can also gain from linking their markets with such a country.

We have shown in this section that agreements to link permit markets can prevail in equilibrium. Such equilibrium agreements can include a large number of countries, and at the same time deliver substantial welfare gains.

4 Conclusion

We consider international trade in emission permits in a situation in which there are investments in renewable energy production capacities. We show that even if countries do

[7] In Table 1, $u_{i1} = 360$ and $R_{i0} = 0$, $\forall i$.

not cooperate on the emission caps they set, a simple linkage between their emission permit markets leads to reduced emissions and higher welfare. This is the case even if countries are identical so that no trade takes place in equilibrium. We also show that agreements to link permit markets between large groups of countries and between groups including countries that value emission reductions very differently can prevail in equilibrium.

In the appendix, we provide a range of extensions to the model. We first consider a case where some countries can cover their entire energy demand with renewable energy. Then, we go on to discuss the welfare effects of linkages when countries differ in their marginal damages. We also discuss the implications of linkages for different countries. Furthermore, we extend the model by adding a convex variable cost of producing renewable energy, and by letting renewables investments be determined by the governments. Finally, we discuss the size of the welfare effects we identify and show how they depend on key parameters of the model.

There are also several other directions in which we believe that the framework in this paper can be developed in future work. One is to identify which permit market linkages are most beneficial to undertake. This can depend, for example, on country characteristics, linking protocols, or the timing of linkages.

We have chosen to investigate a simple, and exogenous, linkage design in this paper. However, there are interesting questions concerning both how different designs would affect the outcome, and what the prevailing design would be if countries were allowed to negotiate it before or after entering the agreement. In particular, in many ETSs, permits are not issued period by period, but can be used and traded over several time periods. The benefits from linking that we identify in this paper are due to the intertemporal strategic complementarity in the emission caps across countries that arise in equilibrium. An opportunity to commit to future permit issuance through issuing permits that will last for several periods could therefore potentially strengthen the incentive to withhold permits. A full treatment of this issue would be an interesting path for future research.

Finally, and related to the previous point, trade sanctions can potentially constitute a powerful incentive for abatement, and investigating the potential for trade sanctions to be a deterrent in a dynamic setting with international permit trade could be an important next step in this literature.

Technical Appendix

E Fossil energy use over time

In the basic model in the paper, the total energy use is constant while the renewables stocks develop over time, meaning that the fossil energy use is also changing over time. Because the renewables stocks depreciate at a constant rate, while equilibrium renewables investments are constant over time, the stocks will eventually reach a steady-state level in each country. The development over time of each country's stock can take two different paths:

- If the stock is large enough in period 0, the depreciation will override the added capacity resulting from investment, and the stock will decrease over time. In this case, the steady-state stock is smaller than the initial stock.
- If the stock is small enough in period 0, the added capacity will override the depreciation, and the stock will increase over time. The steady-state stock will be larger than the initial stock.

The steady-state levels of the renewable energy production capacity stocks are determined by the depreciation rate and the per-period investments, which are again determined by the investment cost and the prevailing equilibrium price . In the paper, we consider only cases where there is always positive fossil energy use in equilibrium. In the following, we first provide a set of conditions that ensure that this will be the case in steady state. Following this, we consider the case where these conditions do not hold for all countries.

E1 Conditions for positive fossil energy use over time

Time subscripts are dropped in this section, unless clearly needed. The constant equilibrium permit price is given by the following expression (see Lemma 2):

$$p^{\mathcal{M}} = \overline{D}^{\mathcal{M}} \frac{1+\Omega}{1+\frac{1}{M}\Omega} > \overline{D}^{\mathcal{M}}, \tag{15}$$

From the investment behavior derived in the paper, it follows that the stock of renewable energy capacity available at the beginning of period t in country $i \in \mathcal{M}$ in the MPE is given by

$$\delta^t R_{i0} + \delta^{t-1} r_i(p_1) + \ldots + \delta r_i(p_{t-1}) = \delta^t R_{i0} + \sum_{s=1}^{t-1} \delta^{t-s} r_i(p_s)$$

which, given the constant equilibrium price, gives the steady-state stock:

$$R_i^{SS} = \frac{\delta}{1-\delta} r_i \left(\frac{p^{\mathcal{M}}}{1-\beta\delta} \right).$$

The steady-state consumption level is given by:

$$e_i^{SS} = e_i(p^{\mathcal{M}}).$$

In the MPE, the following assumptions are sufficient to ensure that no country is completely saturated by renewables in any time period:

$$e_i\left(p^{\mathcal{M}}\right) > \frac{1}{1-\delta} r_i \left(\frac{p^{\mathcal{M}}}{1-\beta\delta} \right) \ \forall i, \tag{16}$$

$$e_i\left(p^{\mathcal{M}}\right) > R_{i0} + r_i \left(\frac{p^{\mathcal{M}}}{1-\beta\delta} \right) \ \forall i. \tag{17}$$

The first equation states that steady state consumption must exceed the steady state stock of renewables capacity in every country, while the second equation states that demand must also exceed the initial stock in every country. These conditions determine an implicit upper bound on β and δ. As $\beta\delta$ goes to 1, investors do not discount the future, and the stock never depreciates. This means that positive investments in every period will lead the stock to explode, and it also means that investors are willing to undertake infinite investments in every period, as long as they expect a positive price in future periods.

Note that there always exist parameters such that any pair (β, δ) satisfies the two conditions, as long as $\beta, \delta < 1$.

Because the consumption levels are lower, and the investment levels are higher in the first-best allocation than in the MPE, the following assumptions are necessary in order to ensure that the same is true in the first best:

$$e_i\left(p^{FB}\right) > \frac{1}{1-\delta} r_i\left(\frac{p^{FB}}{1-\beta\delta}\right) \; \forall i,$$
$$e_i\left(p^{FB}\right) > R_{i0} + r_i\left(\frac{p^{FB}}{1-\beta\delta}\right) \; \forall i,$$

where $p^{FB} = \sum_j D_j$.

E2 Excess renewables supply

In this section, we consider a situation where the conditions given by Equation (16) and (17) do not necessarily hold for all countries. We solve the second stage of the model when the number of time periods is reduced to only two, and time is counted backwards, with $t = 1$ and $t = 0$ (last period). For simplicity, we consider only the second stage of the dynamic game, and we look at N countries that are either all in autarky, or all linked to a common permit market.

Consumers behave as before, leading to energy demand $e_i(p_{it})$ as in the basic model. The representative renewables producer in country i solves the following problem:

$$\max_{r_{it}} \{\hat{p}_{it} r_{it} - c_i(r_{it})\} \Rightarrow r_i(\hat{p}_{it}).$$

where, as before, $\hat{p}_{it}$ denotes the sum of (discounted) current and future domestic prices, hence $\hat{p}_{i0} = p_{i0}$ and $\hat{p}_{i1} = p_{i1} + \beta\delta p_{i0}$. The domestic energy (and permit) price may or may not be equal to an international permit price, here denoted p_t.

If a country's energy demand is completely covered by renewable energy in period t, it must be the case that the domestic market clears such that $R_{it}+r_i(\hat{p}_{it}) = e_i(p_{it})$ at $p_{it} < p_t$. In this case, domestic consumers demand no emission permits, and we say that country i is saturated: $i \in S_t$. Since the domestic energy price in such a country is lower than the international permit price, the supply of renewables from producers in this country is independent of the permit price. If $i \notin S_t$, we say $i \in NS_t$.

In the international permit market, market clearing requires $\sum_i \omega_{it} = \sum_i f_{it}$, which is equivalent to:

$$\sum_i \omega_{it} + \sum_{i \in NS_t} R_{it} = \sum_{i \in NS_t} e_i(p_t) - \sum_{i \in NS_t} r_i(\hat{p}_t),$$

because $e_i(p_{it}) = R_{it} + r_i(\hat{p}_{it}) \; \forall i \in S_t$. This market clearing condition defines the international price in each time period as a function of supply of permits and renewables in that period, s_t, denoted $\tilde{p}(s_t)$, with slope given by:

$$\tilde{p}'(s_t) = \frac{1}{\sum_{i \in NS_t} e_i'(p_t) - \sum_{i \in NS_t} r_i'(\hat{p}_t)}.$$

The government in country $i \in S_0$ solves the following problem in period 0:

$$V_{0,i \in S_0} = u_i(e_i(p_{i0})) - c_i(r_i(\hat{p}_{i0})) + \max_{\omega_{i0}} \left\{ \tilde{p}(s_0)\omega_{i0} - D_i \sum_j \omega_{j0} \right\},$$

giving the first-order condition

$$\tilde{p}(s_0) + \tilde{p}'(s_0) \cdot \omega_{i0} = D_i. \tag{18}$$

The non-saturated countries solve the same problem as in our the basic model:

$$V_{0,i \in NS_0} = \max_{\omega_{i0}} \Big\{ u_i(e_i(\tilde{p}(s_0))) - c_i(r_i(\hat{p}_0)) + \tilde{p}(s_0)(\omega_{i0} + R_{i0} + r_i(\hat{p}_0) - e_i(\tilde{p}(s_0))) - D_i \sum_j \omega_{j0} \Big\},$$

and the first-order condition becomes

$$\tilde{p}(s_0) + \tilde{p}'(s_0) \cdot (\omega_{i0} + R_{i0} + r_i(\hat{p}_0) - e_i(\tilde{p}(s_0))) = D_i.$$

Summing over the N first-order conditions, and invoking market clearing, we get the equilibrium price in the last time period:

$$p_0 = \overline{D},$$

which is independent of the number of saturated countries. Furthermore,

$$\frac{\partial \omega_{i0}^{\mathcal{M}}}{\partial R_{j0}} = \begin{cases} -1, & i = j, i \in NS_0 \\ 0, & \text{else.} \end{cases}$$

The permit issuance of saturated countries is independent of their domestic renewables stocks, while that of the non-saturated countries is not. When $i \in NS_0$, this happens for the same reason as in the basic model. For $i \in S_0$, it follows directly from the first-order condition given by Equation (18). This means that

$$\frac{\partial V_{0,i}}{\partial R_{j0}} = \begin{cases} D_i, & j \in NS_0 \\ p_{i0}, & i = j, j \in S_0 \\ 0, & i \neq j, j \in S_0 \end{cases}$$

The other countries benefit from more renewable energy available in country i only if country i is not saturated.

