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The dynamics of linking permit markets*

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Abstract

We present a novel benefit of linking emission permit markets. We consider a dynamic setting, and let the countries issue permits non-cooperatively. With exogenous technology levels, there are only gains from permit trade if countries are different. With endogenous technology, however, we show that there are gains from trade even if countries are identical. In this case, linking the permit markets of different countries will turn permit issuance into intertemporal strategic complements: If one country issues fewer permits today, other countries will respond by issuing fewer permits in the future. This happens because issuing fewer permits today increases current 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. Even though countries cannot commit to reducing their own emission, 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. The more frequently participating countries reset their caps, the higher the gain from linking permit markers.

Keywords: International agreements; permit markets; dynamic games; green technology investments.
JEL classification: F53, Q54, H87.

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1 Introduction

1.1 International permit trade

There is currently little hope for a global climate change treaty. However, various regions have planned or negotiated linkages between their domestic emissions permit markets. We show that even in a situation where nations non-cooperatively set their caps on emissions, a simple linkage between such markets can dramatically 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.

The failure of free markets to provide efficient levels of public goods, such as a stable climate, is well known. Without intervention from policy makers, public goods will suffer from under-provision. The converse of this problem is the *tragedy of the commons* (Hardin, 1968): common goods are generally over-exploited. However, efficient management of common goods can be achieved by a price on access to the good. This common price should equal the aggregate marginal damage from exploitation (Samuelson, 1954). For common goods that are international, no super-national authority that can introduce such a price exists. Hence, efficient management of such goods requires international cooperation. Though there are examples of well-managed international common goods, such cooperation is in many cases difficult to achieve. 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. We identify a mechanism that will lead countries to voluntarily reduce their emissions when permit markets are linked.

The number of existing emission permit markets is high and increasing. Such permit markets exist on all regulatory levels. National permit markets are currently operated in for instance Kazakhstan, New Zealand, Norway, South Korea and all the EU member countries. Regional within-country markets exist in two Chinese provinces, in the Canadian province of Quebec and in several US states. Furthermore, both Tokyo, Rio, and five Chinese pilot cities currently operate their own city-wide emission permit markets. Additional national markets are planned/under development in China, Indonesia, Thailand and Vietnam[1]

Many of these markets are linked. On the regional level California and Quebec are linked, as is a group of nine eastern US states in the Regional Greenhouse Gas Initiative. At the national level the EU Emissions Trading System (EU ETS) itself constitutes a set of linked countries. Iceland, Liechtenstein and Norway are linked to the EU ETS, and both the EU ETS and New Zealand are linked to the United Nation's Clean Development Mechanism (CDM). For further discussion of existing permit markets, linkages, and various permit market features, see e.g. Liski and Montero (2011), Grubb (2012), Ranson and Stavins (2012), Newell et al. (2013) or Goulder (2013).

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

The large number of existing markets and the existing linkages mentioned above indicate a large potential for further permit market linkages. The lack of international cooperation suggests that such linkages could provide an important path towards global coordination in fighting climate change. Indeed, Newell, Pizer, and Raimi (2013, p. 123) argue that the "[...] late-1990s 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." However, 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 introducing permit market linkages between countries, without assuming that the countries enter into an agreement on the aggregate cap on emissions. Instead, each country is free to issue as many emission permits as it wants. Energy consumers in each country can then buy or sell such permits from consumers in any other country participating in the market. We show that such *non-cooperative* international trade in permits can result in substantial emission reductions compared to a non-cooperative benchmark without international trade in permits.

We construct a dynamic model where a group of countries face damages from climate change. In each country, there are energy consumers and producers who invest in durable renewable energy production capacity. The government in each country non-cooperatively determines a domestic cap on emissions. When there is international trade, emission permits can be traded across borders. We find potentially large welfare gains from such trade, arising from a mechanism that turns the permit issuance of different countries into intertemporal strategic complements. This strategic complementarity leads to lower emissions and higher welfare, without requiring any country to commit to reducing its own emissions or punish other countries that do not. The main contribution of this paper is to show that permit market linkages will lead countries to voluntarily restrict emissions. This conclusion does not depend on countries being different, or permit trade taking place in equilibrium.

The mechanism we identify can be explained in terms of the three following steps. Firstly, more emission permits available in the market in any given time period gives a lower equilibrium permit price. This means that if one country withholds an emission permit today, the permit price will be higher. When there is international trade in permits, the permit price will increase in all countries. Secondly, an increase in the permit price will increase the demand for green energy. This will lead green energy producers in every country to increase their investments. These increased investments will in turn increase the available production capacity in the future since capacity is durable. When the current emission permits expire and countries issue new permits, they will all have higher production capacity for green energy. Thirdly, countries with more green energy capacity will issue fewer permits. 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. There is thus an intertemporal strategic complementarity in permit issuance: if one country withholds a permit today, investments in green energy will increase in every country, and all countries will respond by issuing fewer permits in the future. Countries will exploit this complementarity in order to reduce the costs of climate change imposed on them by other countries.

The mechanism explained here leads to an outcome under international permit trade that is better than the outcome under autarky. The welfare gains from linking permit markets are due to emission reductions and are independent of any trade taking place in equilibrium.

1.2 Related Literature

This paper contributes to a literature on linkages between markets for emission permits. Linking permit markets will lead to gains as marginal abatement costs will be equalized across markets (see e.g. Flachsland et al. (2009)). However, linking permit markets may also affect the incentives and behavior of policy makers. Several authors discuss the effects of permit market linkages and how the effects of linkages depend on the exact institutional framework (see e.g. Newell et al. (2013), Mehling and Haites (2009), Jaffe et al. (2009), Fischer (2003) or Green et al. (2014)).

Helm (2003) and Rehdanz and Tol (2005) are the first authors to explicitly model the incentives to alter the emission cap when national permit markets are linked. Both find that some countries will increase their permit issuance, while others will reduce it. Therefore, there is no ex ante reason to expect emissions to go down when permit markets are linked across countries. The exact welfare results will depend on the model parameters. Following these papers, there is a literature investigating these effects in numerical models, with mixed conclusions (e.g. Carbone et al. (2009) and Holtsmark and Sommervoll (2012)). However, these papers only analyze countries engaging in static games. We show that when dynamics are allowed to play out in a very similar model framework, the effect of introducing permit market linkages changes substantially. Specifically, we identify a mechanism that results in emission reductions and positive welfare effects when permit markets are linked.

Permit market linkages have recently gained increased attention from researchers and policy makers, partly due to the lack of results from global climate negotiations. The observed failure to reach agreement is very much in line with theoretical predictions from the economics literature. Barrett (1994) shows that the number of countries willing to participate in climate coalitions is very small when emission levels are set in order to maximize the aggregate welfare of the coalition members. The incentives to free-ride that all countries face, prevents an efficient global solution to the climate problem (see also Barrett (2005)). Hoel (1992), Carraro and Siniscalco (1993) and Carraro et al. (2006) show that the predictions are the same when different institutional frameworks are considered. Endogenous technology investments will change the workings and optimal design of climate treaties, but generally not solve the free-rider problem (see e.g. Barrett (2006), Hoel and de Zeeuw (2010) and Calvo and Rubio (2013)). Dixit and Olson (2000) demonstrate the failure of Coasian bargaining when many countries face a public good problem such as climate change. This literature demonstrates the need to find mechanisms that do not rely on countries determining emission levels cooperatively. We show that when national permit markets exist, linking these markets will provide countries with incentives to voluntarlity reduce their emissions.

In addition to the literature on permit market linkages, this paper also contributes to a more general literature on dynamic games of public goods provision. A general insight from this literature is that free-rider problems are more severe in dynamic games.

More specifically, several papers show that when technology investments are non-contractible, problems arise that increase the inefficiencies resulting from free-riding. One such problem is the *hold-up problem*: countries know that they will enter into (re)negotiations over emission levels in the future; thus, when they make their green technology investment decisions up front, they take into account that their bargaining position will be weakened if they invest a lot. The result is that all countries invest less in equilibrium. Both Buchholz and Konrad (1994) and Beccherle and Tirole (2011) show that this problem can lead to severe negative welfare consequences. In contrast to these findings, we show that the non-contractiblity of green technology investments can contribute to a mechanism that results in emission reductions when permit markets are linked.

Harstad (2015) demonstrates that, because of the hold-up problem, treaties should be long-lasting. When the next renegotiation will take place far in the future, the perverse incentives to underinvest are much weaker. In our model we show that the emission caps should be reset often, in order to reap larger welfare gains from permit trade. This demonstrates how strongly the implications of including non-contractible green investments depend on the setting.

Finally, there are also other contributions to this literature that find a positive effect of the non-contractibility of green investments. These authors demonstrate how the hold-up problem can be leveraged to produce better outcomes by specifically allowing for renegotiation of the treaties (Harstad, 2012) and exploiting the hold-up problem when punishing defecting countries (Battaglini and Harstad, 2015).

Introducing dynamics in climate change models may produce strategic spillovers that make the free-rider problem more severe. For instance, Hoel (1991) identifies a spillover due to the damages from emissions being convex. He shows that this spillover undermines any single country's incentive to unilaterally reduce emissions because reduced emissions in one country reduces the marginal damage other countries face. Thus, countries respond by increasing their emissions: emissions are strategic substitutes. Fershtman and Nitzan (1991) take the spillovers identified by Hoel (1991) to a dynamic setting, where countries have convex damage functions from a stock of carbon in the atmosphere. In this setting, emissions become intertemporal strategic substitutes, and countries can free ride on both the current and future effort of others. Contrasting this, we show that introducing dynamics can also reduce the free-rider problem.

Such positive strategic spillovers are also found by both Ploeg and de Zeeuw (1992) and Golombek and Hoel (2004). Ploeg and de Zeeuw (1992) assume that technologies are pure public goods, and show how countries will overinvest in green technologies, in order to induce other countries to emit less in the future. Similar results are also found by Golombek and Hoel (2004), who study imperfect green technology spillovers. We show, however, that strategic links between emission levels in different countries can arise even if there are no technical spillovers.

The literature on climate coalitions discussed above, assumes that countries, once inside a coalition, can contract on emission levels. There is another strand of literature that excludes this type of exogenous compliance. This literature studies how cooperative behavior can be enforced by the threat of Nash reversion, when it is taken into account that countries interact repeatedly. This can be thought of as endogenous enforcement of compliance with the agreement in a dynamic framework. Though the conclusions differ somewhat depending on the specific assumptions, this literature shows that low emission levels *can* be sustained in equilibrium in repeated games, when countries are allowed to employ trigger strategies to punish defectors. 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 the assumptions we make in this paper. However, by restricting our attention to Markov perfect equilibria, we show that such punishment schemes are not the *only* way to obtain higher welfare when policies are set non-cooperatively.

The paper proceeds as follows: in Section 2 we introduce the model setup and the benchmark outcomes. We solve for the Markov perfect equilibrium of the dynamic game and present our main results in Section 3. In Section 4, international trade in the substitute technology, rather than international permit trade, is discussed. In Section 5 we relax some of the assumptions and discuss extensions of the model framework, while we conclude in Section 6.

2 The model

In this section we present the model setup. We look at a group of N countries, who all incur some damage from climate change. The model spans an infinite number of discrete time periods, and each country makes policy decisions within each period. In each country there are price-taking energy consumers and renewable energy producers who also make decisions in every period.

We first introduce the problems solved by consumers and producers, and solve for their demand and supply. Then, we derive a first-best benchmark for consumption, investments, and emission levels. Finally, we derive the outcome under autarky, when governments set their optimal policy, but there is no trade among countries. When we later investigate the equilibrium under international permit trade, we compare the emission levels under such trade to the first-best levels and the levels under autarky.

In a given country i, the representative consumer is a price taker and derives utility $u_i(e_{it})$ from consuming e_{it} units of energy in period t. We assume $u_i(\cdot)$ is increasing and concave in the relevant region. Energy is available from two sources, one fossil and the other renewable. For simplicity, assume that there is an abundant supply of fossil energy available for all to consume at zero price. In Section 5.1, we discuss this assumption, and argue that it does not drive our results. Consumption of fossil energy by country i in period t is denoted f_{it}. The consumption of fossil energy drives climate change and hence determines the damage inflicted on all countries.

Given the damage from climate change, countries will want to use a policy instrument to reduce emissions, both under autarky and trade. We assume that each country under autarky sets a cap on domestic emissions and issues emission permits that grant the holder the right to consume fossil energy. The permits can either be auctioned off or distributed for free—for the purpose of this paper, this does not matter. The permits can then subsequently be traded among the country's energy consumers. When discussing the outcome under autarky, the implemented allocation would be equivalent to that under regulation of emissions by use of a tax, or even direct regulation, as there is no uncertainty or asymmetric information in the model. Let ω_{it} denote the number of permits issued in country i. For every unit of fossil energy consumed, the consumer has to buy one emission permit, traded in the market at price p_{it}. Domestic consumption of fossil energy must equal the number of permits issued domestically when permit markets are not linked. When permit markets are linked, the permits can be traded among consumers not only in the same country, but also among consumers in different countries. Domestic fossil energy consumption must then no longer equal domestic permit issuance, but total issuance of permits determines the total cap on emissions in the system. When there is international permit trade, the permit price, p_{it}, will be equalized across countries.

In addition to fossil energy, consumers can consume renewable energy, denoted by z_{it}. Total consumption, e_{it}, is then $f_{it} + z_{it}$, hence we assume the two types of energy to be perfect substitutes. The fact that they are perfect substitues means that in equilibrium, we will have $p_{it} = q_{it}$, where q_{it} denotes the price of renewable energy in country i in period t. This means that international trade in either permits, renewables or both, will equalize the price of both permits and renewables across countries, as long as there is positive demand for both types of energy in all countries. Renewable energy is not freely available, but produced by private firms, who take the price q_{it} to be exogenous. In Section 5, we discuss the implications for our model if investments in renewables were determined politically. We argue that this would not change our main results.

