The dynamics of linking permit markets

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This paper presents a novel benefit of linking emission permit markets. We let countries issue permits non-cooperatively, and with endogenous technology we show that 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. This happens 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.
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I. Introduction

The COP 21 negotiations in Paris in 2015 show that broad international participation in climate action is possible, and for the first time the world is close to a global agreement. Importantly, the contributions are determined nationally, and one key insight from the negotiations is that this approach has proved more successful than the earlier attempts to build an agreement top-down. This is the framework for 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.

Efficient management of global common goods such as a stable climate requires international cooperation. Such cooperation is in many cases difficult to achieve because countries typically face incentives to free-ride on other countries' efforts to reduce exploitation. The resulting over-exploitation is inefficient, but difficult for any single country to prevent.

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However, the number of existing emission permit markets is high and increasing. National permit markets are currently operated in Kazakhstan, New Zealand, South Korea and all the EU member countries. Regional within-country markets exist in China, Canada, Japan and several US states. China has also pledged to launch a national carbon market in 2017. Furthermore, Tokyo, Rio, and five Chinese pilot cities all currently operate their own city-wide emission permit markets. Other national markets are under development.[1] There are also several examples of markets that are linked, for example California and Quebec, a group of eastern US states (the Regional Greenhouse Gas Initiative), and the countries in the EU Emissions Trading System (EU ETS). For discussion, see e.g. Liski and Montero (2011), Grubb (2012), or Newell, Pizer and Raimi (2013). This suggests that permit market linkages could provide an important path towards global coordination in fighting climate change. Indeed, Newell, Pizer and Raimi (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." But the theoretical predictions regarding the effects on emissions of such linkages are mainly negative, see e.g. 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. 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 thus result in higher welfare. We also show that the same benefits can be generated by linkages between renewable energy markets in different countries.

The mechanism we identify can be explained in three steps. First, 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, giving more available production capacity in the future. Third, countries with more green energy 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 immediate. In addition, for a country participating in international permit trade, limiting the number of permits issued has

[1] Reuters, 2014. "China's national carbon market to start in 2016 – official", August 31st. http://uk.reuters.com/assets/print?aid=UKL3N0R107420140831.

a stronger effect on emissions than previously found in much of the literature. Furthermore, our results suggest that emission caps should be reset often. This result is in contrast to the findings of Harstad (2015), 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.

In the literature, it is well understood that linking permit markets will lead to gains as marginal abatement costs are equalized (see e.g. Flachsland, Marschinski and Edenhofer (2009)). Other authors also discuss the effects of permit market linkages on the incentives of policy makers (see e.g. Mehling and Haites (2009) or Green, Sterner and Wagner (2014)). Helm (2003) and Rehdanz and Tol (2005) explicitly model the incentives to alter the cap when markets are linked. Both find that there is no ex ante reason to expect emissions to go down following linkage. There is also a numerical literature, with mixed conclusions (e.g. Carbone, Helm and Rutherford (2009) and Holtsmark and Sommervoll (2012)). However, these papers only analyze static games. We show that including dynamics changes the conclusions.

The failure to reach agreement in international negotiations is in line with theoretical predictions from the literature, see e.g. Barrett (1994) or Hoel (1992). 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 markets are linked, the effect of including dynamics is the opposite.

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.

The paper proceeds as follows: we introduce the model in Section II, we solve for the Markov perfect equilibrium and present our main results in Section III, and we conclude in Section IV.

II. 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. $u(\cdot)$ is strictly concave, twice differentiable and reaches a maximum at some finite level of energy use. We implicitly 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 there is an abundant supply of fossil energy available for all to consume at zero price. In the online Appendix (Section F) 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.[2]

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.[3] ω_{it} denotes the number of permits issued in country i in period t, traded at price p_{it}. When permit markets are linked, the permits can also be traded between consumers in different countries and the permit prices will be equalized.

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 $c_i(0) = 0, c_i'(\cdot) > 0, c_i''(\cdot) > 0$. Investments are immediately available, and contribute to a stock of renewables production capacity, denoted R_{it}. There are no variable costs in supplying renewable energy from the stock. In the online Appendix, Section D, we relax this assumption. Domestic consumption and supply of renewables must be equal: $z_{it} = r_{it} + R_{it}$. $\delta \in (0,1)$ is the survival rate and the stock develops according to

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

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, 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 find the natural timing within each time period to be as follows: First, the governments simultaneously issue permits. Then, the renewables producers invest, and finally, consumption is determined. The political process determining permit issuance is relatively slow. In the EU, for example, there has been a long-lasting debate on a tightening of the cap. Therefore, we find it reasonable to allow investors to react to changes in the permit supply within each time period, and energy consumers are typically able to react to price changes quite quickly.