In period 1, a saturated country solves

$$V_{1,i\in S_1} = u_i(e_i(p_{i1})) - c_i(r_i(\hat{p}_{i1})) + \max_{\omega_{i1}} \left\{ \tilde{p}(s_1) \cdot \omega_{i1} - D_i \sum_j \omega_{j1} + \beta V_{0,i} \right\},$$

with first-order condition

$$\tilde{p}(s_1) + \tilde{p}'(s_1) \cdot \omega_{i1} = D_i - \beta\delta \sum_{j \in NS_1} \frac{\partial V_{0,i}}{\partial R_{j0}} \tilde{p}'(s_1) r_j'(\hat{p}_1).$$

Whereas a non-saturated country solves

$$V_{1,i\in NS_1} = \max_{\omega_{i1}} \Big\{ u_i(e_i(\tilde{p}(s_1))) - c_i(r_i(\hat{p}_1)) + \tilde{p}(s_1) \cdot (\omega_{i1} + R_{i1} + r_i(\hat{p}_1) - e_i(\tilde{p}(s_1))) - D_i \sum_j \omega_{j1} + \beta V_{0,i} \Big\},$$

with first-order condition

$$\tilde{p}(s_1) + \tilde{p}'(s_1)(\omega_{i1} + R_{i1} + r_i(\hat{p}_1) - e_i(\tilde{p}(s_1))) = D_i + \beta\delta\tilde{p}'(s_1) r_i'(\hat{p}_1)\overline{D} - \beta\delta\tilde{p}'(s_1) \sum_{j \in NS_1} \frac{\partial V_{0,i}}{\partial R_{j0}} r_j'(\hat{p}_1).$$

Employing the information above and using the market clearing condition, the N first-order conditions sum to give us

$$p_1 = \overline{D}\left[1 - \beta\delta\tilde{p}'(s_1)\left(\sum_{j\in NS_1} r_j'(\hat{p}_1) - \frac{1}{N}\sum_{i\in NS_1} r_i'(\hat{p}_1)\right)\right] \geq \overline{D}.$$

Recall that the autarky price is given by $\overline{D}$. The price above is greater than the autarky price whenever $|NS| > 0$, and converges on $\overline{D}$ when $|NS| \to 0$. In this two-period model, we have thus shown that the mechanism identified in the main part of this paper is in play also in the case where there is excess supply of renewable energy in some countries, resulting in zero permit demand from consumers in these countries.

In the general model with infinite time span, countries may become saturated at any point in time. Countries that are saturated in the first time period (Equation (17) does not hold), may either stay saturated forever (if Equation (16) does not hold either), or they may eventually be non-saturated.

For countries that are not saturated in the first period, but in which the steady-state value of the renewables stock is such that Equation (16) does not hold, the stock will eventually reach a point where the country is saturated. Since the energy price in a saturated country is decoupled from the international permit price, renewables producers in these countries do not react to increases in this price. As more countries become saturated, there remains fewer countries that can be affected by withholding permits. As a result, the equilibrium permit price decreases.

F Country heterogeneity

In the paper, we discuss welfare implications of linking permit markets in the case where the countries are identical, and in the case where they share only a common marginal damage, $D_i = \overline{D}\ \forall i$. In this section, we present results in the case where countries differ in their marginal damages, and discuss the implications of allowing for full heterogeneity across countries in the model. We here also show how the distribution across countries of the welfare gains from linking markets depends on key parameters in the model. The analytical results in this section are derived under the assumption that the utility and cost functions in all countries are quadratic, meaning that $u'''(\cdot) = c'''(\cdot) = 0$. This assumption makes it possible to provide the analytical results. Again, time subscripts are dropped unless clearly needed.

F1 International permit trade between heterogeneous countries

In the paper, the key to the clear-cut welfare results was the fact that all consumers and producers experience an increased price on emission permits when permit markets are linked. When countries differ in their marginal damage, D_i, it is no longer clear that this will be the case. If some countries face a price decrease following the introduction of international permit trade, emissions from these countries would increase under trade. At the same time, other countries' consumers and producers will face a price increase which will lead to reduced emissions. This means that the aggregate effect on emissions and welfare of linking the permit markets is ambiguous, and it depends on which consumers and producers that react strongest to the price change. However, by restricting the analysis to the case where supply and demand are identical and linear so that the reaction to a given price change is the same for all consumers and investors, the effect of introducing international permit trade is still clearcut: aggregate emissions decrease, and aggregate welfare increases. This is because the strategic complementarity in emission levels results in a price increase in the average country. This is stated in the next result where superscript $\mathcal{N}$ represents values when the N markets are linked:

Proposition 8. *Consider a group of N countries, who all have identical quadratic utility and cost functions. Linking the permit markets of these countries reduces aggregate emissions and increases aggregate welfare by increasing aggregate investments and reducing aggregate consumption:* $\sum_i r_i^{\mathcal{N}} > \sum_i r_i^{aut|\emptyset}$, $\sum_i e_i^{\mathcal{N}} < \sum_i e_i^{aut|\emptyset}$, $\sum_i f_i^{\mathcal{N}} < \sum_i f_i^{aut|\emptyset}$ *and* $\sum_i V_i^{\mathcal{N}} > \sum_i V_i^{aut|\emptyset}$.

Proof. The value functions under autarky and trade respectively are given by:

$$
\begin{aligned}
V_i^{aut|\emptyset}(R_1,\ldots,R_N) =& \frac{1}{1-\beta}\Bigg[u_i(e_i(D_i)) - c_i(r_i(\frac{D_i}{1-\beta\delta})) - D_i\sum_j e_j(D_j) \\
&+\frac{D_i}{1-\beta\delta}\sum_j r_j(\frac{D_j}{1-\beta\delta})\Bigg] + \frac{D_i}{1-\beta\delta}\sum_j R_j, \\
V_i^{\mathcal{N}}\Big(R_1,\ldots,R_N\Big) =& \frac{1}{1-\beta}\Bigg[u_i(e_i(p^{\mathcal{N}})) - c_i(r_i(\hat{p}^{\mathcal{N}})) + p^{\mathcal{N}}\cdot TB_i \\
&- D_i\sum_j e_j(p^{\mathcal{N}}) + \frac{D_i}{1-\beta\delta}\sum_j r_j(\hat{p}^{\mathcal{N}})\Bigg] + \sum_j \frac{D_i}{1-\beta\delta}R_j
\end{aligned}
$$

For notational simplicity, we will in the following let p denote the equilibrium price under permit trade, $p^{\mathcal{N}}$. For each country i, define the welfare gain from introducing permit trade as $\Delta_i = (1-\beta)(V_i^{\mathcal{N}} - V_i^{aut|\emptyset})$. Using the expressions for the value functions, rearranging and simplifying, and remembering the simplifying assumption $u'''(\cdot) = c'''(\cdot) = 0$, the welfare gain can be expressed as:

$$\Delta_i = \underbrace{\left(\frac{r_i'}{(1-\beta\delta)^2} - e_i'\right)}_{\equiv K>0} \left(\frac{1}{2}D_i^2 - \frac{1}{2}p^2 + D_i N p - D_i \sum_j D_j\right) + pTB_i. \tag{19}$$

The equilibrium permit price under international trade (Equation (15)) can be written as $p = B\overline{D}$, $B \in [1, N)$. Inserting this expression for p, rearranging and summing over all i gives this expression for the aggregate welfare gain:

$$\sum_i \Delta_i = K \cdot \left(\frac{1}{2}\sum_i (D_i^2) + \left(\sum_i D_i\right)^2 \underbrace{\left(B - 1 - \frac{1}{2}\frac{B^2}{N}\right)}_{\alpha}\right).$$

The parenthesis labeled α is non-decreasing in B in the relevant region. Hence, if we can prove that $\sum_i \Delta_i$ is positive for $B = 1$, we have proved it for every relevant B. Insert for $B = 1$ to get

$$\sum_i \Delta_i = K\frac{1}{2}\sum_i \left(D_i - \overline{D}\right)^2,$$

where the last term is the non-negative sample variance of D_i. Hence, the aggregate welfare increases when international permit trade is introduced. Only if countries are identical in every respect ($D_i = \overline{D}$, $\forall i$) and we are in the static model ($\beta\delta = 0 \Rightarrow B = 1$), are there no positive aggregate gains from introducing trade in this case. □

If countries differ both in their marginal damages and their cost and utility functions at the same time, the effect on aggregate emissions of introducing international permit trade is ambiguous, and a full calibration of the model is needed in order to give clearcut results. The reason for this is that there might exist countries that experience a price decrease when the markets are linked, that is countries where $D_i > p^{\mathcal{N}}$, when the countries differ in their marginal damages. If in addition, the consumers and producers differ between countries in their reaction to price changes, it might be the case that the effect on consumption and investment - and hence emissions - is stronger in the countries with $D_i > p^{\mathcal{N}}$ than in the countries experiencing a price increase. If this difference is large enough, the total effect on emissions of introducing international permit trade will be positive, and the welfare effect will then be negative.

For a study on this interaction between marginal damage and demand and supply responses in a static setting, see Holtsmark and Sommervoll (2012). They argue that the countries with high marginal damage from climate change are likely to be the largest countries, which can also be expected to have the most price sensitive energy demand and investments, because they have many consumers and investors. In the static model they present, this leads to a net loss in welfare from introducing international permit trade. However, in the dynamic model we consider in this paper this is less likely to be the case because of the strategic incentive to withhold permits that arise. In the static model, the average country will have $D_i = p^{\mathcal{N}}$ while all countries with $D_i > \overline{D}$ will face a price decrease when the markets are linked. In the dynamic model, we have $p^{\mathcal{N}} > \overline{D}$, meaning that fewer countries will experience a lower price when markets are linked. If the strategic incentive to withhold permits that we have identified is sufficiently strong, no country will. And if this is the case, permit market linkage will increase welfare also in the case with fully heterogenous countries.

F2 Welfare implications for different countries

When countries are heterogeneous, some may benefit more than others when international permit trade is introduced. In this section, we study which country characteristics that determine this heterogeneity in outcomes. Whether or not a particular country gains depends on the extent to which this country benefits from reduced emissions and to what extent the country benefits from buying and selling permits in the international market. Countries with higher marginal damage gain more from the reduced emissions following the introduction of international permit trade, but, as the next proposition demonstrates, will also to a larger extent import permits, which is costly.

Proposition 9. *Consider two countries, i and j. Country i will import more permits than country j if either*

1. *country i has a higher marginal damage, $D_i > D_j$, all else equal, or*

2. *country i has less price-responsive renewables producers, $r_i'(\cdot) < r_j'(\cdot)$, all else equal.*

Proof. The first-order condition of country i is given in the paper in Equation (10), and the expression for the continuation value is given in the proof of Lemma 1. Inserting this expression, together with the definition $\Omega_i = -\frac{\beta\delta}{1-\beta\delta} r_i'(\hat{p})p'(s) > 0$, and solving the first-order condition for the country's net sales of permits in the international permit market, $TB_i = \omega_i + R_i + r_i - e_i$, gives

$$TB_i = \underbrace{\frac{\overline{D}(1+\Omega)}{-p'(s)}}_{>0} \left(\frac{1+\Omega_i}{1+\overline{\Omega}} - \frac{D_i}{\overline{D}} \right),$$

where $\overline{D}$ represents the average marginal damage of the countries in the international market and p id the permit price in the common market. □

If countries only differ in their marginal damage, countries with higher-than-average marginal damage will be importers of permits, while countries with lower-than-average marginal damage will be permit exporters. Similarly with the price-responsivity of their renewables producers, countries with the least price-responsive renewables producers will be permit importers. These countries face stronger incentives to withhold permits as their trade partners are more price-responsive and will reduce their future permit issuance the most in response to a permit being withheld today.

Countries with higher-than-average marginal damage gain more from reduced emissions but they must buy permits from the low-damage countries in order to reduce emissions. A priori it is not, therefore, obvious whether high- or low-damage countries gain the most from introducing international permit trade. As the next proposition demonstrates, this depends on the parameters of the model.