Each period, the representative renewables producer in country i can undertake a (non-negative) investment, r_{it}, at a cost $c_i(r_{it})$. We assume this investment cost function to be increasing and convex in the current investments, and independent of the level of the stock. These investments contribute to a stock of renewables production capacity in country i, denoted R_{it}. We assume that the investments undertaken in period t are immediately available, and that there are no variable costs in supplying renewable energy from the stock. All actors in the model share the same discount factor, β. For each country, i, the renewables stock develops according to

$$R_{it+1} = \delta(R_{it} + r_{it}), \tag{1}$$

so that $\delta \in (0, 1)$ is the survival rate, and $(1 - \delta)$ the depreciation rate of the renewables stock.

Define $f_t = \sum_j f_{jt}$ to be aggregate emissions in period t, equal to the aggregate consumption of fossil energy. Further, let S_t be the stock of GHGs in the atmosphere in period t, which develops according to $S_{t+1} = \gamma(S_t + f_t)$, such that $(1 - \gamma)$ is the decay rate of the stock of GHGs. Each country incurs a damage in period t from the stock of GHGs in the atmosphere, represented by the linear damage function $\tilde{D}_i(S_t + f_t)$.[2] This allows us to represent the present value of damages to country i, from emissions in period t, by a constant marginal damage D_i. We can then disregard the GHG stock as a state variable in our model. With this simplification, we focus attention on the strategic incentives created by establishing permit trade among countries, rather than the general effects arising from convex damage costs. This damage function has been extensively applied in the literature. See for instance Dutta and Radner (2009) for a thorough discussion of the implications. In Section 5, we also discuss this damage function and argue that our results are not driven by this assumption.

The welfare of country i in period t will consist of utility from consumption, renewables investment costs, damages from emissions, and, if there is international permit trade, the net cost or revenue from trading permits:

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

where $z_{it} = R_{it} + r_{it}$. If there is no international trade in permits, the net revenue from trade would of course be zero for all countries, as $\omega_{it} = f_{it}$. Under autarky, the prices p_t and q_t will differ across countries.

The timing of decisions within each time period in each country is demonstrated in Figure 1. The assumptions reflect how quickly we anticipate each group of decision makers can react. Consider, for instance, the EU today. There, the current cap on emissions is determined through 2020, and it seems realistic that producers of renewables consider the current policy environment a given. Consumption takes place continuously and reacts to clear the market. Hence, we assume that each government issues permits at the beginning of every time period. Then, the renewables producers decide how much to invest, and

[2] Given $\tilde{D}_i(S_t + f_t)$, the increase in the present value of future damages 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 $D_i = \frac{\tilde{D}_i}{1-\beta\gamma}$.

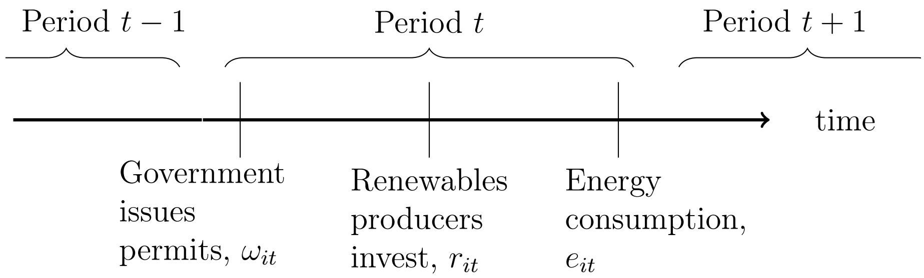

Figure 1: The timing of the game

finally consumption is determined and prices clear the markets. The renewables producers and the consumers of energy are all price takers, while governments realize that they will affect the permit price when issuing permits both under autarky and international permit trade.

2.1 Equilibrium consumption and investments

Consumers and producers are price takers, and behave in the same way, independent of whether or not permits and renewables are traded among countries. The consumer is endowed with a fixed per-period budget, which he allocates between consuming energy and all other goods, which we take to be the numeraire good. We assume that the budget constraint is such that there will always be an interior solution to the consumer's maximization problem, and we therefore disregard this constraint in the following. Generally, we disregard any other possible market failure except for the climate problem.

Observing prices p_{it} and q_{it}, the representative consumer in country i then solves a static problem in each period:

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

with the solution

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

Since the two energy sources are perfect substitutes, the price of renewables and permits must be equal in equilibrium, provided that both are consumed. We denote the common price p_{it}.

We then have $u_i'(e_{it}) = p_{it}$, which defines an energy demand function for country i, $e_{it}(p_{it}) = (u_i')^{-1}(\cdot)$, with a derivative of

$$e_{it}'(p_{it}) = \frac{1}{u_i''(e_{it})} < 0. \tag{4}$$

The representative renewables producers in each country solve an intertemporal problem. In each period, they own a stock of renewables, they take the stream of prices as given, and decide to what extent they want to invest to increase their stock capacity. There is no rental or second-hand market for the stock capacity, and produced energy cannot be stored across periods. The producers solve

$$V_{i,t}^r(R_{it}) = \max_{r_{it}} \left\{ p_{it} \cdot (R_{it} + r_{it}) - c_i(r_{it}) + \beta V_{i,t+1}^r\big(\delta(R_{it} + r_{it})\big) \right\}. \tag{5}$$

Each period, they sell the energy produced from the existing stock plus current investments. They pay investment costs, and take into account how investments today affect the future stock. We show in Appendix A.1 that the renewables producers' problem is solved by

$$\begin{aligned} c_i'(r_{it}) &= p_{it} + \beta\delta p_{it+1} + (\beta\delta)^2 p_{it+2} + \ldots \\ &= \sum_{\tau=t}^{\infty} (\beta\delta)^{\tau-t} p_\tau \equiv \hat{p}_{it}. \end{aligned} \tag{6}$$

As they are price takers, the renewables producers pay no attention to the current stock, and equate the current marginal investment cost with the discounted sum of all future prices, from now on denoted $\hat{p}_{it}$. The inverse of the marginal cost curve defines current investments as a function of this price sequence, denoted $r_i(\hat{p}_{it})$, with

$$r_i'(\hat{p}_{it}) = \frac{1}{c_i''(r_{it})} > 0. \tag{7}$$

From the problems solved by consumers and producers it follows that consumption is lower, and investments are higher, when the price is high. Emissions from any given country will therefore be lower when the permit price is higher. The decrease in emissions resulting from a price increase will depend positively on the slope of the supply/investment curve and the demand curve.

From the derived investment behavior, it follows that the stock of renewable energy capacity available at the beginning of period t in country i is given by

$$\begin{aligned} &\delta^t R_{i0} + \delta^{t-1} r_i(p_{i1}) + \ldots + \delta r_i(p_{it-1}) \\ &= \delta^t R_{i0} + \sum_{s=1}^{t-1} \delta^{t-s} r_i(p_{is}). \end{aligned}$$

Furthermore, in a steady state where the price is constant (given by p^{SS}, for instance) and the stocks are at their steady-state levels, consumption will be given by

$$e_i^{SS} = e_i(p^{SS}), \tag{8}$$

and the stock in country i will be given by

$$R_i^{SS} = \frac{\delta}{1-\delta} r_i \left(\frac{p^{SS}}{1-\beta\delta} \right). \tag{9}$$

Throughout the paper, as we solve for the benchmark cases and the Markov perfect equilibrium under international permit trade, we assume that, in every country, there is not enough renewable energy to completely saturate energy demand. Thus, consumers in every country will consume both renewable energy and fossil energy, which must be accompanied by emission permits. The resulting positive permit demand is sufficient for international permit trade to equalize the price of both permits and renewable energy across countries. If instead, energy demand in country i was saturated by renewables alone, the domestic renewables price in country i would be decoupled from the international permit price. The following assumptions are sufficient to ensure that no country is completely saturated by renewables in any time period:

$$e_i \left(\sum_{j=1}^{N} D_j \right) > \frac{1}{1-\delta} r_i \left(\frac{\sum_{j=1}^{N} D_j}{1-\beta\delta} \right) \; \forall i, \tag{10}$$

$$e_i \left(\sum_{j=1}^{N} D_j \right) > R_{i0} + r_i \left(\frac{\sum_{j=1}^{N} D_j}{1-\beta\delta} \right) \; \forall i. \tag{11}$$

In Section 5, we discuss the implications of relaxing this assumption.

Both these inequalities depend on the parameters of the utility and investment cost functions. Equation (10) states that steady state consumption must exceed the steady state stock of renewable capacity in every country, while Equation (11) also takes into account that demand must exceed the initial stock in every country. Given the other model parameters, this determines an implicit upper bound on β and δ. As β goes to 1, investors do not discount the future and are willing to undertake infinite investments in every period, as long as they expect a positive price in every future period. Furthermore, as δ goes to 1, the stock never depreciates, so positive investments every period mean that the stock will explode.

Note that there always exist parameters such that any pair (β, δ) satisfies (10) and (11), as long as $\beta\delta < 1$.

Before we solve the individual optimization problems of the governments under international permit trade, we will present the first-best solution of the model and the governments' solution under autarky. These two cases make up the benchmarks we use for comparison when we solve the model with international trade.

2.2 First best

Define aggregate welfare by the discounted sum of utility from consumption, costs of investing in renewable energy capacity, and the damages from climate change, for every country.

$$W = \sum_i \sum_{t=0}^{\infty} \beta^t \Big(u_i(f_{it} + z_{it}) - c_i(r_{it}) - D_i f_t \Big)$$

The first-best consumption levels and renewables investments in each period will be given by the solution to the following problem:

$$\begin{aligned} W^{FB} &\equiv \max_{\{\{f_{it}, z_{it}, r_{it}\}_{i=1}^{N}\}_{t=0}^{\infty}} W, \\ \text{subject to} \quad z_{jt} &= (R_{jt} + r_{jt}) \quad \forall j, t \\ \text{and} \quad R_{jt+1} &= \delta(R_{jt} + r_{jt}) \quad \forall j, t. \end{aligned}$$

Given an interior solution, the first-best allocation is characterized by the following: first, marginal utility of consumption for each country and in every period, must equal the sum of the marginal damage of emissions across all countries:

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

Hence, total consumption in the first-best solution is constant over time. Secondly, since renewables investments today will also bear fruit in future periods, the marginal cost of producing renewables should equal the sum of the damages that can be avoided in all countries, discounted over all future periods:

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

First-best emission levels are thus determined by the development of the renewables stock over time. If all countries start out with renewables stocks below their steady state, each stock will increase until it reaches this stable steady state. Emissions will thus decrease over time as the economy's renewables capacity increases. In the steady state, emissions are constant.

Given the behavior of consumers and renewables producers, given by (4) and (6), the first-best allocation can be implemented by a common price on emissions, equal to the sum of the marginal damages in every time period:

$$p_t^{FB} = \sum_j D_j \quad \forall t. \tag{12}$$

Note that this price only depends on the marginal damage of the countries. In particular, it does not depend on the survival rate of the renewables stock. This will be particularily relevant when we consider the outcome when permit markets are linked.

2.3 Autarky

We now introduce governments as decision makers in the case where there is no international permit trade. The permits that each government issues are either auctioned or distributed for free among the domestic consumers and producers. This distinction is irrelevant to our results. These permits can then be freely traded domestically. Autarky thus designates a case where there is domestic permit trade, but no international trade. Under autarky, the per-period welfare of country i is given by:

$$U_{it} = u_i(e_{it}) - c_i(r_{it}) - D_i f_t.$$

Governments are assumed to maximize the discounted sum of future welfare. We set up the problem recursively and let different governments determine domestic emissions simultaneously.

As the model is time-independent, we suppress time indices from now on, unless clearly needed. Next-period stocks are denoted by $^+$.

Under autarky, setting a tax p_i on emissions is equivalent to setting a domestic cap. Emissions in each country will be given by the residual between total consumption and available renewables: $f_i = e_i(p_i) - R_i - r_i(\hat{p}_i)$, where $\hat{p}_i$ is the discounted sum of future prices in country i.

Each country then solves

$$\begin{aligned} V_i^{aut}(\{R_j\}_{j=1}^N) = \max_{p_i} \Big\{ & u_i(e_i(p_i)) - c_i(r_i(\hat{p}_i)) - D_i \sum_j \big(e_j(p_j) - r_j(\hat{p}_j) - R_j\big) \\ & + \beta V_i^{aut}\big(\{\delta(R_j + r_j(\hat{p}_j))\}_{j=1}^N\big) \Big\}, \end{aligned} \tag{13}$$

taking into account the response functions of producers and consumers. Existence of an interior solution follows from the assumption that Equations (10) (11) hold. Emissions in all other countries are taken as given and, due to the linear damage function, they do not affect the optimal policy of country i, even if known ex ante.

Each country trades off marginal utility today against costs and damages today and the benefit of having a higher stock of renewables tomorrow. In Appendix A.2 we show that the problem is solved by

$$p_{it}^{aut} = D_i, \ \forall t. \tag{14}$$

The government sets a price on emissions equal to the domestic marginal damage of emissions in every period, independent of the current renewables stock. This is the standard tragedy of the commons: each country will grant its consumers access to the commons until the private marginal utility equals the private marginal damage from depletion of the commons, and fail to take into account the damage incurred by other countries.

Given that the two policy instruments are equivalent, the same welfare level could of course also be implemented by setting a domenstic cap on emissions, such that:

$$\omega_i^{aut} = e_i(p_i^{aut}) - r_i(\hat{p}_i^{aut}) - R_i.$$

The constant price results in constant consumption and investments in each country, and the stock of renewables converges to some steady-state level. If the stock of renewables starts below this level, it will move along an increasing path and extraction from the commons will, over time, decrease along with it. From a social point of view however, emissions will forever remain suboptimally high.

As in the first-best solution, the carbon price in each country is constant over time, and is independent of the survival rate of the renewables stocks and the discount factors. Furthermore, as emissions are strategically neutral when the damage function is linear, there is no possibility for any country to affect current or future emission levels in other countries. Hence, no strategic considerations are taken and each country's action affects only its own emissions.