[2]Let S_t be the stock of GHGs in the atmosphere in period t, and let $S_{t+1} = \gamma(S_t + f_t)$, with $(1-\gamma)$ as the decay rate. Then, let each country incur a damage in period t from the stock, represented by the linear damage function $\tilde{D}_i(S_t + f_t)$. Golosov et al. (2014) argue in favor of using such a damage function. They demonstrate that the linearity arises naturally as a composition of the concave relationship between the atmospheric carbon stock and mean global temperatures and the convex relationship between temperatures and economic damage. The increase in the present value of current and future damage by a marginal increase in emissions in period 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 $D_i = \frac{\tilde{D}_i}{1-\beta\gamma}$. In Section E in the online Appendix, we discuss the effect of allowing the damage function $\tilde{D}_i(S_t + f_t)$ to be convex.

[3]In reality, the holders of permits will primarily be producers of other goods, but are termed consumers in order to distinguish them from the renewables producers.

These assumptions are crucial for the mechanism we identify.

A. Equilibrium consumption and investments

Consumers and producers behave in the same way independently of whether permits are traded internationally. Let q_{it} denote the price of renewable energy. In each period, the representative consumer in country i solves:[4]

$$\max_{f_{it},z_{it}} u_i(f_{it}+z_{it}) - p_{it}f_{it} - q_{it}z_{it},$$

$$\Rightarrow \quad u_i'(f_{it}+z_{it}) = p_{it} \quad , \quad u_i'(f_{it}+z_{it}) = q_{it}. \tag{3}$$

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, takes prices as given with rational expectations, invests, and sells the energy produced. Subject to stock transition (Equation (1)), they solve:

$$\max_{r_{it}} \quad \left\{ \sum_{\tau=0}^{\infty} \beta^{\tau} p_{it+\tau}\left(R_{it+\tau}+r_{it+\tau}\right) - c_i(r_{it}) \right\},$$

$$\Rightarrow \quad c_i'(r_{it}) = \sum_{\tau=t}^{\infty} (\beta\delta)^{\tau-t} p_{i\tau} \equiv \hat{p}_{it}, \tag{4}$$

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.

B. First best

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

$$W^{FB} \equiv \max_{\{\{f_{it},z_{it},r_{it}\}_{i=1}^{N}\}_{t=0}^{\infty}} \quad \sum_i \sum_{t=0}^{\infty} \beta^t \Big(u_i(f_{it}+z_{it}) - c_i(r_{it}) - D_i f_t \Big),$$

$$\text{subject to} \quad z_{jt} = (R_{jt}+r_{jt}) \;\; \forall j,t \quad \text{and} \quad R_{jt+1} = \delta(R_{jt}+r_{jt}) \;\; \forall j,t.$$

[4]In Section A in the online 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.

The first-best allocation is characterized by the following:

$$u_i'(f_{it} + z_{it}) = \sum_j D_j \quad \forall i, t.$$

$$c_i'(r_{it}) = \sum_j D_j(1 + \beta\delta + (\beta\delta)^2 + \cdots) = \sum_j \frac{D_j}{1 - \beta\delta}, \quad \forall i, t.$$

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

C. Autarky

We consider only Markov perfect equilibria (MPEs), and the only payoff-relevant state variables are the renewables stocks. We suppress time indices unless clearly needed and next-period stocks are denoted by $^+$. Now define the initial supply of energy and permits, *i.e.* 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 and $s = \sum_i s_i$. Under autarky there is no international trade in emission permits. Market clearing therefore 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:

$$V_i^{aut}(\{R_j\}_{j=1}^N) = \max_{s_i} \Bigg\{ u_i(e_i(p_i(s_i))) - c_i(r_i(\hat{p}_i)) - D_i \sum_j (s_j - R_j) + \beta V_i^{aut}\big(\{\delta(R_j + r_j(\hat{p}_j))\}_{j=1}^N\big) \Bigg\}, \tag{5}$$

subject to stock transition (Equation (1)) and the behavior of consumers and producers (Equation (3) and (4)). The first-order condition becomes:

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

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 $\hat{p}_i = D_i/(1 - \beta\delta), \ \forall i$.

The first-best solution and the governments' solution under autarky make up the benchmarks when we solve the model with international trade.