Proposition 10. *Assume that countries have identical, quadratic utility and cost functions but their marginal damages differ ($D_i \neq D_j$, if $i \neq j$). Then:*

1. *In the static model ($\beta = \delta = 0$), low-damage countries gain more from introducing permit market linkages than do high-damage countries:*
   $V_i^{\mathcal{N}} - V_i^{aut|\emptyset} > V_j^{\mathcal{N}} - V_j^{aut|\emptyset}$, *if* $D_i < D_j$.

2. *There exists a threshold $\underline{\beta\delta} \in (0,1)$ such that if $\beta\delta > \underline{\beta\delta}$, high-damage countries gain more from introducing permit market linkages than do low-damage countries:*
   $V_i^{\mathcal{N}} - V_i^{aut|\emptyset} > V_j^{\mathcal{N}} - V_j^{aut|\emptyset}$, *if* $D_i > D_j$.

Proof. We start out by inserting in Equation (19) for the expression for the trade balance. We can then separate the gain to country i from introducing trade into a term that depends on D_i and a term that is independent of D_i:

$$\begin{aligned}
\Delta_i &= A + f(D_i), \text{ where} \\
A &= e_i' \frac{p^2}{2} - r_i' \frac{1}{(1-\beta\delta)^2} \frac{p^2}{2} + p\overline{D}N \left(\frac{1}{1-\beta\delta} r_i' - e_i' \right), \text{ and} \\
f(D_i) &= D_i \left(\frac{D_i}{2} - N\overline{D} \right) \left(\frac{r_i'}{(1-\beta\delta)^2} - e_i' \right) + D_i N p r_i' \frac{\beta\delta}{(1-\beta\delta)^2}.
\end{aligned}$$

We are interested in whether $f(D_i)$ is increasing in D_i or not. We start with the proof for Proposition 10.2, and take it step by step.

1. For simplicity, assume that there is a continuum of different D_i's, such that we can differentiate f. We thus want to know the sign of $f'(D_i)$.

2. We have that

$$\begin{aligned}
f'(D_i) &= \left(D_i - N\overline{D} \right) \left(\frac{r_i'}{(1-\beta\delta)^2} - e_i' \right) + N p r_i' \frac{\beta\delta}{(1-\beta\delta)^2}, \text{ and} \\
f''(D_i) &= \left(\frac{r_i'}{(1-\beta\delta)^2} - e_i' \right) > 0.
\end{aligned}$$

   $f(D_i)$ is thus convex, so if $f'(0) > 0$, then $f' > 0$ for all relevant D_i, and we have that high-damage countries gain more from introducing trade than low-damage countries.

3. We have that $f'(0) < 0$ for $\beta\delta = 0$, while $\lim_{\beta\delta \to 1} f'(0) = \infty$, thus by the intermediate value theorem, there exists some $\underline{\beta\delta}$ such that $f'(0) > 0$ for $\beta\delta > \underline{\beta\delta}$. This $\underline{\beta\delta}$ is the highest $\beta\delta$ for which $f'(0) = 0$, where we need to take into account that as $\beta\delta \in [0,1)$, $p \in [\overline{D}, N\overline{D})$.

4. We now restate Equation (16) for quadratic utility and cost functions:

$$\frac{1}{1-\delta} r_i' \frac{p}{1-\beta\delta} < e_i(0) + e_i' \cdot p. \tag{16 LQ}$$

   As $p \in (\overline{D}, N\overline{D})$, we can, for any $\underline{\beta\delta} < 1$, find some $e_i(0)$ such that there exist β and δ (*i.e.* a pair (β, δ)) such that Equation (16 LQ) is satisfied, given the other parameters, yet $\beta\delta > \underline{\beta\delta}$.

5. For such a pair (β, δ), we have that $f'(0) > 0$, and as $f(D_i)$ is convex, we must have that $f'(D_i)$ is positive for all relevant D_i. For such a pair, it is therefore the case

that high-damage countries gain more from introducing international permit trade than low-damage countries do. This concludes the proof of Propositon 10.2.

To prove Propositon 10.1, note that $f'(0) < 0$, while $f'(N\overline{D}) = 0$, for $\beta\delta = 0$, and f is still convex. Thus $f'(D_i) \leq 0$ for all relevant D_i, and the result follows immediately. □

Proposition 10.1 is a corollary to Proposition 1 in Helm (2003), which states that low-damage countries are permit sellers in the static model. Under constant marginal damages, the static permit market delivers no emission reductions "on average," and the permit market is merely a transfer scheme from high- to low-damage countries. Thus, the low-damage countries benefit and the high-damage countries lose when international permit trade is introduced.

Proposition 10.2 states that in the dynamic model, as the countries become patient enough and the renewables stocks become durable enough, this ranking is reversed. In this case, high-damage countries gain more from introducing international permit trade than do low-damage countries. Although according to Proposition 9, high-damage countries are still permit importers, when $\beta\delta$ is high enough, the permit market delivers sufficient emission reductions for the high-damage countries to gain more than low-damage countries.

G Participation in international permit trade

In the last section, we discussed how the gain from the introduction of permit trade depends on the characteristics of the individual countries. However, it is possible that a given country i gains from the overall introduction of international permit trade, while it would still be *even better off* if the other countries linked their markets, while i remained outside the system.

In this section, we discuss how changes in each of the parameters of the model affect the incentives facing countries in the initial stage of the dynamic game, when they determine whether or not to join the coalition of countries that link their markets.

As in the paper, an agreement made by a coalition $\mathcal{M}$ consisting of M countries to link their permit markets is defined as self-enforcing if and only if

$$\Delta_i^{\mathcal{M}} \geq 0 \ \ \forall i \in \mathcal{M} \qquad \text{and} \qquad \Delta_i^{\mathcal{M}+i} \leq 0 \ \ \forall i \notin \mathcal{M},$$

with

$$\Delta_i^{\mathcal{M}} = -\frac{1}{2}(p^{\mathcal{M}} - D_i)^2 E_i + D_i(p^{\mathcal{M}} - p^{\mathcal{M}-i}) \sum_{j \in \mathcal{M}-i} E_j + p^{\mathcal{M}} TB_i^{\mathcal{M}}. \tag{20}$$

where

$$\begin{aligned}
E_i &= -e_i' + \frac{r_i'}{(1-\beta\delta)^2} \\
TB_i^{\mathcal{M}} &= \sum_{j \in \mathcal{M}} (r_j' - e_j')(p^{\mathcal{M}} - D_i) - \frac{\beta\delta}{1-\beta\delta}\left(D_i \sum_{j \in \mathcal{M}} r_j' - p^{\mathcal{M}} r_i'\right) \\
p^{\mathcal{M}} &= \overline{D}\frac{1+\Omega^{\mathcal{M}}}{1+\frac{1}{M}\Omega^{\mathcal{M}}} \\
\Omega^{\mathcal{M}} &= \frac{\beta\delta}{1-\beta\delta}\frac{\sum_{j \in \mathcal{M}} r_j'}{\sum_{j \in \mathcal{M}}(r_j' - e_j')}
\end{aligned}$$

where we have assumed that the utility function, $u_i(\cdot)$, and the investment cost function, $c_i(\cdot)$, are both quadratic functions $\forall i$.

The following parameters determine the sign and the magnitude of $\Delta_i^{\mathcal{M}}$: β, δ, D_i, e_i', r_i', $\sum_{j \in \mathcal{M}-i} D_j, \sum_{j \in \mathcal{M}-i} e_j', \sum_{j \in \mathcal{M}-i} r_j'$. The initial renewables stocks do not affect $\Delta_i^{\mathcal{M}}$. In the following, we will discuss what determines the sign and size of the derivatives of $\Delta_i^{\mathcal{M}}$ with respect to each of these parameters.

The (postive or negative) net value for country i of being part of the coalition $\mathcal{M}$, consists of three parts:

- The direct loss: Country i must change its own emission level. i must decrease its emissions (decrease energy consumption and increase renewables investments) if $D_i < p^{\mathcal{M}}$, which will be the case for the average D_j in $\mathcal{M}$. i must increase its emission level if $D_i > p^{\mathcal{M}}$.

- The direct gain: An additional country will change the price in the coalition. For very low D_i the price will decrease if i is part of the coalition, but for "most" countries, joining the coalition will give a price increase and hence decrease emissions in all countries $j \in \mathcal{M} - i$.

- The gain or loss from $TB_i^{\mathcal{M}}$: Some countries (all else equal the countries with relatively low D_i, and highly price sensitive energy consumers and renewables investors) will have a positive trade balance, while other countries will have a negative trade balance, if entering the coalition.

G1 Changes in β or δ

β or δ increases either because all countries become more patient or because the renewables stocks become more durable. In both cases, it will strengthen the strategic incentive to withhold permits in the common market and therefore increase the common permit price for any $\mathcal{M}$ as long as $M \geq 2$. This will lead to higher cost of entering in terms of own emission reductions, because the necessary domestic emission reductions increase when $p^{\mathcal{M}}$ increases. On the other hand, it will also increase the gain from entering, because the reactions of renewables producers in all countries to a given price change is strengthened. The effect on country i's trade balance depends on the parameter combination. An increase in β or δ therefore leads to:

- A higher direct loss from entering the agreement.
- A higher direct gain from entering the agreement.
- An ambiguous change in $TB_i^{\mathcal{M}}$.

Hence, the overall effect on the incentive of country i to enter the agreement is ambiguous. This can be confirmed by differentiating Equation (20) with respect to $\beta\delta$. It can be exemplified as follows: On the one hand, think of a situation where the countries $j \in \mathcal{M} - i$ on average have renewables investors that are very sensitive to price changes. An increase in $\beta\delta$ – giving a higher price increase if i chooses to enter the coalition – that makes the gain from entering higher. On the other hand, if the other countries, $j \in \mathcal{M} - i$, have investors that react very little to a given price increase, an increase in $\beta\delta$ could rather increase the loss of entering relative to the gain.

G2 Changes in D_i

When D_i increases the effect that i entering will have on the common permit market price is higher . At the same time, the difference between the common market price $p^{\mathcal{M}}$ and the price that i will set in autarky is lower, as long as $p^{\mathcal{M}} > D_i$. On the other hand, a higher D_i increases the probability that i will get a negative trade balance if it enters. In summary, an increase in D_i leads to:

- A lower direct loss from entering the agreement.

- A higher direct gain from entering the agreement.
- A decrease in $TB_i^{\mathcal{M}}$, decreasing the gain or increasing the loss from entering the agreement.

Hence, the overall effect on the incentive of country i to enter the agreement of an increase in D_i is ambiguous. This can be confirmed by differentiating Equation (20) with respect to D_i.

G3 Changes in $\sum_{j\in\mathcal{M}-i} D_j$

An increase in $\sum_{j\in\mathcal{M}-i} D_j$ will increase the common market price whether or not i is part of the common market. It will not affect the change in price resulting from i entering, but it will affect the gain from entering through the trade balance: In summary, it will lead to:

- A higher direct loss from entering the agreement.
- An increase in $TB_i^{\mathcal{M}}$, increasing the gain or decreasing the loss from entering the agreement.