3 International permit trade

3.1 Setup

In this section, we present our results on the effect of introducing permit market linkages between countries. We show that the common price arising when there is international trade in emission permits changes the incentives countries face in the permit issuance stage.

Introducing international permit trade means allowing emission permits to be traded not only between energy consumers in the same country, but between consumers in all N countries. Our main focus is on how such trade affects total permit issuance, and hence emissions and welfare. In Section 5, we discuss international trade in renewable energy and show that emissions are affected in the same way by either trade in renewables or emission permits.

International permit trade is organized as follows. Countries are free to issue as many permits as they want. In the consumption stage, these permits are traded among consumers in all countries at a common price. One unit of fossil energy consumption requires one emission permit. We assume that countries honor this requirement, and that they do not exempt their consumers from this requirement ex post.

The introduction of international permit trade changes the dynamic game. As opposed to the situation under autarky, countries no longer have dominant strategies. We study Markov perfect equilibria (MPEs), in which the renewables stocks are the only payoff-relevant state variables. The government in each country understands the response functions of all consumers and renewables producers, as derived in Section 2.1.

Recalling that demand and investments depend on prices, market clearing requires

$$\begin{aligned} & z_j(p) = R_j + r_j(\hat{p}) \ \forall j, \\ & \sum_j f_j(p) = \sum_j \omega_j, \\ \Rightarrow & \sum_j (f_j(p) + z_j(p)) \equiv \sum_j e_j(p) = \sum_j (R_j + r_j(\hat{p}) + \omega_j). \end{aligned}$$

A key figure in the following analysis is the *initial* supply of energy, *i.e.* the supply *before* the renewables producers make their investments. At this stage, the N stocks of renewable capacity are known, and the governments have issued their permits, ω_i. Define the initial supply by $s \equiv \sum_j R_j + \sum_j \omega_j$, and substitute it into the market clearing condition, to get

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

Given the behavior of consumers and investors, the price prevailing in the market is only a function of s, $p = p(s)$. An increase in this initial supply will lead to a price decrease. If this were not the case, there would be no change in either consumption or investments, and an increase in s would lead to excess supply. When s increases, demand must increase and/or investments must decrease in order for the market to remain in equilibrium. This happens only if $p'(s)$ is negative. As the renewables producers are rational and farsighted, we might fear that an increase in s today would affect the behavior of the renewables producers in non-obvious ways. However, in Appendix A.3, we prove that this is not the case, and further show that $p'(s) = 1/(\sum_j (e'_j(p) - r'_j(\hat{p}))) < 0$.

3.2 Markov perfect equilibrium

Under international permit trade, the government in country i solves the dynamic problem:

$$V_i^{trade}\big(R_1, \dots, R_N\big) = \max_{\omega_i} \Big\{ u_i(e_i(p(s))) + p(s) \cdot \big(\omega_i + R_i + r_i(\hat{p}) - e_i(p(s))\big) \\ - c_i(r_i(\hat{p})) - D_i \sum_j \omega_j + \beta V_i^{trade}\big(\delta(R_1 + r_1(\hat{p})), \dots, \delta(R_N + r_N(\hat{p}))\big) \Big\}. \tag{15}$$

In a given time period, the number of permits issued by all other countries are taken as given by country i, so permits are issued in a simultaneous Nash equilibrium. However, the country takes into account that the permit price today, and possibly also in the future, will be affected by the total number of permits issued through the initial supply, s. They are not, therefore, price takers. They also realize that the total number of permits issued in the future might depend on their current actions through the state variables R_j^+.

The solution to this problem will give us the permit price and the cap on emissions in each time period. We derive the following N first-order conditions:

$$0 = p(s) + p'(s) \cdot \big(\omega_i + R_i + r_i(\hat{p}) - e_i(p(s))\big) + p'(s)e_i'(p)(u_i'(e_i(p)) - p(s)) \\ + \frac{d\hat{p}}{d\omega_i} r_i'(\hat{p}) \cdot (p(s) - c_i'(r_i(\hat{p}))) - D_i + \beta\delta \frac{d\hat{p}}{d\omega_i} \sum_j r_j'(\hat{p}) \frac{\partial V_i^{trade+}}{\partial R_j^+}, \quad \forall i. \tag{16}$$

Together these conditions define our MPE. When an additional permit is issued by the government in country i, the country experiences a marginal cost and a marginal benefit. Since permits are issued simultaneously, the game resembles a Cournot game: each country acts as a monopolist on the residual demand, given the permit issuance of the other $N-1$ countries. When country i issues one additional permit, its marginal revenue is given by two terms. Firstly, country i has a direct gain from selling the new permit, given by the market price. Secondly, the price will decrease as a result of the increased permit supply. The country will benefit from the price decrease if it is a net importer of permits. The higher the net imports of country i, the higher the benefits. If the country is a net exporter of permits, the price decrease is costly, and again, the cost of a decrease in price increases in the net exports of country i. (The reduced price will also increase the utility of consumption through increased domestic demand for energy, but this cancels out against the price consumers have to pay for that energy.) Furthermore, the lower price will decrease domestic investments in renewables, which costs the country the price p today, although the marginal cost c' is saved. Since the renewables producers are forward-looking, this does not cancel in the same way as the change in consumption. Finally, there are two ways in which country i incurs a cost from issuing an additional permit. Firstly, an increase in the permit supply directly increases emissions, and country i incurs a cost D_i. Secondly, the actions today have an effect in the future: the price change today will lower investments in renewables, not only in country i itself, but in all countries participating in the permit market. This results in a lower future stock of renewables, which may affect the country through the continuation value, $\partial V_i^{trade+}/\partial R_j^+$. As in a Cournot oligopoly model, permits are strategic substitutes within each period: in the stage Nash equilibrium, the number of permits issued by country i is decreasing in the number of permits issued by countries other than i. This is the case because increased issuance by other countries depresses the permit price.

The solution to country i's maximization problem is given by the permit issuance ω_i which equalizes these marginal costs and benefits. The marginal benefit to country i of issuing a permit is strictly decreasing in the number of permits issued: more permits will also lower the price of the inframarginal permits, and the marginal benefit will eventually become negative. Thus no country will ever want to issue an infinite number of permits.

The equilibrium will be given by the N first-order conditions stated in Equation (16). Fudenberg and Tirole (1991) suggest the following selection criterion for MPEs: the infinite-horizon MPE should be the limit of the finite-horizon MPE of the truncated game as the horizon goes to infinity. In Appendix B, we prove that our equilibrium is indeed the limit of the unique finite-horizon SPE of the game (and thus also the limit of the finite-horizon MPE). While the bulk of the calculations are relegated to the appendices, we provide some important results here before explicitly discussing the equilibrium outcome.

Lemma 1.

1. *The equilibrium policy functions satisfy*

$$\frac{\partial \omega_i^{eq}}{\partial R_j} = \begin{cases} -1 & \text{if } j = i, \\ 0 & \text{if } j \neq i. \end{cases}$$

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. See Appendix A.3. □

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. Given the price, p, there is only one level of net supply that is compatible with country i's best response. To see why this has to be, consider the alternative reactions to an increase in R_i. If country i decreased its issuance by less than one unit per unit increase in the stock, then country i's net supply, and the initial supply, s, would increase. This would decrease the price p. This cannot be equilibrium behavior for country i, since every country would want to issue fewer permits when the price is lower. Similarly, we immediately see that if country i reduces its own initial supply of permits in response to a higher stock, then s would decrease, and the price would increase. This cannot be an equilibrium either. The only response that is compatible with equilibrium from country i's perspective is to leave the initial supply, s, unaltered by reducing the number of permits issued one for one. Then the price remains unchanged and no other country would react to the increased stock of renewables in country i.

Given this equilibrium behavior, the only effect of an increased stock of renewables is to replace fossil energy consumption by renewable energy consumption. Reduced emissions benefits country i by avoiding damages D_i, no matter where the emissions were supposed to take place. This turns the domestic stocks of renewable energy into public goods. Lemma 1.2 then follows from the fact that a unit increase in the stock today gives an increase in the stock in the next period of $\beta\delta$, and the period after of $(\beta\delta)^2$ and so forth.

The reactions outlined in Lemma 1.1 form the basis for the mechanism that will produce welfare gains when the countries' permit markets are linked. The next proposition demonstrates that countries can induce each other to issue fewer permits in the future by issuing fewer permits themselves today.

Proposition 1. *When the permit markets of N countries are linked, countries can induce increased investments in other countries by withholding permits today: $\frac{\partial r_j}{\partial p}\frac{\partial p}{\partial \omega_i} < 0,\ \forall i, j$. As a result, emission allowances in the different countries become* intertemporal strategic complements*: $\frac{\partial \omega_j^+}{\partial R_j^+}\frac{\partial R_j^+}{\partial \omega_i} > 0,\ \forall i,\ j$.*[3]

Proof. In Appendix A.3, we prove that $p'(\cdot)$ is negative, and that $d\hat{p}_t/ds_t = p'(\cdot)$. Thus, one less permit issued today will increase the current equilibrium price. By Equation (7), this will further increase investments in every country, $r_i'(\cdot) > 0$, and by Lemma 1.1, future permit issuance will go down in every country, $\partial\omega_j/\partial R_j = -1,\ \forall j$. □

This means that introducing permit market linkages enables countries to induce each other to issue fewer permits in the future, by issuing fewer permits today. This is the case, even though permit issuance decisions are intra-period strategic substitutes. The intertemporal link between issuance in different countries consists of two steps. Firstly, 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. Secondly, when countries experience increased renewable energy stocks in the next period, by Lemma 1.1, they will respond by issuing fewer permits.

In the absence of international trade in permits, countries cannot act strategically in this way. When permits are only traded domestically, countries are unable to affect the permit price in other countries. Under international permit trade, the price is common across countries, and depends on the total number of permits issued. The following lemma solves for the equilibrium permit price.

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

$$p^{trade} = \overline{D}\frac{1+\Omega}{1+\overline{\Omega}} > \overline{D}. \tag{17}$$

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

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

Proof. See Appendix A.3. □

From the reactions outlined in Lemma 1.1, we know that the initial supply, s_t, will be time-independent: whenever a country experiences an increase in their stock of renewable energy capacity, it will respond by issuing fewer permits, one for one. We also know that when s_t is determined so is the price p_t. This means that the equilibrium permit price will be independent of time and the stocks of renewable energy capacity.

Furthermore, Proposition 1 states that a country can induce other countries to issue fewer permits in the future by withholding permits itself today. Its incentive to withhold permits depends on the extent to which it is able to induce increased investments in other countries today. In Equation 17, Ω_j measures the present value of the discounted additional future investments in country j, when one permit is withheld today: investments in country j will increase by $r_j'(\hat{p})$ per unit of price increase. Each unit increase in r_j translates into a δ unit increase in the stock in the next period, a δ^2 increase two periods ahead, and so on ad infinitum. For each unit increase in the renewables stock, country j will issue one less emission permit, by Lemma 1.1. Thus, an increased stock of δ units tomorrow translates into δ fewer units of emissions tomorrow. Including β accounts for the discounting of the value of these emission reductions in terms of welfare. The sum of all Ω_j's is denoted Ω; the present value of the aggregate increase in renewables investments following a one unit decrease in the permit supply. By Lemma 1, Ω thus also measures the present discounted value of the total future emissions avoided when one permit is withheld today. $\overline{D} \cdot (1 + \Omega)$ thus measures the present discounted value in terms of welfare to the average country, of the total emissions avoided when one permit is withheld; it is the value of one unit of emission reduction today plus the present value of the future emission reductions, given by Ω. Finally, $\overline{\Omega}$ is the average Ω_j.

Lemma 2 hence shows that, due to the strategic complementarity outlined in Proposition 1, the equilibrium price under international permit trade is higher than the average marginal damage. The average price under autarky is equal to the average marginal damage (Equation (14)). Hence, the international permit market will increase the average price paid for emission permits relative to the situation under autarky. Countries withhold permits every period to induce other countries to withhold permits in the future, which leads to a higher equilibrium price. Furthermore, the lemma demonstrates that the more able countries are to affect each other in this manner, the higher the permit price is.

By Equation (8) and (9), the steady state level of consumption and the steady state level of the renewables stocks in country i will be given by the following:

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

If the initial renewables stock in country i is lower than this level, it will increase over time until it reaches the steady state level. Similarly, an initial stock above this level leads to a stock that decreases over time until it reaches the same level. The fact that the equilibrium price under international permit trade, p^{trade}, as well as each of the autarky permit prices, p_i^{aut}, $\forall i$, and the first-best price, p^{FB}, are time- and stock-independent means that consumption, investment, emissions, and welfare can easily be compared in all time periods, not only in the steady state. The following results thus hold independently of whether renewables stocks are at their steady state levels or not.

3.3 Welfare implications

We now present the welfare implications of the equilibrium presented above. Intuitively, the introduction of international trade in permits might affect welfare in two ways. Firstly, by equalizing the price on emissions across countries, trade will lead to a cost-efficient distribution of abatement, regardless of the aggregate abatement level. Secondly, we have seen that international permit trade affects the incentives faced by countries when issuing permits and the equilibrium price. Therefore, international permit trade may also affect the prevailing aggregate emission level. The first effect is well understood, and in this paper we are mainly interested in the second. Therefore, when presenting the following result, we first assume that all countries are identical in order to remove the scope for pure cost-efficiency gains.

