Buy coal!
Deposit markets prevent carbon leakage

Bård Harstad*

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Abstract

If a coalition of countries implements climate policies, nonparticipants tend to consume more, pollute more, and invest too little in renewable energy sources. In response, the coalition's equilibrium policy distorts trade and it is not time consistent. By adding a market for the right to exploit fossil fuel deposits, I show that these problems vanish and the first best is implemented. When the market for deposits clears, the coalition relies entirely on supply-side policies, which is simple to implement in practice. The result illustrates that efficiency can be obtained without Coasian negotiations ex post, if key inputs are tradable ex ante.

Key words: Coase, climate change, carbon leakage, supply v demand side policies, trade policies, the green paradox, and environmental agreements
JEL: Q54, Q58, H23, F55

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1. Introduction

"Coal Mine in Montana for sale" (www.tradekey.com)

Not even the Copenhagen Accord was able to secure full participation. The Accord, negotiated last December, recognizes the need to reduce global CO_2 emissions but it does not bind the participants in any way. The intense negotiations revealed that many countries are unlikely to ever sign a legally binding climate treaty. Currently, only 37 countries are committed to binding targets under the Kyoto Protocol.

While nonparticipants are likely to pollute too much, the main concern is that their existence may undermine the climate coalition's effort. When the coalition introduces regulation, the world prices change, market shares shift, industries relocate, and nonparticipants may end up emitting more than they did before. The International Panel on Climate Change (IPCC, 2007: 665) defines carbon leakage as "the increase in CO_2 emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries." Most estimates of leakage are between 5% and 20%, but the number can be higher if the coalition is small, the policy ambitious, and the time horizon long.[1] Carbon leakage discourages countries from reducing pollution and it may motivate tariffs on trade.[2] Thus, Frankel (2009: 507) concludes, "it is essential to find ways to address concerns about competitiveness and leakage."

This paper considers a coalition of countries harmed by the consumption of fossil fuel. Countries outside of the coalition are naturally polluting too much compared to the optimum. In addition, if the coalition reduces its demand for fossil fuel, the world price for fuel declines and the nonparticipating countries consume more. If the coalition

[1] See the surveys in IPCC (2007), Frankel (2009), and Rauscher (1997). The variation in estimates hinges on a number of factors. For the countries signing the Kyoto Protocol, Böhringer and Löschel (2002: 152) estimate leakage to increase from 22% to 28% when the US dropped out. For forest carbon sequestration in the US, Murray et al. (2004) calculate leakage rates between 10% and 90%, depending on the particular region. Demailly and Quirion (2008) estimate a leakage rate of 20% for the cement industry, but the number decreases with border measures. Babiker (2005) takes a long-run perspective by allowing firms to enter and exit, and finds that leakage can be up to 130%.

[2] While estimates of leakage vary, *Financial Times* writes "the fear of it is enough to persuade many companies to lobby their governments against carbon regulation, or in favour of punitive measures such as border taxes on imports." But: "the danger is that arguments over border taxes could make an agreement even more difficult to negotiate," and it is an "easy way to start a trade war." The quotes are dated Dec. 11, 2009; Nov 5, 2009; and Dec. 9, 2009, respectively.

shrinks its supply of fossil fuel, the nonparticipants increase their supply. If countries can invest in renewable energy sources, nonparticipants invest too little. For the coalition, regulating consumption, production, and trade is a second-best solution. However, the policy may not be time consistent and, in equilibrium, the coalition sets policies such as to influence its terms-of-trade as well as the environment.

By allowing for trade in fossil fuel deposits, all these problems vanish and the first-best outcome is implemented. In equilibrium, the coalition purchases the right to exploit the fossil fuel deposits that are most polluting or costly to exploit. This makes the non-participants' supply locally inelastic, the supply-side leakage is eliminated and the coalition chooses to rely entirely on reducing its supply and not its demand. This, in turn, eliminates consumption leakage, the consumption price is equalized across countries and all investments are then efficient.

The first-best policy is simple to implement once the market for deposits has cleared: the coalition only needs to set aside certain deposits, for example by specifying an extraction fee high enough to make them unprofitable. There is neither a desire nor a need to in addition regulate consumption or trade. Note that, rather than purchasing foreign deposits, a leasing arrangement may suffice. In reality, countries are frequently selling, auctioning, licensing, or outsourcing the right to extract oil and other minerals to international companies as well as to major countries such as India and China.[3]

The paper combines two strands of literature. On the one hand, there is a growing literature on carbon leakage, resting on the prediction that some countries will not participate in a climate coalition.[4] Markusen (1975) showed that one country's environmental policy affects world prices and thus consumption and pollution abroad. In addition, capital may relocate (Rauscher, 1997) and firms might move (Markusen et al., 1993 and 1995). The typical second-best remedy[5] is to set tariffs or border taxes (Markusen, 1975; Hoel,

[3]For a history of the oil industry and governmental involvements, see Yergin (2009).