III. International permit trade

A. Markov perfect equilibrium

We will now consider permit market linkages between countries. Emission permits are traded between consumers in all N countries, and countries are still free to issue as many permits as they wish. Consumption and investment decisions are given by Equations (3) and (4), and the supply s is known at the investment stage. Market clearing requires that $z_j(p) = R_j + r_j(\hat{p})$ and that $\sum_j f_j(p) = \sum_j \omega_j$, which gives:

$$\sum_j e_j(p) - \sum_j r_j(\hat{p}) = s. \tag{6}$$

The price prevailing in the market is only a function of s: $p = p(s)$. We show later in this Section that $p'(s) = 1/(\sum_j(e_j'(p) - r_j'(\hat{p}))) < 0$.

Each government determines freely the number of permits to issue, taking into account the costs or revenues the country's own energy consumers will have from purchase or sales of permits. Importantly, the government also takes into account how its own permit issuance affects the equilibrium price: the more permits in the system, the lower the permit price. The reason no government will issue an infinite number of permits in order to raise large amounts of revenue is that this would drive the price to zero, and ultimately give the country zero revenue.

Define the strategy of the government in country i as a function $h : \mathbb{R}_+^N \to \mathbb{R}$. Under international permit trade, the government in country i observes the stocks $\{R_j\}_{j=1}^N$ and chooses the action s_i that solves the following dynamic problem:

$$\begin{aligned} V_i^{trade}\big(\{R_j\}_{j=1}^N\big) = \max_{s_i} \Big\{ & u_i(e_i(p(s))) + p(s)\big(s_i + r_i(\hat{p}) - e_i(p(s))\big) - c_i(r_i(\hat{p})) \\ & - D_i \sum_j (s_j - R_j) + \beta V_i^{trade}\big(\delta(R_1 + r_1(\hat{p})), \ldots, \delta(R_N + r_N(\hat{p}))\big) \Big\}, \end{aligned} \tag{7}$$

subject to stock transition (Equation (1)) and the behavior of producers and consumers (Equations (4) and (3)). 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 (6). The price determines $r_i(\hat{p})$ and $e_i(p)$ and the continuation values, $\forall i$. Each government takes into account how their own permit issuance affects the permit price, and hence investments and consumption in the entire market. N first-order conditions define our MPE:[5]

$$\begin{aligned} 0 = {} & p(s) + p'(s) \cdot \big(s_i + r_i(\hat{p}) - e_i(p(s))\big) + p'(s) e_i'(p)(u_i'(e_i) - p(s)) \\ & + \frac{d\hat{p}}{ds_i} r_i'(\hat{p}) \cdot (p(s) - c_i'(r_i)) - D_i + \beta\delta \frac{d\hat{p}}{ds_i} \sum_j r_j'(\hat{p}) \frac{\partial V_i^{trade+}}{\partial R_j^+}, \qquad \forall i. \end{aligned} \tag{8}$$

[5]The first-order conditions rule out profitable one-step unilateral deviations, and the stage 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.

The first two terms give the marginal 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 total energy consumption, but the benefit is 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 marginal benefit of increasing the supply by issuing a permit will eventually become negative, even for $D_i = 0$. The next two terms represent the effect of the price decrease on the country's consumers and renewables producers. Then, the direct cost of issuing one additional permit due to higher climate damage is D_i.

Finally, the price change lowers investments in renewables capacity in all countries. This results in lower future stocks of renewables, which may affect country i through the continuation value, $\partial V_i^{trade+}/\partial R_j^+$. This is what makes this 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 push the price up, which will increase investments in renewables capacity in all permit market countries. This results in higher renewables capacity in all countries in the next time period.

We see that the value function in Equation (7) is linear in R_j. And differentiating the N first-order conditions with respect to the stocks, R_j, gives a system of $N \times N$ equations defining the policy responses $\partial s_i/\partial R_j,\ \forall i, j$, and thereby $\partial \omega_i/\partial R_j,\ \forall i, j$. This system can be simplified using Equation (3) and (4) and the following result states the solution, with superscript *trade* denoting the MPE under international permit trade:

LEMMA 1:

1) The equilibrium policy functions and permit issuance satisfy

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

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

PROOF:

By inserting the policy response functions given in the Lemma in the value function (Equation (7)), we see that it is given by $V_i^{trade}\big(R_1, \ldots, R_N\big) = A_i +$

$\sum_j B_{ij}R_j$, with

$$B_{ij} = D_i/(1-\beta\delta) \qquad \forall i \tag{9}$$

$$A_i = \frac{1}{1-\beta}\Big[u_i(e_i(p^{trade})) - c_i(r_i(\hat{p}^{trade})) + p^{trade}\cdot TB_i - D_i\sum_j e_j(p^{trade}) + \frac{D_i}{1-\beta\delta}\sum_j r_j(\hat{p}^{trade})\Big] \qquad \forall i, \tag{10}$$

where $TB_i \equiv s_i^{trade} + r_i(\hat{p}^{trade}) - e_i(p^{trade})$ is independent of R_i given the equilibrium policy functions. Differentiating the first-order conditions (Equation (8)) 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. If country i decreased its issuance by less than one unit, it would experience a price decrease at the same time as it raises its net supply. Similarly, if country i decreased its issuance by more than one unit, then s would decrease, and the price would increase. Neither of these can be equilibrium behavior. 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. This benefits country j by avoiding damage D_j, no matter where the emissions were supposed to have taken place. Lemma 1.2 follows.