Proposition 2. *Linking the permit markets of N identical countries reduces emissions and increases welfare in every country by increasing investments and reducing consumption: $r_i^{trade} > r_i^{aut}$, $e_i^{trade} < e_i^{aut}$, $f_i^{trade} < f_i^{aut}$, and $V_i^{trade} > V_i^{aut}$, $\forall i$. There is no trade taking place in equilibrium.*

Proof. The proof follows from Lemma 2. When all N countries are identical, they share the same autarky price, $\overline{D}$. As $p^{trade} > \overline{D}$, it follows that every consumer and every producer experiences a price increase when interntional trade is introduced. This results in reduced consumption and increased investments in every country, and thus reduced emissions. As emissions in each country are inefficiently high under autarky, these emission reductions increase aggregate welfare. For identical countries, this means that welfare is increased in every country. □

We see that welfare is increased when international permit trade is introduced even if all countries are identical. In this setting, there is no scope for traditional gains from trade since abatement efforts are also distributed cost-efficiently across countries under autarky. The welfare improvement is thus due to reduced emissions. Countries will voluntarily withhold permits when permit markets are linked following the intuition provided in the discussion after Lemma 1.

The current literature on non-cooperative international permit trade has not taken into account investments in a durable substitute technology. The typical finding in this literature is that there, a priori, is no reason to expect lower emissions as a result of linking permit markets. Indeed, if all countries face the same marginal damage of emissions, Helm (2003) shows that, in a static model, the price prevailing in the permit market will be the common marginal damage. In Helm's static model, countries have no means to induce other countries to abate more, and they have no incentive to abate in excess of the autarky level. As we have shown, this is no longer the case when the dynamics of the substitute technology stock is taken into account. The durability of the renewables stock creates a mechanism through which future emissions can be affected by current governments.

The incentive to withhold permits leading to the result presented in Proposition 2 is not dependent on the countries being identical. Thus, welfare should increase under international permit trade, even if countries differ along some dimensions. However, the distribution of welfare effects across countries will depend on the characteristics of each country. Our next result deals with the effect of linking permit markets on emissions and welfare when countries differ along all dimensions, except their marginal damages from climate change.

Proposition 3. *Consider a group of N countries with identical marginal damages, $D_i = \overline{D}$, $\forall i$. 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. Follows from Lemma 2. With a common marginal damage, countries share the same autarky price, $\overline{D}$. As $p^{trade} > \overline{D}$, it follows that every consumer and every producer experiences a price increase when international trade is introduced. This leads to reduced consumption and increased investments in every country, and hence reduced emissions. As the marginal costs and utilities equal $\overline{D}$ under autarky, and $\overline{D} < \sum_j D_j$, it follows that aggregate welfare increases when emissions decrease. □

When all countries face the same marginal damage from emissions, introducing international permit trade increases the permit price faced by consumers and investors in every country. With emissions above their first-best level, the resulting emission reductions will increase aggregate welfare. However, if utility from consumption and costs of investments differ greatly among countries, the welfare gain will not be evenly distributed. The gain from emission reduction is the same in all countries whereas the cost of decreased consumption and increased investments will differ. Though aggregate welfare increases, some countries may incur a net loss due to the introduction of international trade in this case.

We further explore such cross-country differences in the gains from linking markets in Section 3.4.

So far, the key to the welfare results has been the fact that all consumers and producers experience an increased price on emission permits. This price increase leads to emissions reductions in every country. The next proposition concerns the welfare effects that arise when countries differ in their marginal damage, D_i. When this is the case, it is no longer clear that *all* consumers and producers will face a price increase when international permit trade is introduced.

Proposition 4. *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:* $\sum_i r_i^{trade} > \sum_i r_i^{aut}$, $\sum_i e_i^{trade} < \sum_i e_i^{aut}$, $\sum_i f_i^{trade} < \sum_i f_i^{aut}$ *and* $\sum_i V_i^{trade} > \sum_i V_i^{aut}$.

Proof. See Appendix A.3. The assumption of quadratic utility and cost functions is sufficient, but not necessary for the proof. □

The equilibrium price (see Lemma 2) is the average across all countries' marginal damages, times a mark-up factor. When countries differ in their marginal damages, it may thus be the case that some countries have a marginal damage that exceeds the equilibrium permit price under international trade. Consumers and producers in such countries will then face a lower price under trade than they do under autarky. This means that 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. 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.

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. The net effect of introducing international permit trade could be positive or negative: the outcome depends on the strength of the reaction of consumers and producers who live in countries facing a price decrease, as compared to the reactions in countries that do not face a price decrease. More precisely, if there are consumers and producers facing a price decrease who have sufficiently strong reactions to the price change compared to the reactions in the other countries, total emissions may increase when international trade is introduced. Due to this fact, it is also difficult to discuss the implications of countries being of different sizes, as this involves particular correlations between the different parameters. For a study on this interaction between marginal damage and demand and supply responses in a static setting, see Holtsmark and Sommervoll (2012).

However, if the strategic incentive to withhold permits that we have identified is sufficiently strong, no country will face a price decrease when international trade is introduced. In this case, aggregate welfare will increase.

We have seen that aggregate welfare increases when international permit trade is introduced, both when countries are identical, and when they differ in their marginal damages or in their cost and utility functions. In the following, we discuss the determinants of the size of these welfare gains. We first consider the effect of the total number of countries, N, and then move to a discussion of the effect of depreciation and discounting.

Proposition 5. *As the number of countries, N, increases, the gain to the average country from participation in the international permit market 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 from Equation (14) it follows that $\partial p_i^{aut}/\partial N = 0$. Average welfare increases with the permit price and the result follows. □

Proposition 5 implies that the average welfare gains from introducing international permit trade are larger if the number of participating countries is larger. The reason is that when the number of countries in the market is large, the scope for each country to reduce the externalities inflicted on themselves by other countries is also large. In other words, the more countries that participate in the market, the more countries will be affected when country i withholds permits. One permit withheld has a smaller impact on the international permit price when N is large. At the same time, the effect of a given price increase on the aggregate foreign stock of renewables is larger when N is larger. The latter effect dominates, resulting in a higher future welfare gain to country i from a decrease in ω_i.

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. Rewrite the discount factor as $\beta = e^{-\rho\Delta}$, where Δ is the length of a period, and ρ is the continuous time-discount rate. Similarly, rewrite the survival rate as $\delta = e^{-\eta\Delta}$. The extent to which countries limit their permit issuance depends on the countries' patience, the stock durability, and the length of the time periods, as highlighted in the following proposition.

Proposition 6. *The aggregate gain from linking permit markets ($\sum_i V_i^{trade} - \sum_i V_i^{aut}$) is higher, if*

- *the length of each time period, Δ, is shorter, or*

- *either the depreciation rate of the renewables stocks, η, or the time discount rate, ρ, is smaller.*

Furthermore, when $\beta\delta$ is close to 1, aggregate welfare under international permit trade is close to the first-best welfare level: for every $\varepsilon > 0$, there exists $\mu > 0$ such that whenever $1 - \beta\delta < \mu$, $W^{FB} - \sum_i V_i^{trade} < \varepsilon$.

Proof. Recall that $\beta\delta = e^{-\sigma\Delta}$, where $\sigma = \eta + \rho$. Both $\frac{\partial\beta\delta}{\partial\sigma} < 0$, and $\frac{\partial\beta\delta}{\partial\Delta} < 0$. Furthermore, p^{trade} increases in $\beta\delta$, while p^{aut} is a constant. Thus, the gains to introducing linkages increases in $\beta\delta$. Note that $\lim_{\beta\delta\to 1}\Omega = \infty$, which gives $p^{trade} = p^{FB}$. Thus, if $\beta\delta$ close to 1 satisfies Equations (10) and (11), the equilibrium price will be close to the first-best price. Furthermore, we can always choose cost and utility functions, $c(\cdot)$ and $u(\cdot)$ such that Equations (10) and (11) are satisfied, as long as $\beta\delta < 1$. Finally, given the expression for V_i^{trade} in Equation (A.9), $\lim_{p^{trade}\to p^{FB}} \sum_i V_i^{trade} = W^{FB}$. □

The proposition states that when $\beta\delta$, the product of the discount factor and the survival rate, is higher, the equilibrium permit price will also be higher. Additionally this product is high if either countries are very patient and the stocks are very durable, or if the time periods are short. Recall that neither the first-best price nor the autarky prices depend on the discount factor or the survival rate of the renewables stocks. However, in the presence of international permit trade, these two parameters become relevant, because they determine the strength of the countries' incentives to withhold permits. A higher survival rate means that withholding permits today will affect future permit issuance more, because increased investments in renewables today will give more long-lasting effects on the stocks. A higher discount factor means that each country values the effect they can get from withholding permits more in terms of welfare. Hence, both long-lasting renewables stocks and patience strengthen the incentives to incur current costs by withholding permits. Shorter time periods will have exactly the same effect, since the future gains become both bigger and more important if the future is closer in time. However, it should be noted that the mechanism behind all our results hinges on the assumption that the renewables producers have sufficient time to react to a change in the equilibrium price before the cap is reset. Very short time periods will of course inhibit such reactions. Furthermore, the assumption of an interior solution also places restrictions on how high the product $\beta\delta$ can be for given parameters in the rest of the model, since renewables investments in each time period will increase monotonically in $\beta\delta$.

From Lemma 2, it is also clear that $\delta = 0$ gives $\Omega = 0$ and $p^{trade} = \overline{D}$. This means that if the renewables stocks are not durable, the equilibrium price under international permit trade is equal to the average of all countries' autarky prices. With no durability, the countries cannot affect their trading partners' permit issuance in the future even if there is international trade, because increased investments following a price increase will only lead to more available renewables within the same time period. In this case, our model only constitutes a static game repeated infinitely many times. This static game is studied by

Helm (2003), who indeed shows that the permit price in equilibrium will be equal to the average marginal damage across countries.

Finally, we show that if the cap on emissions is set once and for all, meaning that countries issue permits only once, there is no strategic incentive to withhold permits. In this case, the strategic complementarity in issuance vanishes because there is no future permit issuance that can be affected by withholding permits today. As long as the renewables producers have incentives to react to current price changes, there is a clear benefit to resetting the cap often. This conclusion stands in contrast to the conclusions of several papers in the literature. Harstad and Eskeland (2010) find that permits should be long-lasting to avoid costly signaling by firms with private abatement costs. 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 the same, and demonstrate that the endogenous duration of the climate treaty can be leveraged to support equilibria with large coalitions. Our conclusions are in line with Battaglini and Harstad (2015) as we show that endogenous and non-contractible technology investments may lead to higher emission reductions.

To summarize, in this sections we show that introducing international permit trade may substantially increase welfare. We identify a mechanism that creates strategic complementarity in permit issuance among countries, which is only in place when there is a common permit price between the countries. Furthermore, we show that the size of the welfare gains which can be reaped by introducing such trade depends strongly on the durability of the renewable energy production capacity stocks, and on the level of patience of the governments in countries participating in the market.

3.4 Implications for different countries

In the previous section, we argue that some countries may benefit more than others when international permit trade is introduced. In this section, we study which country characteristics that determine this heterogeneity. 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 7. *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. Insert the expression for the continuation values from Lemma 1.2 into the first-order condition (Equation (16)). Then insert from the definition of $\Omega_i = -\frac{\beta\delta}{1-\beta\delta} r_i'(\hat{p})p'(s) > 0$. A country's net sales of permits in the international permit market is given by its trade balance ($TB_i = \omega_i + R_i + r_i - e_i$). Solve the first-order condition for TB, to get:

$$TB_i = \underbrace{\frac{\overline{D}(1+\Omega)}{-p'(s)}}_{>0} \left(\frac{1+\Omega_i}{1+\overline{\Omega}} - \frac{D_i}{\overline{D}} \right). \tag{18}$$

□

If countries only differ in marginal damage and we sort them along a line by this parameter, 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 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 8. *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: $V_i^{trade} - V_i^{aut} > V_j^{trade} - V_j^{aut}$, 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: $V_i^{trade} - V_i^{aut} > V_j^{trade} - V_j^{aut}$, if $D_i > D_j$.*

Proof. See Appendix A.3. □

Proposition 8.1 is a corollary to Helm (2003)'s Proposition 1, 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 8.2 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 7, high-damage countries are still permit importers, when $\beta\delta$ is high enough, the permit markets delivers sufficient emission reductions for the high-damage countries to gain more than low-damage countries.

In this section, we demonstrated how high-damage countries tend to be permit importers, while low-damage countries are exporters. When the world resembles the static model ($\beta\delta$ low), this means that low-damage countries benefit more from international trade. As the dynamic dimension becomes more pronounced ($\beta\delta$ high enough), high-damage countries will gain more than low-damage countries. The reason is that the incentives to withhold permits increase strongly in the discount factor and the survival rate of the renewables stocks, as demonstrated in Proposition 6.

4 Trade in technology

Under neither autarky nor international permit trade do we allow for international trade in renewables. This is done in order to focus on the effect of opening up the permit market. However, the mechanism leading to welfare gains from introducing trade in permits is driven by the common price on emission permits—and thus renewables—among countries. It is this common price that makes it possible for each country to affect renewables investments in other countries, and by extension, future permit issuance in other countries. The common price and the possibility of affecting issuance decisions in other countries can, however, also be achieved by simply establishing trade in renewables, even absent international permit trade. Given an assumption that guarantees an interior solution to the problem of each country, a stricter emission cap in one country would—through the common price on renewables, and thus permits—affect investments in exactly the same way as in our basic model with international permit trade. Our next proposition underlines that trade in renewables is sufficient to generate welfare gains.

Proposition 9. *International trade in renewable energy alone is sufficient for countries to face strategic incentives to limit domestic permit issuance and for the welfare effects established in earlier results to accrue. Specifically, Propositions 1, 2, 3, 4, 5, and 6 carry over to a setting with international trade only in renewables provided that* $e_i(p^{trade}) > \omega_i > 0$ *for every country* i.