Hence, the overall effect on the incentive of country i to enter the agreement of an increase in $\sum_{j\in\mathcal{M}-i} D_j$ is ambiguous. This can be confirmed by differentiating Equation (20) with respect to $\sum_{j\in\mathcal{M}-i} D_j$.

G4 Changes in r_i'

When r_i' increases the effect on the common market price of i entering is increased, because it increases the strategic incentive to withhold permits for all the other countries $j \in \mathcal{M}-i$. A higher r_i' also strengthens the effect on i's investors of entering the common market and it affects the trade balance positively. In summary, it leads to

- A higher direct loss from entering the agreement.
- A higher direct gain from entering the agreement.
- An increase IN $TB_i^{\mathcal{M}}$, increasing the gain or decreasing the loss from entering the agreement.

Hence, the overall effect on the incentive of country i to enter the agreement of an increase in r_i' is ambiguous. This can be confirmed by differentiating Equation (20) with respect to r_i'. Again, an example can illustrate this: In very many cases, a higher r_i' will increase the gain from entering the coalition, because it induces the other countries to withhold more permits if i is part of the common market. However, this is not generally true. For example, for a country with a very low marginal damage, the induced emission reductions are of low value, and the increase in the loss from being part of the coalition dominates so that an increase in r_i' instead makes it more costly to enter the coalition.

G5 Changes in $\sum_{j\in\mathcal{M}-i} r_j'$

An increase in $\sum_{j\in\mathcal{M}-i} r_j'$ increases the strategic incentive to withhold permits in the common market, both for country i and for the countries $j \in \mathcal{M} - i$. This means that the common market permit price is increased, and it also means that the effect on the common price of i entering will be higher, but more importantly that the effect of this price increase on investments in $j \in \mathcal{M} - i$ is strengthened. The effect on i's trade balance of an increase in $\sum_{j\in\mathcal{M}-i} r_j'$ is ambiguous. In summary, an increase in $\sum_{j\in\mathcal{M}-i} r_j'$ leads to:

- A higher direct loss from entering the agreement.
- A higher direct gain from entering the agreement.
- An ambiguous change in $TB_i^{\mathcal{M}}$.

Hence, the overall effect on the incentive of country i to enter the agreement of an increase in $\sum_{j\in\mathcal{M}-i} r_j'$ is ambiguous. This can be confirmed by differentiating Equation (20) with respect to $\sum_{j\in\mathcal{M}-i} r_j'$. This is easy to understand thinking of a country with very high versus very low D_i. If D_i is high the increase i the induced emission reductions if i enters will affect i's incentives to enter the agreement strongly, and $\Delta_i^{\mathcal{M}}$ will increase, while if D_i is low the increased cost of entering might dominate.

G6 Changes in e_i'

An increase in e_i' will decrease the effect on the common price of i entering the agreement, but it will also directly affect the cost of entering through the cost of reducing emissions. Furthermore, while e_i' affects the trade balance of country i, the sign of the effect is ambiguous. This is because lower permit price pulls in the direction of a lower trade balance, while the direct effect of more price sensitive consumers pulls in the other direction. In summary, an increase in e_i' gives:

- An ambiguous effect on the direct loss from entering the agreement.
- A lower direct gain from entering the agreement.
- An ambiguous effect on $TB_i^{\mathcal{M}}$.

Hence, the overall effect on the incentive of country i to enter the agreement of an increase in e_i' is ambiguous. This can be confirmed by differentiating Equation (20) with respect to e_i'.

G7 Changes in $\sum_{j\in\mathcal{M}-i} e_j'$

An increase in $\sum_{j\in\mathcal{M}-i} e_j'$ will decrease the common market permit price whether or not i enters the coalition. This means that the cost of entering in terms of own emission reductions for i is lowered. At the same time, the direct gain from entering is increased because the effect on emissions of the price change induced by i if entering is strengthened. On the other hand, the effect on i's trade balance is ambiguous, and can potentially be negative. In sum, an increase in $\sum_{j\in\mathcal{M}-i} e_j'$ gives:

- A lower direct loss from entering the agreement.
- A higher direct gain from entering the agreement.
- An ambiguous effect on $TB_i^{\mathcal{M}}$.

Hence, the overall effect on the incentive of country i to enter the agreement of an increase in $\sum_{j\in\mathcal{M}-i} e_j'$ is ambiguous. This can be confirmed by differentiating Equation (20) with respect to $\sum_{j\in\mathcal{M}-i} e_j'$.

H Convex variable cost of renewable energy production

In the basic model in the paper, we assume that the only costs related to production of renewable energy are the costs of investment in production capacity. In this section, we add a positive and convex cost of *production* of renewable energy to the model, and we show that this does not change our main results.

For simplicity, we consider only two time periods, with period 0 as the last period and period 1 as the first period. We also here assume that the utility from energy consumption, $u_i(\cdot)$, and that the investment cost function, $c_i(\cdot)$ are quadratic $\forall i$. Furthermore, we consider the case where the countries share a common marginal damage from emissions: $D_i = D\ \forall i$. As before, e_{it} denotes energy consumption, R_{it} is the renewable energy production capacity stock and r_{it} is investment. In order to simplify notation throughout, we assume $\beta\delta = 1$. The stock then develops according to $R_{it+1} = R_{it} + r_{it}$.

The supply of renewable energy in the market is now given by the *production*, denoted x_{it}, no longer necessarily equal to the full capacity. The production cost depends on the production and on the available capacity, and is given by the function $k_i(x_{it}, R_{it} + r_{it})$. In order for this extension to the model to give a different equilibrium than the one we calculate in the paper, the cost function must be such that the corner solution where production is equal to the full capacity is not the optimal solution for the producers. At the same time, the extension is not very interesting if the producers choose the opposite corner solution: no production. For the interior solution to be chosen, the marginal production cost must increase sufficiently in the capacity. In the following, we use general expressions for the derivatives of this function, but one explicit cost function that would satisfy these criteria is the following:

$$k_i(x_{it}, R_{it} + r_{it}) = k_i^0 \ln\left(\frac{R_{it} + r_{it}}{R_{it} + r_{it} - x_{it}}\right). \qquad (21)$$

The production cost does not change the problem facing the governments in autarky, and the autarky price is equal to D.

Again, we look at the second stage of the dynamic game. Consider N countries that can either be linked in a common market or not, with p representing the international permit price. When there is international trade, the market clearing condition:

$$\sum_i \omega_{it} + \sum_i x_{it} = \sum_i e_{it}$$

must be satisfied. Finally, the timing of decisions is as before, but the renewable energy producers now make two subsequent decisions, they first decide their investment level, and then their production level. As before, p_t denotes the permit price, equal to the renewable energy price.

The representative consumer maximizes utility in each time period exactly as in the basic model, with the first-order condition:

$$u_i'(e_{it}) = p_t \quad \Rightarrow \quad e_{it}(p_t). \tag{22}$$

In each period, the energy production is given by the solution to the following problem:

$$W_{it}^R(R_{it} + r_{it}) = \max_{x_{it}} \left\{ p_t x_{it} - k_i(R_{it} + r_{it}, x_{it}) \right\},$$

given by

$$p_t = \frac{\partial k_i}{\partial x_{it}} \quad \Rightarrow x_{it}(R_{it} + r_{it}, p_t). \tag{23}$$

The marginal value of the production capacity is given by:

$$W_{it}^{\prime R}(R_{it}) = -\frac{\partial k_i}{\partial (R_{it} + r_{it})}.$$

In period 0, in the investment stage, the representative renewable energy producer in country i solves the problem:

$$V_{i0}^R(R_{i0}) = \max_{r_{i0}} \left\{ -c_i(r_{i0}) + W_{i0}^R(R_{i0} + r_{i0}) \right\}.$$

The solution is given by the first-order condition:

$$-c_i(r_{i0}) + W_{i0}^{R\prime}(R_{i0}) = 0 \quad \Leftrightarrow \quad c_i'(r_{i0}) = -\frac{\partial k_i}{\partial (R_{i0} + r_{i0})} \quad \Rightarrow \quad r_{i0}(p_0, R_{i0}), \tag{24}$$

and the marginal value of increased capacity at this stage is, not surprisingly, the same as in the production stage:

$$V_{i0}^{\prime R}(R_{i0}) = W_{i0}^{\prime R}(R_{i0}) = -\frac{\partial k_i}{\partial (R_{i0} + r_{i0})}.$$

In the first stage of the last period, the government in country i solves:

$$V_{i0}(R_{10},\ldots,R_{N0}) = \max_{\omega_{i0}} \Big\{ u_i(e_{i0}(p_0)) - c_i(r_{i0}(p_0,R_{i0})) \\ - k_i\Big(R_{i0}+r_{i0}(R_{i0},p_{i0}), x_{i0}(R_{i0}+r_{i0}(R_{i0},p_{i0}),p_{i0})\Big) \\ + p_0\left(\omega_{i0}+x_{i0}(R_{i0}+r_{i0}(R_{i0},p_0),p_0)-e_{i0}(p_0)\right) - D\sum_j \omega_{j0}\Big\}.$$

When the first-order condition is simplified by taking into account those of the consumers and producers (Equation (22), (23) and (24), envelope theorems), it is given by:

$$0 = p_0 - D + \frac{\partial p_0}{\partial \omega_{i0}}\Big(\omega_{i0}+x_{i0}(R_{i0}+r_{i0}(R_{i0},p_0),p_0)-e_{i0}(p_0)\Big) \tag{25}$$
$$\Rightarrow \quad \omega_{i0}(R_{10},\ldots,R_{N0}).$$

where $\frac{\partial p_0}{\partial \omega_{i0}}$ is the derivative of the function $p_0(R_{10},\ldots,R_{N0},\sum_j \omega_{j0})$, determined by the market clearing condition:

$$\sum_j \omega_{j0} + \sum_j x_{j0}(R_{j0}+r_{j0}(R_{j0},p_0),p_0) = \sum_j e_{j0}(p_0)$$
$$\Rightarrow \quad p_0(R_{10},\ldots,R_{N0},\sum_j \omega_{j0}).$$

Summing the first-order conditions over all i gives the second-period price:

$$p_0 = D.$$

Because the second-period price is independent of the stocks, it must be the case that the effect on the price through the total renewable energy production $\sum_j x_{j0}$ of a change in any R_{j0} due to changes in period-1 invstments is completely counteracted by a change in the number of permits issued, $\sum_j \omega_{j0}$. This means that the governments do not have to take into account changes in p_0 when they issue permits in the *first* period. It is now straightforward to use the first-order condition in Equation (25) to find the equilibrium policy responses:

$$\frac{\partial \omega_{i0}^{eq}}{\partial R_{j0}} = \begin{cases} -\frac{\partial x_{i0}}{\partial (R_{i0}+r_{i0})}\left(1+\frac{\partial r_{i0}}{\partial R_{i0}}\right) < 0, & \text{if } i=j \\ 0 & \text{if not.} \end{cases}$$