Given Lemma 1.1, the total supply of energy and permits is independent of the renewables stocks. This means that the price must also be independent of the stocks, and therefore constant over time. It follows that s_τ, for $\tau > t$, and $\hat{p}_t$ are also independent of R_{jt} and $d\hat{p}/ds = p'(s)$. And by differentiating the market clearing condition (Equation (6)), we get $p'(s) = \frac{1}{\sum_j(e_j'(\cdot)-r_j'(\cdot))}$. Finally, the effect on the price itself of an increase in the permit supply does not depend on the renewables stocks.

PROPOSITION 1: *When the permit markets of N countries are linked, countries can induce increased investments in other countries by withholding permits today:* $\frac{dr_j}{dp}\frac{dp}{d\omega_i} < 0$, $\forall i, j$. *As a result, permit supply in the different countries become* intertemporal strategic complements*:* $\frac{d\omega_j^+}{dR_j^+}\frac{dR_j^+}{d\omega_i} > 0$, $\forall i, j$.[6]

PROOF:

We have $d\hat{p}/ds = p'(\cdot) < 0$: one less permit issued today will increase the current equilibrium price. By Equation (4), this will increase investment in every

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

country, $r_i'(\cdot) > 0$, and by Lemma 1.1, future permit issuance will go down in every country, $\partial\omega_j^{trade}/\partial R_j = -1$, $\forall j$. The renewables stocks constitute the only link between current and future permit supply. □

The Proposition states that there is intertemporal strategic complementarity in permit issuance, meaning that if one country issues fewer (more) permits in one period, then the other countries 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 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 two steps: first, the permit price increases when fewer permits are issued today. Renewable energy producers in every country respond to the increase in permit prices by increasing their investments. Second, when countries experience increased renewable energy stocks in the next period, by Lemma 1.1, they respond by issuing fewer permits. When permits are only traded 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.

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

$$p^{trade} = \overline{D}\frac{1+\Omega}{1+\overline{\Omega}} > \overline{D}, \tag{11}$$

where $\overline{D} \equiv \sum_j D_j/N$ *is the average marginal damage from emissions across countries, and where we have defined, for notational purposes,*
$\Omega_j \equiv -\frac{\beta\delta}{1-\beta\delta} r_j'(\hat{p})/(\sum_j(e_j'(p) - r_j'(\hat{p}))) > 0$, $\Omega \equiv \sum_j \Omega_j$ *and* $\overline{\Omega} \equiv \Omega/N$.

PROOF:

Given Lemma 1, the first-order conditions (Equation (8)) can be simplified to:

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

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 $r'(\hat{p}) = \sum_j r_j'(\hat{p})$. Insert this into the first-order condition, sum over all i and divide by N to get

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

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 N and $\overline{D}$, the equilibrium price depends on the strength of the reaction to price changes by consumers and producers, and on the survival rate 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 determine 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^{trade}, 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.

B. 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. 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 start out by assuming identical marginal damage across all countries to remove the scope for pure cost-efficiency gains.

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

PROOF:

The proof follows from Lemma 2. As $p^{trade} > \overline{D}$, every consumer and every producer experiences a price increase when international trade is introduced. This results in reduced consumption and increased investment in every country, 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 cost of decreased consumption and increased investments will differ, and some countries may incur a net loss.

In the online Appendix (Section B.B2), 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 $p^{trade} > \overline{D}$, while in autarky $p_i^{aut} = D_i$. Now, let countries differ in D_i. In any country with $D_i \leq \overline{D}$, international trade leads to a price increase, and hence to emission reductions.

This will also be the case for countries with $\overline{D} < D_i < p^{trade}$. However, there might exist countries with $D_i > p^{trade}$, and consumers and producers in these countries will face a price decrease, resulting in increased emissions following the introduction of international permit trade. If countries are identical with respect to their energy demand and renewables supply, overall emissions will decrease when international trade is introduced, as we show in a simplified version of the model in the online Appendix (Section B.B1). However, when $u_i(\cdot)$ and $c_i(\cdot)$ differ across countries, overall emissions could increase. This is what is shown in a static model by Holtsmark and Sommervoll (2012). A full calibration of the model is necessary in order to give clear-cut results in the case of full heterogeneity.