Proof. Consider international trade only in renewables. Market clearing requires

$$f_{jt} = \omega_{jt}, \quad \forall j, t,$$

$$\sum_j z_{jt} = \sum_j (R_{jt} + r_{jt}), \quad \forall t$$

$$\Rightarrow \sum_j (f_{jt} + z_{jt}) = \sum_j (e_{jt}) = \sum_j (R_{jt} + r_{jt} + \omega_{jt}) \quad \forall t,$$

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

The model presented in this paper has been applied to climate change. Though every common good problem is different, some of our findings might also be useful for other international common good problems. In these cases, Proposition 9 can potentially be of importance. Permit trade, including trade between consumers in different countries, has been established in several places. One example is the EU Emissions Trading System. Another example is the link between the permit markets of California and Quebec, implemented as of January 2014. Introducing international permit trade therefore seems feasible in the case of climate change. Furthermore, because international trade in renewables could potentially involve large transaction costs, there is reason to believe that trade in emission permits is the simplest way to reap the gains from a common price. However, it is likely that there are other international common good problems where trade in substitute goods or technologies can more easily be implemented than trade in allowances to exploit the good. Furthermore, in various international common good problems, there may be political constraints that make permit markets difficult to establish. Proposition 9 shows that the positive welfare effects can still be reaped if there are durable substitutes to exploitation.

5 Discussion

In this section, we discuss some of the assumptions that were made in Section 3.

5.1 Endogenous fossil energy

Throughout Section 3, we simplify the way fossil energy supply enters our model by allowing fossil energy to be available at zero price to all consumers. We claim that this does not drive our results. Though a full analysis of the inclusion of fossil energy in our model is out of scope, here we provide the basis for that claim. Our results rely on the fact that international permit trade turns permit issuance into intertemporal strategic complements between countries. This complementarity arises because fewer permits in the market today increases investments in all countries, leading to reduced permit issuance by every country in the future.

We argue that endogenous fossil energy supply could provide a separate channel of intertemporal strategic complementarity. Within a time period, the equilibrium producer price of fossil energy increases with the number of permits available in the market, all else equal. Hence, by withholding permits, a country will decrease the price of fossil energy. Furthermore, we assume that investments in fossil energy production capacity, such as exploration of new fields, are increasing functions of the current producer price. If so, any permit withheld will lead to lower fossil production capacity in countries where fossil energy production is possible. Finally, the higher the production capacity for fossil energy in a country, the more costly a tight cap on emissions will be for this country. Thus, lower fossil investments in one time period will lead the country to issue fewer permits in future periods because its marginal cost of lowering the price of fossil energy is lower. This means that any country can, by withholding permits today, induce other countries to reduce their future permit issuance not only by increasing investments in renewables, but also by reducing investment in fossil energy. By this logic, endogenous fossil energy supply provides a separate channel for strategic complementarity in permit issuance. Though a model taking all features of fossil energy supply into account is out of scope for this paper, we provide a simple two-period model in Appendix C.1, illustrating the mechanism outlined here.

5.2 Politically determined investments

So far, we have 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 have briefly investigated how robust our results are to allowing the government in each country to regulate its own renewables producers. In Appendix C.2, we solve a two-period model where the governments politically determine investments in renewables under the same timing as in the basic model. However, 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. In a situation in which the governments determine renewables investments, the equilibrium permit price under international permit trade will be higher than the average price under autarky. Thus, the main result from our basic model also prevails in this setting, where renewables investments are politically determined.

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 the our basic model, there is still, therefore, a benefit to withholding permits that goes beyond the direct effect on emissions.

5.3 The shape of the damage function

In Lemma 1.1 we see that the linear damage function resulted in countries reducing their permit issuance one for one when their stocks of renewable energy capacity increased. If instead we assumed the damage function to be convex in the atmospheric stock, countries would not respond by reducing issuance one for one. Instead, they would reduce issuance by $1 - \varepsilon$. The basic reason is that a convex damage function introduces a strategic substitutability, as explained for instance by Fershtman and Nitzan (1991). To see this, note that if country i responded by reducing its issuance one for one when its stock of renewables increased, the marginal damage faced by other countries would be reduced, while their marginal revenue would remain unchanged. All other countries would thus want to increase their issuance, which in turn decreases the permit price. The equilibrium response with convex damages for country i would then be to decrease its issuance by $1 - \varepsilon$, while the other countries marginally increase their issuance. Although a convex damage function would complicate the analytical solution to our model, this argument shows that the main mechanism we identify in this paper does not depend on our simplification of the damage function. Even with a convex damage function, countries could still induce their trading partners to emit less in the future, by emitting less themselves today. The intuition from Lemma 1.1 thus carries over to a setting with convex damages. Furthermore, the incentive to react slightly less to a higher renewables stock induced by the convexity would be exactly the same under autarky as under international permit trade.

5.4 Excess renewables supply

Throughout the paper, we have assumed that Equations (10) and (11) hold in order to ensure that both permits and renewable energy are consumed in all countries. This ensures that the international permit price will equalize the price of renewable energy across countries. In Appendix C.3 we present a two-period model in order to shed some light on the case when these conditions fail to hold for some subset of countries. We consider a situation where, at the current international permit price, domestic energy demand in some country i is completely saturated by domestic renewable energy. In this case, the consumers in country i demand no permits, but their government can still issue and sell permits on the international market. In a one-shot game, or if the decision-makers were completely mypoic, this would only have a distributional impact on the equilibrium. The efficiency-properties—here understood in terms of the implemented permit price—would be independent of the fact that one country no longer demands permits. The marginal effects of issuing another emission permit—increased domestic damage from an increase in global emissions and a depressed permit price—does not depend on whether or not domestic consumers consume fossil energy. The positive marginal utility stemming from increased consumption of the cheaper fossil energy is canceled against the price paid for the cheaper permits. Thus the marginal tradeoff a myopic government faces does not change.

In the dynamic model, however, the fact that international permit demand is absent from a subset of countries changes the equilibrium more substantially. If domestic demand in country i is saturated by renewables, the renewables producers of country i do not react to a change in the international permit price. Only the domestic energy price in country i will be relevant and this price is decoupled from the international permit price. Neither will the permit issuance decision of government i be affected by a change in its domestic stock of renewable energy capacity, as its marginal revenue from issuing another permit only depends on the number of permits issued. So far, this is parallell to the static case.

Imagine a situation where all countries start out with a renewables stock, R_{i0}, which is below its steady-state value. For countries in which the steady-state value is such that Equations (10) and (11) do not hold, this means that the renewables stock will eventually reach the point where the country is saturated, meaning that at the international permit price, there is no demand for permits from this country. 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. Furthermore, since the permit price does not affect its consumers and producers, the government in such a country does not adjust its permit issuance in response to changes in the price. Therefore, the more countries whose domestic demands are saturated, the weaker the intertemporal strategic complementarity. The future permit issuance of saturated countries cannot be affected by the current issuance and permit price. As more countries become saturated, fewer countries that can be affected by withholding permits remain. As a result, the equilibrium permit price decreases. This suggests the following intuition: At first, every country has some residual demand for permits, and the international permit price is given by the stationary expression in Lemma 2. Then, as the renewable energy stocks increase, some countries may gradually be saturated by renewables and Equations (10) and (11) no longer hold for these countries. They thus become unresponsive to changes in the permit price. This weakens the incentive other countries face to withhold permits and the permit price gradually declines as more and more countries become saturated. The permit price stabilizes at some level between the price given in Lemma 2 and the myopic price $\overline{D}$, where potentially only a subset of the countries still consume fossil fuels.

6 Conclusion

The global climate is an international common good and suffers from the tragedy of the commons. Since there is no super-national decision maker who can implement efficient emission levels, it is important to identify institutions and mechanisms that can change the incentives countries face. Linkages between national emission permit markets could potentially constitute such an institution and the number of existing domestic and regional emission permit markets is high and increasing. The effect of linkages between such markets is therefore important to understand.

In this paper, we consider a situation in which there are investments in renewable energy production capacities such as hydro power plants or wind farms. 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 we allow for countries to be identical so that no trade takes place in equilibrium.

The findings in this paper highlight the importance of including dynamics when studying international permit trade. Without investments in durable renewable energy capacity, there are no links between current and future permit issuance in the market. Countries are then unable to influence each other, and have no incentives to reduce their permit issuance. The existing literature on non-cooperative permit trade typically concludes that there is no a priori reason to expect permit trade to reduce emissions. We show that allowing for dynamics changes this conclusion.

In the wider literature on provision of public goods, the typical finding is that the outcome is worse when dynamics are taken into account. Our conclusions challenge this finding, as inlcuding dynamics in our model leads to increased welfare from linking permit markets. Furthermore, our conclusions also differ from those of the existing literature along other dimensions. One important difference is that while we find that welfare increases when permits are short-lived, the typical finding is that permits should be long-lasting.

According to our results, there can be substantial gains from linking permit markets. An important issue for future research is to identify which links are most beneficial to undertake. This will depend on properties of the links that are considered, such as country characteristics, linking protocols or the timing of linkages. Finally, the insights from this paper are also applicable to other international common good problems. Further research should seek to shed light on the dynamic effects of introducing international trade in either exploitation allowances or substitute technologies for other international common good problems.

A Appendix - the dynamic game

A.1 The renewables producers

The renewables producers solve

$$V^r_{i,t}(R_{it}) = \max_{r_{it}} \Big\{ p_t \cdot (R_{it} + r_{it}) - c_i(r_{it}) + \beta V^r_{i,t+1}\big(\delta(R_{it} + r_{it})\big)\Big\}.$$

The first-order condition becomes

$$0 = p_t - c_i' + \beta\delta V'_{i,t+1},$$

and the envelope theorem tells us that

$$V'_{i,t} = p_t + \beta\delta V'_{i,t+1}.$$

By recursion, it follows that

$$V'_{i,t+1} = p_{t+1} + \beta\delta p_{t+2} + (\beta\delta)^2 p_{t+3} + \dots \ .$$

Inserting this into the first-order condition, we find that

$$\begin{aligned} c_i'(r_{it}) &= p_t + \beta\delta p_{t+1} + (\beta\delta)^2 p_{t+2} + \dots \\ &= \sum_{\tau=t}^{\infty} (\beta\delta)^{\tau-t} p_\tau \equiv \hat{p}_t. \end{aligned}$$

This defines $r_{it}(\hat{p}_t)$, with $r_i'(\hat{p}_t) = 1/c_i''(r_i(\hat{p}_t)) > 0$.

A.2 Equilibrium under autarky

The first-order condition solving country i's maximization problem becomes:

$$0 = u_i'(e_{it})e_i'(p_{it}) - c_i'(r_{it})r_i'(\hat{p}_{it})\frac{d\hat{p}_{it}}{dp_{it}} - D_i\left(e_i'(p_{it}) - r_i'(\hat{p}_{it})\frac{d\hat{p}_{it}}{dp_{it}}\right) + \beta\delta r_i'(\hat{p}_{it})\frac{d\hat{p}_{it}}{dp_{it}}\frac{\partial V^{aut}_{it+1}}{\partial R_{it+1}} \tag{A.1}$$

To find the continuation values, we differentiate through (13) with respect to R_{it}, using the envelope theorem:

$$\begin{aligned} \frac{\partial V^{aut}_{it}}{\partial R_{it}} &= D_i + \beta\delta\frac{\partial V^{aut}_{it+1}}{\partial R_{it+1}} \\ &= D_i + \beta\delta D_i + (\beta\delta)^2 D_i + \cdots \\ &= \frac{D_i}{1-\beta\delta} = \frac{\partial V^{aut}_{it+1}}{\partial R_{it+1}} \end{aligned}$$

Inserting for $c_i'(r_{it})$ from (6), for $u_i'(e_{it})$ from (3) and for $\partial V_{it+1}^{aut}/\partial R_{it+1}$, the first order condition can now be rewritten as follows:

$$0 = e_i'(p_{it})(p_{it} - D_i) - r_i'(\hat{p}_{it})\frac{d\hat{p}_i}{dp_i}(\hat{p}_{it} - \frac{D_i}{1-\beta\delta}),$$

and we see that $p_{it}^{aut} = D_i$, giving $\hat{p}_{it} = \frac{D_i}{1-\beta\delta}$, solves the problem in every period. Future prices are then independent of the price set today, hence $d\hat{p}_i/dp_i = 1$.

Under autarky, prices are time- and stock independent, and each country will always set its own price on emissions equal to its own marginal damage.

The value function is linear, and given by:

$$\begin{aligned} V_i^{aut}(R_1, \dots, R_N) = \frac{1}{1-\beta}\Bigg[&u_i(e_i(D_i)) - c_i(r_i(\frac{D_i}{1-\beta\delta})) - D_i\sum_j e_j(D_j) \\ &+\frac{D_i}{1-\beta\delta}\sum_j r_j(\frac{D_j}{1-\beta\delta})\Bigg] + \frac{D_i}{1-\beta\delta}\sum_j R_j, \end{aligned} \tag{A.2}$$

where time indices are dropped for simplicity.

A.3 Markov perfect equilibrium under permit trade

Throughout this appendix, we omit the superscript *trade* on the value functions.

Proof of Lemma 1

The government solves

$$\begin{aligned} V_{i,t}(R_{1t}, \dots R_{Nt}) = \max_{\omega_{it}} \Bigg\{ &u_i(e_i(p_t(s_t))) + p_t(s_t)\cdot(\omega_{it} + R_{it} + r_i(\hat{p}_t) - e_i(p_t(s_t))) \\ &- c_i(r_i(\hat{p}_t)) - D_i\sum_j \omega_{jt} + \beta V_{i,t+1}\big(\delta(R_{1t} + r_1(\hat{p}_t)), \dots, \delta(R_{Nt} + r_N(\hat{p}_t))\big)\Bigg\}, \end{aligned} \tag{A.3}$$

subject to Equations (10) and (11), and where $e_i(p)$ is given by the solution to the representative consumer's problem, and $r_i(\hat{p})$ by the representative renewables producer's solution. Furthermore, $p_t(s_t)$ is implicitly given by the market clearing condition:

$$\sum_j e_{jt}(p_t) = \sum_j (\omega_{jt} + R_{jt} + r_{jt}(\hat{p}_t)) \quad \text{with} \quad \sum_j (\omega_{jt} + R_{jt}) \equiv s_t. \tag{A.4}$$

$\hat{p}_t$ can also potentially depend on s_t through the effect current supply will have on future stocks, and not only in the current period.