Finally, we can then find the value of a marginal increase in the capacity in the beginning of the period:

$$\frac{\partial V_{i0}}{\partial R_{i0}} = -\frac{\partial k_i}{\partial R_{i0}} > 0$$
$$\frac{\partial V_{i0}}{\partial R_{j0}} = -D\frac{\partial \omega_{j0}}{\partial R_{j0}} = D\frac{\partial x_{j0}}{\partial R_{j0} + r_{j0}}\left(1 + \frac{\partial r_{j0}}{\partial R_{j0}}\right) > 0 \quad \text{for} \quad i \neq j.$$

Now, go to period 1. The consumers behave according to Equation (22), while the production of renewables is determined by Equation (23) . At the investment stage, the producers solve the problem:

$$V_{i1}^R(R_{i1}) = \max_{r_{i1}} \left\{-c_i(r_{i1}) + W_{i1}^R(R_{i1} + r_{i1}) + V_{i0}^R(R_{i0})\right\}.$$

The solution is given by the first-order condition:

$$-c_i'(r_{i1}) + W_{i1}^{R'}(R_{i1}) + V_{i0}^{R'}(R_{i0}) = 0$$
$$\Leftrightarrow \quad c_i'(r_{i1}) = -\frac{\partial k_i}{\partial(R_{i1} + r_{i1})} - \frac{\partial k_i}{\partial(R_{i0} + r_{i0})} \quad \Rightarrow \quad r_{i1}(p_1, p_0, R_{i1}),$$

The number of permits issued in the first time period - and hence emissions and welfare - is determined by the solutions to the governments' problems:

$$\begin{aligned} V_{i1}(R_{11}, \dots, R_{N1}) = \max_{\omega_{i1}} \Big\{ & u_i(e_{i1}(p_1)) - c_i(r_{i1}(p_1, p_0, R_{i1})) - D\sum_j \omega_{j1} \\ & - k_i\Big(R_{i1} + r_{i1}(p_1, p_0, R_{i1}), x_{i1}(R_{i1} + r_{i1}(p_1, p_0, R_{i1}), p_1)\Big) \\ & + p_1\left(\omega_{i1} + x_{i1}(R_{i1} + r_{i1}(p_1, p_0, R_{i1}), p_1) - e_{i1}(p_1)\right) + V_{i0}(R_{10}, \dots, R_{N0})\Big\}. \end{aligned}$$

Again, the first-order condition can be simplified by applying the first-order conditions of the consumers and producers, and it becomes:

$$0 = p_1 - D + \frac{\partial p_1}{\partial \omega_{i1}} TB_{i1} + \sum_{j \neq i} \frac{\partial r_{j1}}{\partial p_1}\frac{\partial p_1}{\partial \omega_{i1}} D\frac{\partial x_{j0}}{\partial(R_{j0} + r_{j0})}\left(1 + \frac{\partial r_{j0}}{\partial R_{j0}}\right),$$

with $TB_{i1} = \omega_{i1} + x_{i1} - e_{i1}$. Summing over all i gives this expression for the first-period price:

$$p_1 = D - \frac{1}{N}\sum_i \sum_{j\neq i} \frac{\partial r_{j1}}{\partial p_1} p_1' D \frac{\partial x_{j0}}{\partial (R_{j0} + r_{j0})}\left(1 + \frac{\partial r_{j0}}{\partial R_{j0}}\right) > D,$$

and it is clear that the strategic incentive to withhold permits, leading to reduced emissions and higher welfare, is in place also in this extended model, as long as (a) the renewables investments increase in the price, (b) the production depends positively on the production capacity, and (c) the effect on production capacity plus investments of an increase in the stock at the beginning of the period is positive, all within each time period. This is the case if the cost function in Equation (21) is used.

I The shape of the damage function

In the paper, we assume throughout that the damage from climate change is linear in the stock of greenhouse gases (GHGs) in the atmosphere, and therefore also in emissions. In reality the shape of the damage function is not necessarily this simple, and in the economics literature the function is often assumed to be convex in the atmospheric stock (see e.g. Hoel (1991) or Fershtman and Nitzan (1991)), although Golosov et al. (2014) argue that it a linear functions in perhaps not a very bad approximation. The reason we apply this assumption is in any case that we want to focus on the effect of introducing permit trade, which is not dependent on the shape of the damage function. That is because the strategic effects of a convex damage function will be in place independently of whether there is international permit trade or not. In this section, we provide a short discussion on the relation between permit market linkages and the shape of the damage function.

Consider a damage function $\tilde{D}_i(S_t)$, where $S_t = \gamma(S_{t-1} + f_{t-1})$ is the stock of GHGs at time t with a decay rate of $(1-\gamma)$, and with $D_i'(\cdot) > 0,\ D_i''(\cdot) > 0$. This shape of the damage function means that one unit of emissions is more harmful if the stock of GHGs is larger, which creates a strategic incentive for each country to increase their emissions at any point in time, in order to reduce emissions in other countries in the future. This incentive arises because increased emissions - or permit issuance - in a country i in period t increases the stock in future periods, S_{t+s} for $s > 0$, and a larger stock means a higher marginal damage and therefore lower emissions - or permit issuance - in all countries in all periods $t+s$.

In isolation, this strategic incentive gives rise to a more severe free-rider problem in the dynamic setting than in a static model, as is shown by both Hoel (1991) and Fershtman and Nitzan (1991). And this strategic incentive is the exact opposite of the incentive that we identify when permit markets are linked. When permit markets are linked, it is therefore not clear how the equilibrium of the dynamic game differs from the equilibrium of a game with only myopic players. The net effect on permit issuance of the strategic considerations arising in a dynamic setting may be positive or negative. It depends on how convex the damage function is (determining the strategic incentive to issue *more* permits) and on the strength of the reaction of renewables producers to price changes and of permit issuance to the renewables stocks (determining the strategic incentive to issue *fewer* permits).

The strategic effect due to the convex damage function is, however, present irrespective of whether permit markets are linked or not. The isolated effect of linking permit markets in presence of convex damages is therefore the same as in the basic model: as international permit trade allows countries to affect each other's renewables investments, countries face an incentive to issue fewer permits than they would have issued absent international trade.

Compared to a static model - or a model with only myopic agents - the net effect of introducing both a convex damage function and international permit trade is unclear. The pure effect of linking permit markets given a convex damage function is still as in the basic model: emissions will be lower and welfare higher under trade, as compared to under autarky.

J Endogenous fossil energy capacity

In the basic model in the paper, we assume that fossil energy is available at zero cost. If the group of countries considered is small, and these are price takers in the market for fossil energy, this is only a normalization. However, if we want to consider a large group of countries it is not the case. A full analysis of fossil energy investments and production is out of scope for this paper, but in this section we include the possibility for countries to invest in fossil energy production capacity and let the countries take into account their effect on the fossil energy price. We arrive at the same results as in the basic model.

Consider the second stage of the dynamic game, and let N countries link their markets. Let ϕ_t be the price on fossil energy. The permit price is now τ_t, and the price to renewables producers is p_t. For simplicity, we will here consider only two time periods, and we count time backwards. Period 0 is the last period, while period 1 is the first. We now introduce producers of fossil energy in the model. These producers invest in costly production capacity in every time period, and the capacity depreciates over time. As for renewable energy production, we let the production cost itself be zero. The investment cost of a fossil producer in country i of increasing the capacity in period t with g_{it}, is given by the increasing and convex cost function $h_i(g_{it})$. The stock of fossil energy production capacity develops according to $G_{it+1} = \delta(G_{it} + g_{it})$, with δ as the survival rate (equal to the survival rate of the renwables stock). The fossil energy producers thus solve a problem equivalent to that of the renewables producers. The consumers and the renewables producers solve the same problems as in the basic model. Perfect substitutability for consumers implies that in equilibrium we have $p_t = \phi_t + \tau_t$.

The solutions to the producers' problems now give investments in each time period, given by the following:

$$
\begin{aligned}
&c_i'(r_{i0}) = p_0 \equiv \hat{p}_0 \Rightarrow r_{i0}(p_0), && c_i'(r_{i1}) = p_1 + \beta\delta p_0 \equiv \hat{p}_1, \Rightarrow r_{i1}(\hat{p}_1),\\
&h_i'(g_{i0}) = \phi_0 \equiv \hat{\phi}_0 \Rightarrow g_{i0}(\phi_0), && h_i'(g_{i1}) = \phi_1 + \beta\delta\phi_0 \equiv \hat{\phi}_1, \Rightarrow g_{i1}(\hat{\phi}_1).
\end{aligned}
$$

Market clearing requires

$$
\begin{aligned}
\sum_j \omega_{jt} &= \sum_j G_{jt} + \sum_j g_{jt}(\hat{\phi}_t)\\
\sum_j e_{jt}(p_t) &= \sum_j \omega_{jt} + \sum_j R_{jt} + \sum_j r_{jt}(\hat{p}_t).
\end{aligned}
$$

Define ω_t, e_t, r_t, g_t, G_t and R_t as the sum over all countries of the respective variables. The market clearing conditions then implicitly define the equilibrium prices $\phi_0(\omega_0 - G_0)$, $\phi_1(\omega_1 - G_1|\phi_0)$, $p_0(\omega_0 + R_0)$ and $p_1(\omega_1 + R_1|p_0)$. Together, these define the equilibrium permit prices $\tau_0(\omega_0, R_0, G_0)$, and $\tau_1(\omega_1, R_1, G_1|p_0, \phi_0)$. Differentiation gives us

$$
\begin{aligned}
&\phi_0' = \frac{1}{g_0'}, && p_0' = \frac{-1}{r_0' - e_0'}, &&\\
&\phi_1' = \frac{1}{g_1'}, && p_1' = \frac{-1}{r_1' - e_1'}, &&\\
&\frac{\partial \tau_0}{\partial \omega_0} = p_0' - \phi_0', && \frac{\partial \tau_0}{\partial G_0} = \phi_0', && \frac{\partial \tau_0}{\partial R_0} = p_0',\\
&\frac{\partial \tau_1}{\partial \omega_1} = p_1' - \phi_1', && \frac{\partial \tau_1}{\partial G_1} = \phi_1', && \frac{\partial \tau_1}{\partial R_1} = p_1'.
\end{aligned}
$$

The problem facing country i in period 0 is now

$$\begin{aligned} V_{i0}(R_{10},\ldots,R_{N0},&G_{10},\ldots,G_{N0}) \\ = \max_{\omega_{i0}} \Bigg\{ & u_i(e_i(p_0)) - c_i(r_i(p_0)) - h_i(g_i(\phi_0)) - D_i \sum_j \omega_{j0} + \tau_0 \omega_{i0} \\ & + \phi_0(G_{i0} + g_i(\phi_0)) + p_0(R_{i0} + r_i(p_0) - e_i(p_0)) \Bigg\}, \end{aligned} \tag{26}$$

with first-order condition

$$\begin{aligned} 0 =& u'_{i0} e'_{i0} p'_0 - c'_{i0} r'_{i0} p'_0 - h'_{i0} g'_{i0} \phi'_0 - D_i + \tau_0 + (p'_0 - \phi'_0)\omega_{i0} + \phi'_0(G_{i0} + g_{i0}) \\ & + \phi_0 g'_{i0} \phi'_0 + p'_0(R_{i0} + r_{i0} - e_{i0}) + p_0(r'_{i0} p'_0 - e'_{i0} p'_0). \end{aligned}$$

Given that $u'_{i0} = p_0$, $c'_{i0} = p_0$ and $h'_{i0} = \phi_0$, this simplifies to:

$$D_i = \phi'_0(G_{i0} + g_{i0} - \omega_{i0}) + p'_0(R_{i0} + r_{i0} - e_{i0} + \omega_{i0}) + \tau_0.$$

Given the market clearing conditions, summing the first-order conditions over i gives us the equilibrium permit price:

$$\tau_0 = \overline{D},$$

which is independent of any stock.