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

PROPOSITION 3: *As the number of countries, N, increases, the gain to the average country from linking the permit markets also increases:*

$$\frac{\partial}{\partial N}\left(\frac{1}{N}\sum_{i=1}^{N} V_i^{trade} - \frac{1}{N}\sum_{i=1}^{N} V_i^{aut}\right) > 0,$$

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

PROOF:

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

First, one permit withheld has a smaller impact on the international permit price when N is large. Second, the effect of a given price increase on the aggregate foreign stock of renewables is larger when N is larger, because $\sum_i r_i$ is more strongly affected. The latter effect dominates and a larger N results in a stronger incentive to withhold permits and hence in a larger welfare gain when international permit trade is introduced.

For a given number of participating countries, the strength of the incentives countries have to withhold permits depends strongly on the discount factor and the depreciation rate of the renewables stocks, as is highlighted in the following Proposition:

PROPOSITION 4: *The increase in the permit price following linkage of the permit markets of N countries is higher if the discount rate, β, and the survival rate of the renewables stocks, δ, are higher.*

PROOF:

From Equation (11) in Lemma 2 we can see that $dp^{trade}/d(\beta\delta) > 0$, while $p^{aut} = \overline{D}$ is independent of $\beta\delta$. □

$\beta\delta = 0$ gives $p^{trade} = \overline{D} = \frac{1}{N}\sum_i p_i^{aut}$ 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. On the other hand, it is clear that for $\beta\delta \to 1$, 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 the incentives faced by the governments result in lower emissions and higher welfare under international permit trade than under autarky. And the parameters β and δ can also be interpreted as a representation of the length of the time periods. The static model in Helm (2003) represents the case where the cap is set once and for all, while shorter time periods imply higher $\beta\delta$. In light of this, our results can be interpreted as a support for resetting the caps in international permit markets more often. This conclusion stands in contrast to those of several papers in the literature. Harstad and Eskeland (2010) find that permits should be long-lasting to avoid costly signaling by firms. Harstad (2015) finds that climate agreements should be long-lasting to avoid that the costly hold-up problem appears "too often". Battaglini and Harstad (2015) find that this problem can be leveraged to support equilibria with large coalitions. Our conclusions are therefore in line with Battaglini and Harstad (2015) as we show that endogenous technology investments may lead to emission reductions.

So far, we have not considered trade in renewable energy, in order to focus on the effect of linking permit markets. However, the mechanism leading to welfare gains is driven by the common price on emission permits – and thus 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 $e_i(p^{trade}) > \omega_i^{trade} > 0$ for every country i.*

PROOF:

Consider international trade only in renewables. Market clearing requires $f_{jt} = \omega_{jt},\ \forall j,t$ and $\sum_j z_{jt} = \sum_j (R_{jt} + r_{jt}),\ \forall t$, which gives

$$\sum_j e_{jt} = \sum_j (s_{jt} + r_{jt}) \quad \forall t.$$

This is the same aggregate condition as in the case with international permit trade only. As long as $e_i(p^{trade}) > \omega_i^{trade} > 0$, the equilibrium remains unchanged. This condition is trivially satisfied if countries are identical. □

The result states that the welfare gains that we have found in this paper can be reaped in two ways: by establishing international trade in either permits or renewable energy. But trade in renewable energy often involves large transaction costs because energy transportation is costly. Therefore, permit market linkages may in many cases be the simplest way to reap the gains from a common price. However, this final result shows the potential for welfare gains also in situations where permit trade is difficult to establish – for example for political reasons.

IV. 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 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.

In the online 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 damage. We also discuss the implications for different countries of linkages, and consider a situation where one or more countries can commit to future permit issuance. 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 will depend for example on country characteristics, linking protocols or the timing of linkages. We also believe that the insights from this paper can be applied to other international common good problems, and future research should investigate this. Furthermore, in this paper, the linkage design itself has been given exogenously and we have chosen the simplest possible design: when there is international trade all permits can be traded between consumers in all countries, and there are no transfer prices. However, there are interesting questions concerning both how different designs would affect the outcome, and what the prevailing design would be if the countries were allowed to negotiate over this before or after entering the agreement. Finally, and related to the previous point, trade sanctions can potentially constitute a powerful incentive for abatement, and investigating the potential of trade sanctions as a deterrent in a dynamic setting with international permit trade could be an important next step in this literature.

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