We are looking for a Markov perfect Nash equilibrium (MPE) in which each country sets its number of permits in a Cournot stage game, taking other countries' permit allowances as given within each time period, and taking into account their own effect on the equilibrium price, and on renewables investments today.

We get the following N first-order conditions:

$$\begin{aligned} u'_{it}e'_{it}p'_t + p'_t \cdot (\omega_{it} + R_{it} + r_{it} - e_{it}) + p_t \cdot (1 + r'_{it}\frac{d\hat{p}_t}{d\omega_{it}} - e'_{it}p'_t) \\ - c'_{it}r'_{it}\frac{d\hat{p}_t}{d\omega_{it}} - D_i + \beta\delta\frac{d\hat{p}_t}{d\omega_{it}}\sum_j r'_{jt}\frac{\partial V_{i,t+1}}{\partial R_{j,t+1}} = 0 \quad \forall i, t. \end{aligned} \tag{A.5}$$

Using the consumers' first-order condition, we can eliminate $e'_{it}p'_t(u'_{it} - p_t) = 0$, but we also have to figure out the continuation values, in order to be able to use these first order conditions to characterize the equilibrium. Differentiating through (A.3) wrt. R_{jt}, we get

$$\begin{aligned} \frac{\partial V_{i,t}}{\partial R_{jt}} &= u'_{it}e'_{it}p'_t\frac{ds_t}{dR_{jt}} + p_t \cdot (\frac{\partial\omega_{it}}{\partial R_{jt}} + \frac{dR_{it}}{dR_{jt}} + r'_{it}\frac{d\hat{p}_t}{dR_{jt}} - e'_{it}p'_t\frac{ds_t}{dR_{jt}}) \\ &+ p'_t\frac{ds_t}{dR_{jt}} \cdot (\omega_{it} + R_{it} + r_{it} - e_{it}) - c'_{it}r'_{it}\frac{d\hat{p}_t}{dR_{jt}} - D_i\sum_k\frac{\partial\omega_{kt}}{\partial R_{jt}} \\ &+ \beta\delta\frac{\partial V_{i,t+1}}{\partial R_{j,t+1}} + \beta\delta\frac{d\hat{p}_t}{dR_{jt}}\sum_k r'_{kt}\frac{\partial V_{i,t+1}}{\partial R_{k,t+1}}, \end{aligned}$$

which of course depends on the policy functions $\omega_{it}(\{R_{jt}\}_{j=1}^N)$. To find these, we will differentiate through the first-order conditions (Equation (A.5)) with respect to R_{jt}. At this point, we will guess that because of the linear damage function, the value functions will be linear in each technology stock, such that $\partial V_{it}/\partial R_{jt} = a_{ijt}$, a constant. This guess will later be verified (see Appendix A.3).

$$
\begin{aligned}
\frac{dFOC_{\omega_{it}}}{dR_{jt}} : p_t' \cdot (\frac{\partial \omega_{it}}{\partial R_{jt}} + \frac{dR_{it}}{dR_{jt}} + r_{it}' \frac{d\hat{p}_t}{dR_{jt}} - e_{it}' p_t' \frac{ds_t}{dR_{jt}}) + p_t' \frac{ds_t}{dR_{jt}} \cdot (1 + r_{it}' \frac{d\hat{p}_t}{d\omega_{it}}) \\
+ p_t' r_{it}'' \frac{d\hat{p}_t}{d\omega_{it}} \frac{d\hat{p}_t}{dR_{jt}} + r_{it}' \frac{d}{dR_{jt}} \left(\frac{d\hat{p}_t}{d\omega_{it}} \right) \cdot (p_t - c_{it}') - c_{it}'' \cdot (r_{it}')^2 \frac{d\hat{p}_t}{d\omega_{it}} \frac{d\hat{p}_t}{dR_{jt}} \\
- c_{it}' r_{it}'' \frac{d\hat{p}_t}{d\omega_{it}} \frac{d\hat{p}_t}{dR_{jt}} + p_t'' \cdot (\omega_{it} + R_{it} + r_{it} - e_{it}) \frac{ds_t}{dR_{jt}} \\
+ \beta\delta \sum_k \frac{\partial V_{it+1}}{\partial R_{kt+1}} r_{kt}'' \frac{d\hat{p}_t}{d\omega_{it}} \frac{d\hat{p}_t}{dR_{jt}} + \beta\delta \sum_k \frac{\partial V_{it+1}}{\partial R_{kt+1}} r_{kt}' \frac{d}{dR_{jt}} \left(\frac{d\hat{p}_t}{d\omega_{it}} \right) \\
+ \underbrace{\beta\delta^2 \sum_k \frac{\partial^2 V_{it+1}}{\partial R_{kt+1} \partial R_{jt+1}} r_{kt}' \frac{d\hat{p}_t}{d\omega_{it}} \left(1 + \sum_l r_{lt}' \frac{d\hat{p}_t}{dR_{jt}} \right)}_{= 0 \text{ by our guess on functional form}} = 0.
\end{aligned}
\tag{A.6}
$$

The solution to (A.6) is $N \times N$ equilibrium responses $\partial\omega_i/\partial R_j$. Knowing these responses will enable us to calculate the continuation values, and then to simplify the first-order conditions, in order to characterize the equilibrium. A solution to this set of equations is given by:

$$
\frac{\partial \omega_{it}}{\partial R_{it}} = -1, \quad \frac{\partial \omega_{it}}{\partial R_{jt}} = 0, \quad j \neq i, \ \Rightarrow \sum_k \frac{\partial \omega_{kt}}{\partial R_{jt}} = -1, \quad \frac{ds_t}{dR_{jt}} = 0, \quad \forall j, t, \tag{A.7}
$$

which is stated in Lemma 1.1.

To see this, note that given these reactions, an increase in the renewables stock of country j, R_{jt}, will not change the equilibrium price, since s_t is independent of R_{jt}. Neither will it change future prices, since these can only be affected through the future supply s, which is independent of the renewables stocks:

$$
\begin{aligned}
\frac{ds_{t+\tau}}{dR_{jt}} &= \sum_k \frac{ds_{t+\tau}}{dR_{kt+\tau}} \frac{dR_{kt+\tau}}{dR_{jt}} = 0, && \forall k, t. \\
\Rightarrow \quad \frac{d\hat{p}_t}{dR_{jt}} &= \sum_{\tau=t}^{\infty} (\beta\delta)^{\tau-t} p_\tau'(s_\tau) \frac{ds_\tau}{dR_{jt}} = 0 && \forall k, t.
\end{aligned}
$$

Furthermore, changes in the renewables stocks will not affect the price change following from an increase in the permit supply, since it follows that:

$$
\frac{d}{dR_{jt}} \left(\frac{d\hat{p}_t}{d\omega_{it}} \right) = 0, \ \forall k, t.
$$

Given these reaction functions, we can also calculate the price change following an increase in the supply, s. Because the only way future supply can possibly be affected by current supply is through the renewables stocks, we have:

$$\frac{d\hat{p}_t}{ds_t} = \sum_{\tau=t}^{\infty} (\beta\delta)^{\tau-t} p'_\tau(s_\tau) \frac{ds_\tau}{ds_t}$$
$$= p'_t(s_t) + \sum_{\tau=t+1}^{\infty} (\beta\delta)^{\tau-t} p'_\tau(s_\tau) \frac{ds_\tau}{dR_{j\tau}} \frac{dR_{j\tau}}{ds_t} = p'_t(s_t),$$

By the market clearing condition (Equation (A.4)), we must have:

$$\sum_j e'_{jt} p'_t(s_t) = 1 + \sum_j r'_{jt} \frac{d\hat{p}_t}{ds_t}$$
$$= 1 + \sum_j r'_{jt} p'_t(s_t)$$
$$\Rightarrow p'_t(s_t) = \frac{1}{\sum_j (e'_{jt} - r'_{jt})} < 0.$$

Note here, that given the market clearing condition, the price in period t is determined only by s_t. Given the results demonstrated here, this means that p_t will be independent of state and time.

Returning to the continuation values, we now have

$$\frac{\partial V_{i,t}}{\partial R_{jt}} = -D_i + \beta\delta \frac{\partial V_{i,t+1}}{\partial R_{j,t+1}},$$

which clearly is independent of both j and t. It follows that:

$$\frac{\partial V_i}{dR_j} = \frac{D_i}{1-\beta\delta}, \quad \forall\ i, j, t,$$

as stated in Lemma 1.2.

The proof of Lemma 1 is concluded by verifying our assumption of a linear value function:

Verifying linear value function

By assuming the value function of each country to be linear in the state variables, we solved the dynamic game, and found the reaction functions stated in Lemma 1.1;

$$\frac{\partial \omega_i^{eq}}{\partial R_j} = \begin{cases} -1 & \text{if } j = i \\ 0 & \text{if } j \neq i. \end{cases}$$

In this section, we show explicitly that given these policy responses to changes in the state variables, the value functions will indeed be linear, and we calculate the value functions.

Given the assumption that:

$$V_{it}(R_1, \dots, R_N) = A_{it} + \sum_j B_{ijt} R_{jt},$$

we must of course have that:

$$\begin{aligned} A_{it} + \sum_j B_{ijt} R_{jt} = \max_{\omega_{it}} \Big\{ & u_i(e_i(p_t(s_t))) + p_t(s_t) \cdot (\omega_{it} + R_{it} + r_i(\hat{p}_t) - e_i(p_t(s_t))) \\ & - c_i(r_i(\hat{p}_t)) - D_i \sum_j \omega_{jt} + \beta A_{it} + \beta\delta \sum_j B_{ijt}(R_{jt} + r_{jt}(\hat{p}_t)) \Big\}. \end{aligned} \tag{A.8}$$

Differentiating through (A.8) with respect to R_j gives:

$$\begin{aligned} B_{ijt} =& u'_{it} e'_{it} p'_t \frac{ds_t}{dR_{jt}} + p'_t \frac{ds_t}{dR_{jt}} (\omega_{it} + R_{it} + r_{it} - e_{it}) \\ & + p_t \cdot \big(\frac{\partial \omega_{it}}{\partial R_{jt}} + \frac{dR_{it}}{dR_{jt}} + r'_{it} \frac{d\hat{p}_t}{ds_t} \frac{ds_t}{dR_{jt}} - e'_{it} p'_t \frac{ds_t}{dR_{jt}} \big) - c'_{it} r'_{it} \frac{d\hat{p}_t}{ds_t} \frac{ds_t}{dR_{jt}} \\ & - D_i \sum_k \frac{\partial \omega_{kt}}{\partial R_{jt}} + \beta\delta B_{ijt+1} + \beta\delta \sum_k B_{ikt+1} r'_{kt} \frac{d\hat{p}_t}{ds_t} \frac{ds_t}{dR_{jt}}, \end{aligned}$$

and if we insert for the reaction functions, it follows that:

$$\begin{aligned} B_{ijt} &= D_i + \beta\delta B_{ijt+1} \\ &= D_i \beta\delta D_i (\beta\delta)^2 D_i + \cdots \\ \Rightarrow B_{ijt} &= \frac{D_i}{1 - \beta\delta} \qquad \forall j, t, \end{aligned}$$

verifying the slope of the value function found earlier.

Secondly, inserting this in Equation (A.8) gives:

$$\begin{aligned} A_{it} + \frac{D_i}{1-\beta\delta} \sum_j R_{jt} =& u_i(e_i(p_t(s_t^{trade}))) + p_t(s_t^{trade}) \cdot (\omega_{it}^{trade} + R_{it} + r_i(\hat{p}_t^{\,trade}) - e_i(p_t(s_t^{trade}))) \\ & - c_i(r_i(\hat{p}_t^{\,trade})) - D_i \sum_j \omega_{jt}^{trade} + \beta A_{it} + \beta\delta \frac{D_i}{1-\beta\delta} \sum_j (R_{jt} + r_{jt}(\hat{p}_t^{trade})), \end{aligned}$$

where *trade* denotes Markov perfect equilibrium values under permit trade.

Using the fact that market clearing implies $\sum_j \omega_{jt} = \sum_j (e_{jt} - R_{jt} - r_{jt})$ in all time periods, we can solve for A_{it}:

$$\begin{aligned} A_{it} =& \frac{1}{1-\beta} \Big[u_i(e_i(p_t^{trade})) - c_i(r_i(\hat{p}_t^{trade})) + p_t^{trade} \cdot TB_i \\ & + \frac{D_i}{1-\beta\delta} \sum_j r_j(\hat{p}^{trade}) - D_i \sum_j e_j(p^{trade}) \Big] \qquad \forall t, \end{aligned}$$

which is independent of $R_{jt}, \forall j, t$, since $TB_i \equiv \omega_{it}^{trade} + R_{it} - r_i(\hat{p}_t^{trade}) - e_i(p_t^{trade})$ is independent of R_{it}.