Turning to period 1, the problem facing country i is now

$$\begin{aligned} & V_{i1}(R_{11},\ldots,R_{N1},G_{11},\ldots,G_{N1}) \\ & \quad = \max_{\omega_{i1}} \Bigg\{ u_i(e_i(p_1)) - c_i(r_i(\hat{p}_1)) - h_i(g_i(\hat{\phi}_1)) - D_i \sum_j \omega_{j1} + \tau_1 \omega_{i1} + \phi_1(G_{i1} + g_i(\phi_1)) \\ & \qquad + p_1(R_{i1} + r_i(p_1) - e_i(p_1)) + \beta V_{i0}(R_{10},\ldots,R_{N0},G_{10},\ldots,G_{N0}) \Bigg\}. \end{aligned}$$

Given the constant second-period price, we have that $\frac{d\hat{p}_1}{d\omega_1} = p'_1$ and $\frac{d\hat{\phi}_1}{d\omega_1} = \phi'_1$, and we get the first-order condition:

$$D_i = \tau_1 - r'_{i1}p'_1\beta\delta p_0 - g'_{i1}\phi'_1\beta\delta\phi_0 + p'_1(\omega_{i1} + R_{i1} + r_{i1} - e_{i1})$$
$$+ \phi'_1(G_{i1} + g_{i1} - \omega_{i1}) + \beta\delta\sum_j \frac{\partial V_{i0}}{\partial R_{j0}} r'_{j1}p'_1 + \beta\delta\sum_j \frac{\partial V_{i0}}{\partial G_{j0}} g'_{j1}\phi'_1.$$

To find the price, we sum over all i and divide by N to find:

$$\tau_1 = \overline{D} - \frac{\beta\delta}{N}\left[p'_1\sum_j r'_{j1}\cdot\left(\sum_i \frac{\partial V_{i0}}{\partial R_{j0}} - p_0\right) + \phi'_1\sum_j g'_{j1}\cdot\left(\sum_i \frac{\partial V_{i0}}{\partial G_{j0}} - \phi_0\right)\right].$$

We see that we need to find $\sum_i \partial V_{i0}/\partial R_{j0}$ and $\sum_i \partial V_{i0}/\partial G_{j0}$ in order to derive the equilibrium period 1 permit price. The reason is that countries will, when issuing permits in the first period, take into account its effect on investments in both renewables and fossil energy, and the impact on the number of permits that will be issued in the last period. From market clearing, we have that p'_1 is negative, while ϕ'_1 is positive. It means that the permit price in period 1 will be higher to the extent that the social value of a higher future stock of renewables (fossil energy) is higher (lower) than its private value p_0 (ϕ_0).

To derive these values, we differentiate through (26), and use the investors' and consumers' first-order conditions to find

$$\sum_i \frac{\partial V_{i0}}{\partial G_{j0}} = \phi_0 - (N\overline{D} - \tau_0)\frac{\partial \omega_0^{eq}}{\partial G_0}, \quad \text{and}$$
$$\sum_i \frac{\partial V_{i0}}{\partial R_{j0}} = p_0 - (N\overline{D} - \tau_0)\frac{\partial \omega_0^{eq}}{\partial R_0}.$$

Finally, given that $\tau_0 = \overline{D}$ we deduce that $\partial\omega_0^{eq}/\partial R_0$ is negative while $\partial\omega_0^{eq}/\partial G_0$ is positive. The equilibrium permit price in period 0 reduces to

$$\tau_1 = \overline{D}\left(1 + \frac{N-1}{N}\beta\delta\left[p'_1 r'_1\frac{\partial \omega_0^{eq}}{\partial R_{j0}} + \phi'_1 g'_1\frac{\partial \omega_0^{eq}}{\partial G_{j0}}\right]\right) > \overline{D}\ . \tag{27}$$

It is clear that the permit price implementing the first best in this economy - as in the basic model - would be $p^{FB} = \sum_j D_j$, and that the autarky price in country i would be D_i. Hence, the results derived here are qualitatively identical to the results stated in the paper, even though the supply of fossil energy is endogenously determined. We have that the fossil energy channel and the renewables channel both contribute towards a higher first-period permit price, and that the permit price exceeds the average marginal damage. Endogenous fossil energy alone would be sufficient for our mechanism to arise. Thus, our mechanism is still at work, and it is strengthened, not weakened by the presence of endogenous fossil energy.

K Politically determined investments

In the basic model, we assumed that investments in renewables are made by price-taking private investors and that the governments employ no policy instrument other than the traded emission permits. There are results in the literature indicating that if countries are allowed to set their own domestic policies in addition to participating in a permit market, the benefits of the permit market may be dissipated. Godal and Holtsmark (2011) show that, when allowed to, every country will implement policies that maximize its welfare ex post, and the permit market will only act as a transfer mechanism from low- to high-damage countries. It is also the case that investments in renewable energy are highly politicized in many countries.

Therefore, we investigate how robust our results are to allowing the government in each country to regulate its own renewables producers. In this section, we solve a two-period model where the governments politically determine investments in renewables under the same timing as in the basic model. Now, we do not assume that the governments act as price takers when they decide on the optimal investments. Instead, they take the price decrease following higher investments into account. We show that withholding permits today also affects renewables investments in the case where the governments determine these investments. The equilibrium permit price under international permit trade will therefore be higher than the average price under autarky, even in a situation in which the governments determine renewables investments. Thus, the main result from our basic model also prevails in this setting.

For simplicity, we consider only two time periods, the last period is denoted by 0, while 1 denotes the first period. We also assume throughout this section that the representative renewables producers and consumers in all countries share identical and quadratic cost and utility functions, meaning that $c_i'''(\cdot) = u_i'''(\cdot) = 0 \ \forall i$. Furthermore, we disregard investments in the last time period as these are not affected by strategic incentives. Consider the second stage of the dynamic game, and let N countries link their permit markets.

Consumers behave as before, and the market clearing conditions are now given by:

$$\sum_i e_{i1}(p_1) = \sum_i \omega_{i1} + \sum_i R_{i1} + \sum_i r_{i1},$$
$$\sum_i e_{i0}(p_0) = \sum_i \omega_{i0} + \sum_i R_{i0},$$

determining the prices, as functions of total supply.

In the last period, the governments solve the following problem

$$W_{i0}(R_{10}, \ldots, R_{N0}) = \max_{\omega_{i0}} \left\{ u_i(e_i(p_0)) - D_i \sum \omega_{j0} + p_0(R_{i0} + \omega_{i0} - e_i(p_0)) \right\},$$

which gives the following equilibrium

$$p_0 = \overline{D}, \quad \frac{\partial \omega_{i0}}{\partial R_{j0}} = \begin{cases} -1 & i = j \\ 0 & i \neq j \end{cases}, \quad \frac{\partial W_{i0}}{\partial R_{j0}} = D_i, \ \forall i, j.$$

In period 1, the governments make decisions in two stages. Let

$$W_{i1}(R_{11}, \ldots, R_{N1}) = \max_{\omega_{i1}} \left\{ -D_i \sum \omega_{j1} + V_{i1}(R_{11}, \ldots, R_{N1}, \omega_{11}, \ldots, \omega_{N1}) \right\} \tag{28}$$

be the government's value function at the permit decision stage, where V_{i1} is the value function at the investment stage. Then we have

$$\begin{aligned} V_{i1}&(R_{11}, \ldots, R_{N1}, \omega_{11}, \ldots, \omega_{N1}) \\ &= \max_{r_{i1}} \Big\{ u_i(e_i(p_1)) - c_i(r_{i1}) + p_1(\omega_{i1} + R_{i1} + r_{i1} - e_i(p_1)) \\ &\qquad + \beta W_{i0}(\delta(R_{11} + r_{11}), \ldots, \delta(R_{N1} + r_{N1})) \Big\}. \end{aligned}$$

The first-order condition for this problem is given by:

$$0 = p_1 - c_i'(r_{i1}) + p_1'(\omega_{i1} + R_{i1} + r_{i1} - e_i(p_1)) + \beta\delta D_i, \tag{29}$$

determining renewables investments as functions of permit issuance and renewables stocks:

$$r_{i1}(R_{11}, \ldots, R_{N1}, \omega_{11}, \ldots, \omega_{N1}).$$

We now turn to the permit issuing stage, the problem given by Equation (28). When the governments issue permits in the first stage, they will take into account how their issuance affects investments, now chosen by governments. Their first-order condition is given by:

$$D_i = \frac{\partial V_{i1}}{\partial \omega_{i1}} = p_1 + p_1' + \sum_j \frac{\partial r_{j1}}{\partial \omega_{i1}} (p_1' TB_i + \beta\delta D_i) + \frac{\partial r_{i1}}{\partial \omega_{i1}} (p_1 - c_{i'}).$$

From (29) we have that $p_1 - c_{i1}' = -(p_1' TB_i + \beta\delta D_i)$. So in deciding on permits, the government can ignore the effect on their own investments, since these are set optimally from the government's perspective (the envelope theorem). This is different from the case with price-taking investors in the main body of the paper. Use this to get:

$$D_i = p_1 + p_1' TB_i + \sum_{j \neq i} \frac{\partial r_{j1}}{\partial \omega_{i1}} (p_1' TB_i + \beta\delta D_i). \tag{30}$$

where $\sum_{j \neq i} \partial r_{j1} / \partial \omega_{i1} \in [-1, 0]$. Sum over (30) to find

$$p_1 = \overline{D} \left(1 - \beta\delta \sum_{j \neq i} \frac{\partial r_{j1}}{\partial \omega_{i1}} \right) > \overline{D}. \tag{31}$$

Hence, the strategic incentive to withhold permits in order to reduce future issuance in other countries through increasing their stocks, is present also in the case where the governments determine the renewables investments. Although somewhat weakened, the strategic mechanism created by international permit trade is still in place. This is because each government *will* let investments react to price changes, meaning that in this case, as in the basic model, a higher permit price results in higher investment in all countries. As in our basic model, there is still, therefore, a benefit to withholding permits that goes beyond the direct effect on emissions.

L The size of the welfare gain

Though the model we present in the paper is purely theoretical - its main purpose is to identify a mechanism - it could be useful to investigate a little further the potential size of the welfare gains associated with linking permit markets. We have therefore included here two tables, summarizing how the price increase following permit market linkages depends on the model parameters.

Table 2: $(p^{\mathcal{N}} - \overline{p}^{aut|‰})/(p^{FB} - \overline{p}^{aut|‰})$

		$r'(\hat{p})/\lvert e'(p)\rvert$				
		0.1	0.5	1	2	10
	0	0	0	0	0	0
	0,2	0,0005	0,0017	0,0025	0,0033	0,0045
	0,6	0,0027	0,0099	0,0148	0,0196	0,0265
$\beta\delta$	0,9	0,0161	**0,0566**	0,0826	0,1071	0,1406
	0,94	0,0277	0,0946	0,1354	0,1728	0,2217
	0,98	0,0818	0,2462	0,3289	0,3952	0,4712
	0,9999	0,9479	0,9852	0,9901	0,9926	**0,9945**

N=50

Table 3: $(p^{\mathcal{N}} - \overline{p}^{aut|‰})/(p^{FB} - \overline{p}^{aut|‰})$

		$r'(\hat{p})/\lvert e'(p)\rvert$				
		0.1	0.5	1	2	10
	0	0	0	0	0	0
	0,2	0,0112	0,0400	0,0588	0,0769	0,1020
	0,6	0,0638	0,2000	0,2727	0,3333	0,4054
$\beta\delta$	0,9	0,2903	**0,6000**	0,6923	0,7500	0,8036
	0,94	0,4159	0,7231	0,7966	0,8393	0,8769
	0,98	0,6901	0,8909	0,9245	0,9423	0,9570
	0,9999	0,9978	0,9994	0,9996	0,9997	**0,9998**

N=2

The tables show the difference between the price under international trade between all N countries and the average autarky price, relative to the difference between the first-best price and the average autarky price. If this fraction is close to zero, the welfare gain produced by permit market linkage is very small, while if this number is close to one linking permit markets implements an allocation close to the first-best allocation.

In the first table, the number of countries is $N = 50$, while the number is reduced to $N = 2$ in the second table. We vary the product of the survival rate and the discount factor, $\beta\delta$, from 0 to $0,9999$. The relevant value of this product of course strongly depends on the length of the periods between each time the caps are set. The fraction $r'(\cdot)/\lvert e'(\cdot)\rvert$

represents the effect of a price increase on the renewable energy supply relative to the effect on demand for energy/permits. We let this fraction range from $0,1$ to 10. Intuitively, $r'(\cdot)$ is most important here: the larger this effect, the stronger is the intertemporal strategic complementarity in permit issuance, and hence the incentive to withhold permits.

As is clear from the tables, the effect of international trade is potentially large when measured in terms of this price increase. For example, for $N = 2$ the gap between the average market price and the first-best price is reduced by more than 50% ($(p^{\mathcal{N}} - p^{aut|\emptyset})/(p^{FB} - p^{aut|\emptyset}) = 0,6$) when two countries are linked in the case where the investment response to a price change is half of the response from energy demand, $r'/|e'| = 0,5$, while $\beta\delta = 0,9$. And as is clear from the tables, in the case where $\beta\delta$ is very high, while the renewables investments are very price responsive compared to energy demand, the price under international trade gets very close to the first-best price, in the two-country case. When $N = 50$, the first-best price is very much larger than the non-cooperative autarky price. It is therefore not surprising that international trade does not increase the price to a level that is close to this, though the price increase is still significant.

Both Carbone et al. (2009) and Holtsmark and Sommervoll (2012) numerically investigate the effect of linking markets in a static setting. For a future and more thorough investigation of the size of the effects discussed in this section, the parameter values in these papers should be used as a starting point.

M Finite-horizon convergence

In the paper, we have identified one Markov perfekt equilibirum (MPE), but we cannot rule out the existence of other MPEs. The equilibrium we have found in the second stage of the game has attractive properties because it is *simple*. The equilibrium strategies are linear in the state variables $\{R_1, \ldots, R_N\}_{j=1}^{N}$, and the equilibrium permit price is independent of the state variables. However, for obvious reasons this does not suffice as a selection criterion. In this section, we show that the MPE we have found is the limit of the unique finite-horizon subgame perfect equilibrium (SPE) of the stage two-game.

We will find this SPE in the finite horizon version of the game, and then let the number of periods, T, run to infinity. As the equilibrium in every truncated subgame is unique, the SPE of the whole game is also unique. We verify that the infinite horizon-equilibrium with a constant price is the limit of the unique finite-horizon SPE. The way we do this is to start in the last period and solve backwards, until we can guess some pattern for the price t periods from the end. We then take this guessed pattern and prove it is true by induction. Given the prevailing price function p_t, we can see what happens to the price as the length of the horizon approaches infinity. In order to get an analytical solution to this problem, we assume in the following that the utility function $u_i(\cdot)$ and the investment cost function $c_i(\cdot)$ are both quadratic. For convenience, we will count time backwards.

A country in autarky have a dominant strategy - choose the number of permits, ω_i such that $p_i = D_i$ in all time periods. Hence we only need to consider the countries that choose to link their markets.

For all countries, from the representative consumers' behavior, it follows that $u_i'(e_{it}) = p_t$, $\forall t$. In the last period, 0, the renewables producers also solve a static problem, giving $c_i'(r_{i0}) = p_0$, giving the renewables supply as a linear function of the price in period 0.

Define the supply of energy in the common market before the period-t investments by $s_t \equiv \sum_{j\in\mathcal{M}} R_{jt} + \sum_{j\in\mathcal{M}} \omega_{jt}$. The above first-order conditions imply that p_0 is a function of s_0, and that p_0' is a constant, denoted p' and given by: $p' = 1/(\sum_{j\in\mathcal{M}} e_j' - \sum_{j\in\mathcal{M}} r_j')$. In earlier time periods, the price may depend on changes in supply also through changes in future prices, through the effect these will have on the renewables investments. However, the effect of increased supply in period t, s_t, on the price, p_t, *conditional* on the future prices, will always be given by p'.

In the following we will simplify notation by denoting the sum over all linked countries of the respective variables as e_t, r_t, ω_t and R_t. $\overline{D}$ represents the average marginal damage for the countries in $\mathcal{M}$ and p_t represent the permit price in the common market.

The government in a linked country in period 0 solves

$$V_{i0}(\{R_{j0}\}_{j=1}^{N}) = \max_{\omega_{i0}} \Big\{ u_i(e_i(p_0)) + p_0 \cdot (\omega_{i0} + R_{i0} + r_i(p_0) - e_i(p_0)) \\ - c_i(r_i(p_0)) - D_i\omega_0 \Big\},$$

with first-order condition

$$\begin{aligned} u_i'e_i'p' + p_0 \cdot (1 + r_i'p' - e_i'p') + p' \cdot (\omega_{i0} + R_{i0} + r_{i0} - e_{i0}) - c_i'r_i'p' - D_i = 0 \\ e_i'p' \cdot (u_i' - p_0) - p'r_i' \cdot (c_i' - p_0) + p_0 + p' \cdot (\omega_{i0} + R_{i0} + r_{i0} - e_{i0}) = D_i \\ p_0 + p' \cdot (\omega_{i0} + R_{i0} + r_{i0} - e_{i0}) = D_i. \end{aligned} \tag{32}$$

This is a necessary condition for equilibrium. Since the trade balances all sum to zero, we see by summation that all equilibria must satisfy

$$p_0 = \overline{D}. \tag{33}$$

The equilibrium price is independent of the current stock of renewables in the final period. Then, the profile of ω_j that solves the set of first-order conditions is unique, and satisifies:

$$\frac{d\omega_{i0}^{eq.}}{dR_{i0}} = -1, \quad \frac{d\omega_{i0}^{eq.}}{dR_{j0}} = 0 \; \forall j \neq i, \quad \frac{dp_0}{dR_{j0}} = 0, \quad \frac{dV_{i0}}{dR_{j0}} = D_i.$$

The same argument, giving a unique solution profile, will apply in every previous period, as shown below.

In any period $t > 0$, the renewables producers solve a dynamic problem, with the solution

$$c_i'(r_{it}) = \sum_{s=0}^{t} p_s(\beta\delta)^{t-s} \equiv \hat{p}_t,$$

and the renewables investments are linear in $\hat{p}_t$.

Equation (33) implies that $d\hat{p}_1/d\omega_1 = dp_1/d\omega_1 = p'$, as the equilibrium price in period 0 is independent of the history.

In period 1, the government then solves the following problem

$$V_{i1}(\{R_{j1}\}_{j=1}^N) = \max_{\omega_{i1}} \Big\{ u_i(e_i(p_1)) + p_1 \cdot \Big(\omega_{i1} + R_{i1} + r_i(p_1 + \beta\delta p_0) - e_i(p_1)\Big) \\ - c_i(r_i(p_1 + \beta\delta p_0)) - D_i\omega_1 + \beta V_{i0}(\{\delta(R_{j1} + r_{j1}(p_{i1} + \beta\delta p_{i0}))\}_{j=1}^N) \Big\},$$

where $p_{it} = p_t$ for the countries in $\mathcal{M}$. The first-order condition becomes:

$$\begin{aligned} 0 &= u_i'e_i'p' + p_1 \cdot (1 + r_i'p' - e_i'p') + p' \cdot (\omega_{i1} + R_{i1} + r_{i1} - e_{i1}) \\ &\quad - c_i'r_i'p' - D_i + \beta\delta r'p'V_{i0}' \\ 0 &= e_i'p' \cdot (u_i' - p_1) - p'r_i' \cdot (c_i' - p_1) + p_1 + p' \cdot (\omega_{i1} + R_{i1} + r_{i1} - e_{i1}) \\ &\quad - D_i + \beta\delta r'p'D_i \\ 0 &= p_1 - r_i'p'\beta\delta p_0 + p' \cdot (\omega_{i1} + R_{i1} + r_{i1} - e_{i1}) - D_i + \beta\delta r'p'D_i. \end{aligned} \tag{34}$$

Summing over this, we get

$$p_1 = \frac{r'p'}{M}\beta\delta p_0 + \overline{D} - \beta\delta r'p'\overline{D},$$

which is again independent of the state variables.

Taking the derivative of the first-order condition, (34), with respect to R_{j1} now gives:

$$p'\left(1 + \frac{d\omega_1}{dR_{j1}}\right)(1 + r_i'p' - e_i'p') + p'\left(\frac{d\omega_{i1}}{dR_{j1}} + \frac{dR_{i1}}{dR_{j1}}\right), \tag{35}$$

and summing over i we get:

$$p'\left(1 + \frac{d\omega_1}{dR_{j1}}\right) \cdot N = 0.$$

From the last two equations, we see that we must have:

$$\frac{d\omega_{i1}}{dR_{i1}} = -1, \quad \frac{d\omega_{i1}}{dR_{j1}} = 0 \ \forall j \neq i.$$

Given these reaction functions, we must have:

$$\frac{dV_{i1}}{dR_{j1}} = D_i + \beta\delta D_i.$$

This again implies that $d\hat{p}_2/d\omega_2 = dp_2/d\omega_2 = p'$.