Since A_{it} and B_{ijt} solves Equation (A.8), the value function is indeed linear, and given by:

$$
\begin{aligned}
V_i^{trade}(R_1, \dots, R_N) = \frac{1}{1-\beta}\Big[& u_i(e_i(p^{trade})) - c_i(r_i(\hat{p}^{trade})) \\
& + p^{trade} \cdot \left(\omega_i^{trade} + r_i(\hat{p}^{trade}) + R_i - e_i(p^{trade})\right) \\
& - D_i \sum_j e_j(p^{trade}) + \frac{D_i}{1-\beta\delta} \sum_j r_j(\hat{p}^{trade}) \Big] + \frac{D_i}{1-\beta\delta} \sum_j R_j.
\end{aligned}
\tag{A.9}
$$

where time-subscripts are dropped for simplicity. □

Proof of Lemma 2

Given Lemma 1, the first-order conditions (Equation (A.5)) can now be simplified to:

$$
0 = p_t + p_t' \cdot (\omega_{it} + R_{it} + r_{it} - e_{it}) - p_t' r_{it}'(c_{it}' - p_t) - D_i + \beta\delta p_t' \frac{D_i}{1-\beta\delta} \sum_j r_{jt}',
$$

when we note that $d\hat{p}_t / d\omega_{it} = p_t'(s_t)$. We also know that $c_{it}' - p_t = \sum_{\tau=t+1}^{\infty} (\beta\delta)^{\tau-t} p_\tau$, and we define $r_t' = \sum_j r_{jt}'$. We can insert this into the first-order condition, sum over all i and divide over by N to get (in three steps)

$$
0 = p_t + p_t' \cdot (\omega_{it} + R_{it} + r_{it} - e_{it}) - p_t' r_{it}' \left(\sum_{\tau=t+1}^{\infty} (\beta\delta)^{\tau-t} p_\tau \right) - D_i + \beta\delta p_t' r_t' \frac{D_i}{1-\beta\delta},
$$

$$
0 = N p_t + p_t' \cdot \underbrace{\left(\sum_i \{\omega_{it} + R_{it} + r_{it} - e_{it}\} \right)}_{=0 \text{ by market clearing)}} - p_t' r_t' \sum_{\tau=t+1}^{\infty} (\beta\delta)^{\tau-t} p_\tau - N\overline{D} + p_t' r_t' N \overline{D} \frac{\beta\delta}{1-\beta\delta},
$$

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

Given that the supply in the market, s_t, is independent of the renewables stocks by Lemma 1, the price is independent of state and time, and solving for a constant p gives:

$$
p^{trade} = \overline{D} \frac{1 - \frac{\beta\delta}{1-\beta\delta} p' r'}{1 - \frac{\beta\delta}{1-\beta\delta} \frac{p' r'}{N}} > \overline{D}, \ \forall t,
$$

because

$$
\frac{1 - \frac{\beta\delta}{1-\beta\delta} p' r'}{1 - \frac{\beta\delta}{1-\beta\delta} \frac{p' r'}{N}} > 1, \quad \text{for } N > 1.
$$

This is what is stated in Lemma 2.

The MPE price will depend on the parameters, β, δ, $\overline{D}$, N, e' and r', which will also be constant over time, given the same price in all periods. $\square$

For identical countries, this means that consumers and investors in all countries face a higher permit- and renewables price than under autarky, giving the result stated in Proposition 2.

Over time, the renewables stock in each country will develop, until it reaches its steady-state value. Hence, the number of permits issued in all countries - and thus emissions - will also change over time until the steady state is reached.

In Appendix B, we solve the model for a finite number of time periods, under the assumption of quadratic utility and cost functions, $u(\cdot)$ and $c(\cdot)$. We show that the equilibrium price calculated above, is the limit of the unique finite-horizon price, as the horizon tends to infinity, in this case.

Proof of Proposition 4

We want to prove that when countries share the same quadratic utility and cost functions, yet differ in their marginal damage, emissions decrease and aggregate welfare increases when international trade in permits is introduced.

The value functions for country i under autarky and permit trade, respectively are given by Equations (A.2) and (A.9), respectively. For notational simplicity, we will in the following let p denote the equilibrium price under permit trade, p^{trade}. For each country i, define the welfare gain from introducing permit trade as

$$\begin{aligned}
\Delta_i &= (1-\beta)\left(V_i^t - V_i^{Aut}\right) \\
&= \left[u_i(e_i(p)) - c_i(r_i(\frac{p}{1-\beta\delta})) + pTB_i - D_i\sum_j e_j(p) + \frac{D_i}{1-\beta\delta}\sum_j r_j(\frac{p}{1-\beta\delta})\right] \\
&\quad - \left[u_i(e_i(D_i)) - c_i(r_i(\frac{D_i}{1-\beta\delta})) - D_i\sum_j e_j(D_j) + \frac{D_i}{1-\beta\delta}\sum_j r_j(\frac{D_j}{1-\beta\delta})\right] \\
&= u_i(e_i(p)) - u_i(e_i(D_i)) + c_i(r_i(\frac{D_i}{1-\beta\delta})) - c_i(r_i(\frac{p}{1-\beta\delta})) + pTB_i \\
&\quad + D_i\sum_j e_j(D_j) - D_i\sum_j e_j(p) + \frac{D_i}{1-\beta\delta}\sum_j r_j(\frac{p}{1-\beta\delta}) - \frac{D_i}{1-\beta\delta}\sum_j r_j(\frac{D_j}{1-\beta\delta}).
\end{aligned}$$

Throughout this section, we will assume that all countries share the same utilility and cost functions, and that both these functions are quadratic. These assumptions are sufficient, but not necessary to obtain the results stated in Proposition 4. The common utility from consumption and cost of investment, where indices are suppressed, are given by:

$$u_i(e_i) = \zeta + \eta e_i - \frac{1}{2}\theta e_i^2 \qquad \forall i, \tag{A.10}$$

$$c_i(r_i) = \phi + \chi r_i + \frac{1}{2}\psi r_i^2 \qquad \forall i, \tag{A.11}$$

$$\Rightarrow e_i(p) = \frac{\eta - p}{\theta}, \text{ and } e_i' = -\frac{1}{\theta} \qquad \forall i,$$

$$r_i(\hat{p}) = \frac{\hat{p} - \chi}{\psi}, \text{ and } r_i' = \frac{1}{\psi} \qquad \forall i,$$

where all parameters are non-negative. Given the behavior of consumers and producers derived in Section 2.1, and these functional forms, we have that:

$$u_i(e_i(p)) - u_i(e_i(D_i)) = \frac{1}{2}e_i'p^2 - \frac{1}{2}e_i'D_i^2,$$

$$c_i(r_i(\frac{D_i}{1-\beta\delta})) - c_i(r_i(\frac{p}{1-\beta\delta})) = \frac{1}{2}r_i'\frac{D_i^2}{(1-\beta\delta)^2} - \frac{1}{2}r_i'\frac{p^2}{(1-\beta\delta)^2},$$

$$D_i\sum_j e_i(D_j) - D_i\sum_j e_i(p) = D_ie_i'\sum_j D_j - D_ie_i'Np$$

$$\frac{D_i}{1-\beta\delta}\sum_j r_i(\frac{p}{1-\beta\delta}) - \frac{D_i}{1-\beta\delta}\sum_j r_i(\frac{D_j}{1-\beta\delta}) = \frac{D_i}{(1-\beta\delta)^2}r_i'Np_j - \frac{D_i}{(1-\beta\delta)^2}r_i'\sum_j D_j.$$

We can insert this back into the expression for Δ_i to get

$$\begin{aligned}\Delta_i &= \frac{1}{2}e_i'p^2 - \frac{1}{2}e_i'D_i^2 + \frac{1}{2}r_i'\frac{D_i^2}{(1-\beta\delta)^2} - \frac{1}{2}r_i'\frac{p^2}{(1-\beta\delta)^2} + D_ie_i'\sum_j D_j - D_ie_i'Np \\ &\quad + \frac{D_i}{(1-\beta\delta)^2}r_i'Np - \frac{D_i}{(1-\beta\delta)^2}r_i'\sum_j D_j + pTB_i, \\ &= \underbrace{\left(\frac{r_i'}{(1-\beta\delta)^2} - e_i'\right)}_{\equiv K>0}\left(\frac{1}{2}D_i^2 - \frac{1}{2}p^2 + D_iNp - D_i\sum_j D_j\right) + pTB_i. \end{aligned} \tag{A.12}$$

Note here that Δ_i can be written as follows when $D_i = \overline{D}$, and when we recall that the equilibrium permit price $p = B\overline{D}$, $B \in [1, N)$:

$$\Delta_i = K\overline{D}^2(B-1)(N - \frac{1}{2}(B+1))$$

This expression equal to 0 when $B = 1$ and it is strictly increasing in B for $B \in [1, N)$. Hence, we have that $\Delta_i > 0$ $\forall i$ for $B > 1$, when $D_i = \overline{D}$, which is exactly what is stated in Proposition 2.

In order to show that aggregate welfare increases when permit trade is introduced and $D_i \neq \overline{D}$, we sum Δ_i over all i:

$$\sum_i \Delta_i = K \cdot \left(\frac{1}{2} \sum_i (D_i^2) - \frac{1}{2} N p^2 + \sum_i D_i N p - \sum_i D_i \sum_j D_j \right) + 0.$$

Then we insert for p and join terms:

$$\sum_i \Delta_i = K \cdot \left(\frac{1}{2} \sum_i (D_i^2) + \left(\sum_i D_i \right)^2 \underbrace{\left(B - 1 - \frac{1}{2} \frac{B^2}{N} \right)}_{\alpha} \right). \tag{A.13}$$

The parenthesis labeled α is non-decreasing in B in the relevant region. Hence, 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

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

where the last term is the sample variance of D_i, thus non-negative. Hence, we have proved that aggregate welfare increases when international permit trade is introduced, when countries share identical quadratic utility and cost functions. 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. This concludes the proof of Proposition 4.

Note that in the static case, the reason that $\sum_i \Delta_i > 0$ is not the strategic incentives to reduce issuance, since these are only present in the dynamic model. Rather, these gains are due to increased cost efficiency in abatement. When countries are equal in all respects except in their marginal damage, the costs of emission reductions are the same in all countries, and hence an equal price on emissions across countries will implement any given level of emission reductions in the lowest possible cost. As B increases from 1, the $\sum_i \Delta_i$ increases due to the strategic incentives to withhold permits.

Proof of Proposition 8

Also in this proof, we assume quadratic utility and cost functions (see Equations (A.10) and (A.11)), to simplify the calculations. We start out by inserting in Equation (A.12) for the expression for the trade balance (Equation (18)). We can then separate the gain to country i from itroducing 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 8.2, 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 (10) for quadratic utility and cost functions:

$$
\frac{1}{1-\delta} r_i' \frac{p}{1-\beta\delta} < e_i(0) + e_i' \cdot p. \tag{10 LQ}
$$

   As $p \in (\overline{D}, N\overline{D})$, we can, for any $\underline{\beta\delta} < 1$, find some $e_i(0)$ such that there exists β and δ (*i.e.* a pair (β, δ) such that Equation (10 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 8.2.

To prove Propositon 8.1, 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. □

Thus, as we move from the static case ($\beta = \delta = 0$) to the limit of the dynamic case ($\beta, \delta \to 1$), we move from a case where the low-damage countries gain more to a case where the high-damage countries gain more from introducing permit trade. This coincides with the permit market delivering lower and lower emissions, and a higher and higher equilibrium permit price.

B Appendix - finite-horizon convergence

We here find the unique subgame perfect equilibrium (SPE) in the finite horizon game, and let the number of periods, T, run to infinity. 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 this 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.

In every period, the firms consuming the energy solve a static problem, and we will have that

$$u_i'(e_{it}) = p_t,$$

for every period t, defining demand as a linear function of the price. For convenience, we will count time backwards. In the last period, 0, the renewables producers also solve a static problem, leading us to

$$c_i'(r_{i0}) = p_0,$$

giving the renewables supply as a linear function of the price in period 0.

Define the supply of energy before the period-t investments by $s_t \equiv \sum_j R_{jt} + \sum_j \omega_{jt}$. 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:

$$p' = \frac{1}{\sum_j e_j' - \sum_j r_j'}$$

In earlier time periods, the price p_t 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 countries of the respective variables as e_t, r_t, ω_t and R_t.

The government in period 0 solves

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

with first-order condition

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

If we sum over all i and divide by N, we get

$$p_0 = \overline{D}. \tag{B.2}$$

The equilibrium price is therefore independent of the current stock of renewables in the final period. If, say, country i experiences an increase in its stock, equilibrium reactions must ensure that the price remains constant. If country i is to maintain Equation (B.1), the only possible solution is that it issues fewer permits, one for one with the increase in R_{i0}. The reason is that there is only one net position in the energy market country i is willing to take for the constant price p_0, when the marginal damage is constant. So higher supply of renewables implies lower supply of permits. When country i keeps its net position fixed, and the price remains constant, no other country has any incentive to react. As in the basic model, this is due to the constant marginal damage in other countries. In total, we have that there is one unique equilibrium, and it satisfies:

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

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 (B.2) 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

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

with first-order condition

$$\begin{aligned}
0 &= u_i'e_i'p' + p_1 \cdot (1 + r_i'p' - e_i'p') + p' \cdot (\omega_{i1} + R_{i1} + r_{i1} - e_{i1}) \\
&\quad - c_i'r_i'p' - D_i + \beta\delta r'p'V_{i0}' \\
0 &= e_i'p' \cdot (u_i' - p_1) - p'r_i' \cdot (c_i' - p_1) + p_1 + p' \cdot (\omega_{i1} + R_{i1} + r_{i1} - e_{i1}) \\
&\quad - D_i + \beta\delta r'p'D_i \\
0 &= p_1 - r_i'p'\beta\delta p_0 + p' \cdot (\omega_{i1} + R_{i1} + r_{i1} - e_{i1}) - D_i + \beta\delta r'p'D_i. \qquad \text{(B.3)}
\end{aligned}$$

Summing over this, we get

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

which is again independent of the state variables.

Taking the derivative of the first-order condition, (B.3), with respect to R_{j1} now gives:

$$p'\left(1 + \frac{d\omega_1}{dR_{j1}}\right)(1 + r_i'p' - e_i'p') + p'\left(\frac{d\omega_{i1}}{dR_{j1}} + \frac{dR_{i1}}{dR_{j1}}\right), \qquad \text{(B.4)}$$

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

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

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

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

which, if we insert for p_1, simplifies to

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

We hypothesize

$$p_t = ap_0 d^{t-1} + b(1 + a\sum_{s=0}^{t-2} d^s) - c_t - a\sum_{s=1}^{t-1} c_s d^{t-1-s}, \ \forall t \geq 2 \text{ and} \tag{B.5}$$

$$\sum_{s=0}^{t} p_s(\beta\delta)^{t-s} \equiv \hat{p}_t = p_0 d^t + b\sum_{s=0}^{t-1} d^s - \sum_{s=1}^{t} c_s d^{t-s}, \ \forall t \geq 2 \text{ where} \tag{B.6}$$

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

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 (B.5) solves the problem in all time periods. We show that given that (B.5) and (B.6) hold in period t, (B.5) and (B.6) will also characterize the unique subgame perfect equilibrium in period $t + 1$, for any p_0 independent of stocks. Given that we know that (B.5) and (B.6) 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 (B.5) and (B.6) 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

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

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

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

which fits the hypothesized form (B.5).