In period 2, the government solves

$$V_{i2}(\{R_{j2}\}_{j=1}^N) = \max_{\omega_{i2}} \Big\{ u_i(e_i(p_2)) + p_2 \cdot \Big(\omega_{i2} + R_{i2} + r_i(\hat{p}_2) - e_i(p_2)\Big) - c_i\Big(r_i(\hat{p}_2)\Big) - D_i\omega_2 + \beta V_{i1}(\{\delta(R_{j2} + r_{j2})\}_{j=1}^N)\Big\},$$

whose first-order condition reduces to

$$0 = p_2 - r_i'p'\Big(\beta\delta p_1 + (\beta\delta)^2 p_0\Big) + p' \cdot (\omega_{i2} + R_{i2} + r_{i2} - c_{i2}) - D_i + \beta\delta r'p'D_i(1 + \beta\delta).$$

Also in period 2, we can use the first-order condition to show that we must have:

$$\frac{d\omega_{i2}}{dR_{i2}} = -1, \quad \frac{d\omega_{i2}}{dR_{j2}} = 0 \ \forall j \neq i, \quad \frac{dV_{i2}}{dR_{j2}} = D_i(1 + \beta\delta + (\beta\delta)^2).$$

Next, we sum over all i to get

$$p_2 = \frac{r'p'}{M}\Big(\beta\delta p_1 + (\beta\delta)^2 p_0\Big) + \overline{D} - \beta\delta r'p'\overline{D}(1 + \beta\delta),$$

which, if we insert for p_1, simplifies to

$$p_2 = (\frac{r'p'}{M}\beta\delta)(\frac{r'p'}{M}\beta\delta + \beta\delta)p_0 + \overline{D}(1 + \frac{r'p'}{M}\beta\delta) - (\frac{r'p'}{M}\beta\delta)r'p'\beta\delta\overline{D} - r'p'\beta\delta(1 + \beta\delta)\overline{D}.$$

We hypothesize

$$p_t = ap_0 d^{t-1} + b(1 + a\sum_{s=0}^{t-2} d^s) - c_t - a\sum_{s=1}^{t-1} c_s d^{t-1-s}, \ \forall t \geq 2 \text{ and} \tag{36}$$

$$\sum_{s=0}^{t} p_s(\beta\delta)^{t-s} \equiv \hat{p}_t = p_0 d^t + b\sum_{s=0}^{t-1} d^s - \sum_{s=1}^{t} c_s d^{t-s}, \ \forall t \geq 2 \text{ where} \tag{37}$$

$$a = \frac{r'p'}{N}\beta\delta, \quad b = \overline{D}, \quad d = a + \beta\delta, \quad c_t = r'p'\overline{D}\sum_{\tau=1}^{t}(\beta\delta)^\tau,$$

implying that the price is independent of the state variables in all time periods.

This reduces p_2 to $adp_0 + b(1 + a) - ac_1 - c_2$. We will now prove by induction that the equilibrium defined by Equation (36) solves the problem in all time periods. We show that given that (36) and (37) hold in period t, (36) and (37) will also characterize the subgame perfect equilibrium in period $t + 1$, for any p_0 independent of stocks. Given that we know that (36) and (37) hold in period 2, this would be sufficient in order to prove that the two equations characterize the equilibrium price in this game, for any finite horizon. Assume (36) and (37) hold in period t. Then in period $t + 1$, we have that $d\hat{p}_{t+1}/d\omega_{t+1} = dp_{t+1}/d\omega_{t+1} = p'$, and the government solves

$$V_{i,t+1}(\{R_{j,t+1}\}_{j=1}^N) = \max_{\omega_{i,t+1}} \Big\{ u_i(e_i(p_{t+1})) + p_{t+1} \cdot \Big(\omega_{i,t+1} + R_{i,t+1} + r_i(\hat{p}_{t+1}) - e_i(p_{t+1})\Big) - c_i\Big(r_i(\hat{p}_{t+1})\Big) - D_i\omega_{t+1} + \beta V_{it}(\{\delta(R_{j,t+1} + r_{j,t+1}(\hat{p}_{t+1}))\}_{j=1}^N) \Big\},$$

whose first-order condition reduces to

$$
\begin{aligned}
0 = p_{t+1} - r_i' p' \Big(\beta\delta p_t + (\beta\delta)^2 p_{t-1} + \cdots + (\beta\delta)^{t+1} p_0 \Big) \\
+ p' \cdot (\omega_{i,t+1} + R_{i,t+1} + r_{i,t+1} - e_{i,t+1}) - D_i + \beta\delta \sum_j \frac{\partial V_{it}}{\partial R_{jt}} r_j' p'.
\end{aligned}
$$

Given that the price in period t is independent of the period t-stocks, we know that the value function must be linear in these stocks. Using this, we can take the derivative of the first-order condition with respect to R_{jt+1}, and show that we must have:

$$
\frac{d\omega_{it+1}}{dR_{it+1}} = -1, \quad \frac{d\omega_{it+1}}{dR_{jt+1}} = 0 \ \forall j \neq i,
$$

as before. Finally, we can then again find the derivative of the value function:

$$
\begin{aligned}
\frac{dV_{it+1}}{dR_{jt+1}} &= D_i + \beta\delta \frac{dV_{it}}{dR_{jt}} \\
&= D_i (1 + \beta\delta + (\beta\delta)^2 + \ldots + (\beta\delta)^{t+1}).
\end{aligned}
$$

The first-order condition then reduces to:

$$
\begin{aligned}
0 = p_{t+1} - r_i' p' \Big(\beta\delta p_t + (\beta\delta)^2 p_{t-1} + \cdots + (\beta\delta)^{t+1} p_0 \Big) \\
+ p' \cdot (\omega_{i,t+1} + R_{i,t+1} + r_{i,t+1} - e_{i,t+1}) - D_i + r' p' D_i \sum_{s=1}^{t} (\beta\delta)^s.
\end{aligned}
$$

We can sum over all i to get

$$
\begin{aligned}
p_{t+1} &= \frac{r'p'}{M} \Big(\beta\delta p_t + (\beta\delta)^2 p_{t-1} + \cdots + (\beta\delta)^{t+1} p_0 \Big) + \overline{D} - r'p'\overline{D} \sum_{s=1}^{t} (\beta\delta)^s \\
&= \beta\delta \frac{r'p'}{M} \sum_{s=0}^{t} p_s (\beta\delta)^{t-s} + \overline{D} - r'p'\overline{D} \sum_{s=1}^{t+1} (\beta\delta)^s \\
&= a \sum_{s=0}^{t} p_s (\beta\delta)^{t-s} + b - c_{t+1} \\
&= a \left(p_0 d^t + b \sum_{s=0}^{t-1} d^s - \sum_{s=1}^{t} c_s d^{t-s} \right) + b - c_{t+1} \\
&= a p_0 d^t + b \Big(1 + a \sum_{s=0}^{t-1} d^s \Big) - c_{t+1} - a \sum_{s=1}^{t} c_s d^{t-s},
\end{aligned}
$$

which fits the hypothesized form (36).

For the sum, we have

$$
\begin{aligned}
\sum_{s=0}^{t+1} p_s(\beta\delta)^{t+1-s} &= p_{t+1} + \beta\delta \sum_{s=0}^{t} p_s(\beta\delta)^{t-s} \\
&= p_{t+1} + \beta\delta p_0 d^t + \beta\delta b \sum_{s=0}^{t-1} d^s - \beta\delta \sum_{s=1}^{t} c_s d^{t-s} \\
&= a p_0 d^t + b\Big(1 + a\sum_{s=0}^{t-1} d^s\Big) - c_{t+1} - a\sum_{s=1}^{t} c_s d^{t-s} \\
&\quad + \beta\delta p_0 d^t + \beta\delta b \sum_{s=0}^{t-1} d^s - \beta\delta \sum_{s=1}^{t} c_s d^{t-s} \\
&= (a+\beta\delta) p_0 d^t + b\Big(1 + (a+\beta\delta)\sum_{s=0}^{t-1} d^s\Big) - c_{t+1} - (a+\beta\delta)\sum_{s=1}^{t} c_s d^{t-s} \\
&= p_0 d^{t+1} + b + b\sum_{s=1}^{t} d^s - c_{t+1} - \sum_{s=1}^{t} c_s d^{t+1-s} \\
&= p_0 d^{t+1} + b\sum_{s=0}^{t} d^s - \sum_{s=1}^{t+1} c_s d^{t+1-s},
\end{aligned}
$$

exactly the hypothesized form (37).

So now we have proved that the price in the second stage of the finite horizon-game follows the form (36). What remains is to demonstrate that this price converges to the infinite horizon price as the length of the horizon, T, runs to infinity. First, rewrite the last term in (36). We have

$$
\sum_{s=1}^{t-1} c_s d^{t-1-s} = r'p'\overline{D} \sum_{s=1}^{t-1} \Big(d^{t-1-s} \sum_{u=1}^{s} (\beta\delta)^u\Big) = r'p'\overline{D} \sum_{s=1}^{t-1} \Big((\beta\delta)^s \sum_{u=0}^{t-1-s} d^u\Big)
$$

which is better seen by example. For $t = 4$, we have:

$$\begin{aligned}\sum_{s=1}^{3} c_s d^{3-s} &= d^2 c_1 + d c_2 + c_3 \\ &= r'p'\overline{D}\Big(d^2\beta\delta + d\big(\beta\delta + (\beta\delta)^2\big) + \big(\beta\delta + (\beta\delta)^2 + (\beta\delta)^3\big)\Big) \\ &= r'p'\overline{D}\Big(\beta\delta\big(1 + d + d^2\big) + (\beta\delta)^2\big(1 + d\big) + (\beta\delta)^3\Big) \\ &= r'p'\overline{D}\sum_{s=1}^{3}\Big((\beta\delta)^s \sum_{u=0}^{3-s} d^u\Big).\end{aligned}$$

Since $p' = 1/(r' - e')$, we have $d \in (0, 1)$, so in total, as $t \to \infty$, the sum converges to:

$$r'p'\overline{D}\frac{\beta\delta}{1-\beta\delta}\frac{1}{1-d}.$$

Substituting this, we can restate (36):

$$p_t = a p_0 d^{t-1} + b(1 + a\sum_{s=0}^{t-2} d^s) - c_t - a r'p'\overline{D}\sum_{s=1}^{t}\Big((\beta\delta)^s \sum_{u=0}^{t-s} d^u\Big).$$

Letting t run to infinity, we have

$$\begin{aligned}\lim_{t\to\infty} p_t &= 0 + b(1 + \frac{a}{1-d}) - \lim_{t\to\infty} c_t - a r'p'\overline{D}\frac{\beta\delta}{1-\beta\delta}\frac{1}{1-d} \\ &= \big(b - r'p'\overline{D}\frac{\beta\delta}{1-\beta\delta}\big)\big(1 + \frac{a}{1-d}\big) \\ &= \overline{D}\frac{1 - r'p'\frac{\beta\delta}{1-\beta\delta}}{1 - \frac{r'p'}{N}\frac{\beta\delta}{1-\beta\delta}} = \overline{D}\frac{1+\Omega}{1+\frac{\Omega}{N}}.\end{aligned}$$

Thus we have proved that the second stage of the infinite-horizon equilibrium with a constant price is the limit of the SPE of the second stage of the finite-horizon game. The first stage is unchanged, so we have also proved that the limit of the SPE of the entire game in finite horizon is the MPE we present in the paper.

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