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 (B.6).

So now we have proved that the price in the finite horizon-game follows the form (B.5). 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 (B.5). 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 (B.5):

$$p_t = ap_0 d^{t-1} + b(1 + a\sum_{s=0}^{t-2} d^s) - c_t - ar'p'\overline{D}\sum_{s=1}^{t}\big((\beta\delta)^s \sum_{u=0}^{t-s} d^u\big).$$

Letting t run to infinity, we have

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

Thus we have proved that the infinite-horizon equilibrium with a constant price is the limit of the unique SPE of the finite-horizon game.

C Extensions

C.1 Endogenous fossil energy

We here introduce endogenous investments in fossil energy production capacity, in addition to investments in renewables. We keep the model here as simple as possible, in order to avoid very comprehensive calculations. Most importantly, we solve the model only for a two-period game. However, since the dynamics play out in the same way in a two-period model, the general insight will be equivalent. We will model the supply of fossil energy the same way we model renewables, so we abstract away from the possibility of exhaustibility of the fossil energy.

Firstly, we introduce a positive price ϕ_t on fossil energy. The permit price is now τ_t, and the price to renewables producers is p_t. We count time backwards, thus period 0 is the last period, while period 1 is one period before the last. 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 $h_i(g_{it})$. As for the renewables stock, we assume that 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 hence solve a problem equivalent to that of the renewables producers, given by (6). 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 gives investments in each time period given by the following:

$$c_i'(r_{i0}) = p_0 \equiv \hat{p}_0 \Rightarrow r_{i0}(p_0), \qquad c_i'(r_{i1}) = p_1 + \beta\delta p_0 \equiv \hat{p}_1, \Rightarrow r_{i1}(\hat{p}_1), \tag{C.1}$$

$$h_i'(g_{i0}) = \phi_0 \equiv \hat{\phi}_0 \Rightarrow g_{i0}(\phi_0), \qquad h_i'(g_{i1}) = \phi_1 + \beta\delta\phi_0 \equiv \hat{\phi}_1, \Rightarrow g_{i1}(\hat{\phi}_1). \tag{C.2}$$

Market clearing requires

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

Defining 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 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

$$\phi_0' = \frac{1}{g_0'}, \qquad p_0' = \frac{-1}{r_0' - e_0'},$$
$$\phi_1' = \frac{1}{g_1'}, \qquad p_1' = \frac{-1}{r_1' - e_1'},$$
$$\frac{\partial \tau_0}{\partial \omega_0} = p_0' - \phi_0', \qquad \frac{\partial \tau_0}{\partial G_0} = \phi_0', \qquad \frac{\partial \tau_0}{\partial R_0} = p_0',$$
$$\frac{\partial \tau_1}{\partial \omega_1} = p_0' - \phi_0', \qquad \frac{\partial \tau_1}{\partial G_1} = \phi_0', \qquad \frac{\partial \tau_1}{\partial R_1} = p_0'. \tag{C.3}$$

The problem facing country i in period 0 is now

$$\begin{aligned} V_{i0}(R_{10}, \ldots, R_{N0}, & G_{10}, \ldots, G_{N0}) \\ &= \max_{\omega_{i0}} \Big\{ u_i(e_i(p_0)) - c_i(r_i(p_0)) - h_i(g_i(\phi_0)) - D_i \sum_j \omega_{j0} + \tau_0 \omega_{i0} \\ &\qquad + \phi_0(G_{i0} + g_i(\phi_0)) + p_0(R_{i0} + r_i(p_0) - e_i(p_0)) \Big\}, \end{aligned} \tag{C.4}$$

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:

$$D_i = \phi'_0(G_{i0} + g_{i0} - \omega_{i0}) + p'_0(R_{i0} + r_{i0} - e_{i0} + \omega_{i0}) + \tau_0. \tag{C.5}$$

Given the market clearing conditions, summing (C.5) over i gives us the equilibrium permit price:

$$\tau_0 = \overline{D}, \tag{C.6}$$

which is independent of any stock.

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

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

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:

$$\begin{aligned}0 =& u'_{i1}e'_{i1}p'_1 - c'_{i1}r'_{i1}p'_1 - h'_{i1}g'_{i1}\phi'_1 - D_i + \tau_1 + (p'_1 - \phi'_1)\omega_{i1} + \phi'_1(G_{i1} + g_{i1}) \\ &+ \phi_1 g'_{i1}\phi'_1 + p'_1(R_{i1} + r_{i1} - e_{i1}) + p_1 r'_{i1}p'_1 - p_1 e'_{i1}p'_1 \\ &+ \beta\delta \sum_j \frac{\partial V_{i0}}{\partial R_{j0}} r'_{j1}p'_1 + \beta\delta \sum_j \frac{\partial V_{i0}}{\partial G_{j0}} g'_{j1}\phi'_1,\end{aligned}$$

which after canceling terms becomes

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

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

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

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 (C.4), 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, from (C.6) we deduce that $\partial\omega_0^{eq}/\partial R_0$ is positive while $\partial\omega_0^{eq}/\partial G_0$ is negative. The equilibrium permit price in period 0 reduces to

$$\tau_1 = \overline{D}\left(1 + \frac{N-1}{N}\beta\delta\left[p_1' r_1' \frac{\partial \omega_0^{eq}}{\partial R_{j0}} + \phi_1' g_1' \frac{\partial \omega_0^{eq}}{\partial G_{j0}}\right]\right) > \overline{D}\ . \tag{C.7}$$

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 Section 3, 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.

C.2 Politically determined investments

We here let the government in each country regulate the producers, by letting the government decide the size of the renewables investment, in each time period. In order to simplify the calculations, we look only at a two-period model. Furthermore, we assume that the representative consumers in every country share the same, quadratic, utility function, and that investment costs are quadratic and identical across countries (see Equations (A.10) and (A.11)). The timing within each time period is as in the basic model, and we now disregard renewables investments in the last time period, since these are not affected by strategic incentives. The last period is denoted by 0, while 1 denotes the first period.

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:

$$p_1\left(\sum_i \omega_{i1} + \sum_i R_{i1} + \sum_i r_{i1}\right), \qquad p_1' = \frac{1}{\sum_i e_{i1}'},$$
$$p_0\left(\sum_i \omega_{i0} + \sum_i R_{i0}\right), \qquad p_0' = \frac{1}{\sum_i e_{i0}'}.$$

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 produces the following equilibrium

$$p_0 = \overline{D}, \quad \frac{\partial \omega_{i0}}{\partial R_{j0}} = \begin{cases} -1 & i = j \\ 0 & i \neq j \end{cases}, \quad \frac{\partial W_{i0}}{\partial R_{j0}} = D_i, \ \forall i, j. \tag{C.8}$$

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

$$W_{i1}(R_{11}, \ldots, R_{N1}) = \max_{\omega_{i1}} \left\{ -D_i \sum \omega_{j1} + V_{i1}(R_{11}, \ldots, R_{N1}, \omega_{11}, \ldots, \omega_{N1}) \right\} \tag{C.9}$$

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

$$\begin{aligned} &V_{i1}(R_{11}, \ldots, R_{N1}, \omega_{11}, \ldots, \omega_{N1}) \\ &\quad = \max_{r_{i1}} \Big\{ u_i(e_i(p_1)) - c_i(r_{i1}) + p_1(\omega_{i1} + R_{i1} + r_{i1} - e_i(p_1)) \\ &\qquad\qquad + \beta W_{i0}(\delta(R_{11} + r_{11}), \ldots, \delta(R_{N1} + r_{N1})) \Big\}. \end{aligned} \tag{C.10}$$

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

$$0 = p_1 - c_i'(r_{i1}) + p_1'(\omega_{i1} + R_{i1} + r_{i1} - e_i(p_1)) + \beta\delta D_i, \tag{C.11}$$

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, (C.9). 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:

$$\begin{aligned}
D_i &= \frac{\partial V_{i1}}{\partial \omega_{i1}} \\
&= p_1' \left(1 + \sum_j \frac{\partial r_{j1}}{\partial \omega_{i1}}\right) TB_i + p_1 \left(1 + \frac{\partial r_{i1}}{\partial \omega_{i1}}\right) - e_i' \frac{\partial r_{i1}}{\partial \omega_{i1}} + \beta\delta D_i \sum_j \frac{\partial r_{j1}}{\partial \omega_{i1}} \\
&= p_1 + p_1' + \sum_j \frac{\partial r_{j1}}{\partial \omega_{i1}} \left(p_1' TB_i + \beta\delta D_i\right) + \frac{\partial r_{i1}}{\partial \omega_{i1}} (p_1 - c_{i'}).
\end{aligned}$$

From (C.11) 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:

$$D_i = p_1 + p_1' TB_i + \sum_{j \neq i} \frac{\partial r_{j1}}{\partial \omega_{i1}} (p_1' TB_i + \beta\delta D_i). \tag{C.12}$$

In order to determine the equilibrium price, we need to know how the renewables investments react to changes in permit issuance. Differentiate (C.11) wrt. ω_{j1} to find

$$0 = p_1' \left(1 + \sum_k \frac{\partial r_{k1}}{\partial \omega_{j1}}\right) + p_1' \left(\frac{\partial \omega_{i1}}{\partial \omega_{j1}} + \frac{\partial r_{i1}}{\partial \omega_{j1}} - e_{i1}' p_1' \left(1 + \sum_k \frac{\partial r_{k1}}{\partial \omega_{j1}}\right)\right) - c_{i1}'' \frac{\partial r_{i1}}{\partial \omega_{j1}}. \tag{C.13}$$

We now introduce explicit expressions for the utility and cost functions, in order to simplify notation slightly. The functions $u_i(\cdot)$ and $c_i(\cdot)$ are as defined in Equations (A.10) and (A.11), respectively. Using the fact that $c_{i1}'' = \psi$, $e_{i1}' = -1/\theta$, and $e_{i1}' p_1' = 1/N$, we can use this expression (by summing over all i and all $i \neq j$, respectively), to find:

$$\begin{aligned}
\sum_k \frac{\partial r_{k1}}{\partial \omega_{j1}} &= -\frac{\theta}{\psi + \theta} \in [-1, 0]. \\
\sum_{j \neq i} \frac{\partial r_{j1}}{\partial \omega_{i1}} &= (-1) \frac{(N-1)^2}{N} \frac{\theta}{N\psi + \theta} \frac{\psi}{\psi + \theta} \in [-1, 0].
\end{aligned}$$

Finally, we can sum over (C.12) to find

$$p_1 = \overline{D} \left(1 - \beta\delta \sum_{j \neq i} \frac{\partial r_{j1}}{\partial \omega_{i1}}\right) > \overline{D}. \tag{C.14}$$

Hence, the strategic incentive to withhold permits in order to reduce future issuance in other countries through increasing their stocks, is still present.

C.3 Excess renewables supply

In this appendix, we solve a two-period model for the case when Equations (10) and (11) do not hold for all countries.

Assume a two-period model, with time periods $t = 1$ and $t = 0$ (last period).

In both time periods, domestic consumers solve the static problem:

$$\max_{e_{it}} \{u_i(e_{it}) - p_{it}e_{it}\} \Rightarrow e_i(p_{it}),$$

as in our basic model.

The domestic renewables producers solve 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 the international permit price, p_t.

In period t, domestic market clearing requires that $R_{it} + r_i(\hat{p}_{it}) = e_i(p_{it})$. If this domestic market clears at a price $p_{it} < p_t^{eq}$, domestic consumers demand no emission permits, and we say that country i is saturated: $i \in S_t$. Since the domestic energy price in a 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:

$$\begin{aligned}
\sum_i \omega_{it} &= \sum_i f_{it} \\
&= \sum_i e_i(p_t) - \sum_i R_{it} - \sum_i r_i(\hat{p}_t) \\
&= \sum_{i \in NS_t} e_i(p_t) - \sum_{i \in NS_t} R_{it} - \sum_{i \in NS_t} r_i(\hat{p}_t) + \underbrace{\sum_{i \in S_t} e_i(p_{it}) - \sum_{i \in S_t} R_{it} - \sum_{i \in S_t} r_i(\hat{p}_{it})}_{=0}
\end{aligned}$$

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

This market clearing condition defines the price in each time period as a function of supply in that period, s_t: $\tilde{p}(s_t)$, 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:

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

giving the first-order condition

$$\tilde{\tilde{p}}(s_0) + \tilde{\tilde{p}}'(s_0) \cdot \omega_{i0} = D_i. \tag{C.15}$$

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

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

and the first-order condition becomes (after applying the envelope theorem)

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

Summing over the N first-order conditions, and employing the permit market clearing condition, $\sum_i \omega_i = \sum_i f_i$, we get the equilibrium price in the last time period:

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

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

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

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 (C.15). The permit issuance of saturated countries is independent of their domestic renewables stocks, while that of the non-saturated countries is not. This means that

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

A given country benefits only from more renewable energy in other countries whe these are not saturated.

In period 1, a saturated country solves

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

with first-order condition

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

Whereas a non-saturated country solves

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

with first-order condition

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

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

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

In Appendix B, we solve for the finite-horizon version of the dynamic permit trade game where no countries are saturated, and derive the finite-horizon equilibrium prices $\tilde{p}_0$ and $\tilde{p}_1$. The price derived above satisfies $p_1 \in [\overline{D}, \tilde{p}_1]$, and takes on the limit values as $|NS|$ is 0 and N, respectively. Hence, we have 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.

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