[4]Although there is no consensus on how to model coalition formation, environmental agreements have often been modeled as a two-stage process: first, a country decides whether to participate; second, the participants maximize their joint utility by choosing appropriate policies. This procedure typically leads to free-riding (Barrett, 2005, surveys the literature).

[5]Other second-best suggestions include reducing the harshness of the policy (Rauscher, 1997; Böhringer and Löschel, 2002), grandfathering emission quotas (Böhringer and Löschel, 2002), and restricting trade in pollution permits (Copeland and Taylor, 2005).

1996; and Rauscher, 1997).[6] However, countries have incentives to let the tariff influence their terms-of-trade.[7] In fact, Liski and Tahvonen (2004) show that a country may benefit from being harmed by pollution if this justifies border measures. Most of this literature focuses on demand-side climate policies. In many ways, Hoel (1994) provides the most general model by also allowing the coalition to limit its supply. Since the game by Hoel is a proper subgame of the game I present, this paper generalizes several of the above results before obtaining its main result.

On the other hand, the literature following Coase (1960) argues that the parties can attain efficiency by negotiating activities ex post, no matter the allocation of property rights. The coalition should then be able to negotiate with and bribe nonparticipating countries to reduce their consumption of fuel. The literature on leakage must thus assume that transaction (or contracting) costs prevent such effective ex post negotiations. Coase (1960: 15) admits that such transaction costs often exist. But, rather than predicting leakages, Coase (1937 and 1960) suggested that such transactions should and will take place inside “the firm.” This has inspired Williamson’s (1975) theory of the firm as well as literatures on vertical integration and horizontal mergers.[8]

The two strands of literature have remained distinct since it would not be realistic to politically integrate "only" to mitigate climate change. However, note that Perry and Porter (1985) model mergers basically as trade in input factors. Similarly, Esö et al. (2010) investigate when a market for capacity leads an industry to maximize its total surplus. In the electricity sector, trading the transmission rights before generating power may help the providers maximize joint profit (Joskow and Tirole, 2000). These papers suggest that trading inputs may substitute for ex post negotiation, but they study concentration of market powers and not the internalization of externalities, more generally.[9] To my

[6] Certain environmentally motivated border measures are indeed permitted by the WTO, and the Montreal Protocol on Substances that Deplete the Ozone Layer, signed in 1987, does contain the possibility to restrict trade from noncompliant countries.

[7] Rauscher (1997: 3) admits that "Green arguments can easily be abused to justify trade restrictions that are in reality only protectionist measures and it is often difficult to discriminate between true and pretended environmentalism."

[8] See Gaudet and Salant (1991) or Kamien and Zang (1990) on horizontal mergers, and the survey by Katz (1989) or Rey and Tirole (2007) on vertical integration.

[9] A literature on international trade, initiated by Mundell (1957) and surveyed by Jones (2000), investigates whether trade in input factors is a perfect substitute to trade in final goods. In this paper, trading factors is strictly better since there are externalities and the factor owner can unilaterally decide

knowledge, Bohm (1993) is the only other paper studying how analogous trade in fossil fuel deposits may help a coalition curb climate change. Assuming linear demand and supply curves, Bohm investigated when a reduction in consumption should be accompanied by an identical reduction in supply. This may necessitate purchasing or leasing foreign deposits, and Bohm documented that this could be realistic in practice.[10]

Building on these contributions, this paper shows that efficiency is often obtained, even if Coasian bargaining on ex post actions is impossible, if just key inputs, such as fossil fuel deposits, are tradable ex ante. This provides an argument against a climate policy primarily focused on reducing demand, and a strong case for instead reducing the supply - including the supply of nonparticipating countries.

This insight can certainly be applied to other situations. For example, boycotting timber is an ineffective way of preserving tropical forests since the timber price declines and other buyers increase their consumption. A more effective solution, according to this paper, is to pay developing countries to reduce their deforestation. The recent emergence of REDD (Reducing Emissions from Deforestation and Forest Degradation) funds is consistent with this conclusion. Such funds have now been set up by the United Nations, the World Bank, and Norway.

While the next section presents the basic model, the main result (Theorem 1) is discussed in Section 3. Section 4 generalizes the model and the result by allowing for investments in technologies, multiple periods, heterogeneous fossil fuels, and it endogenizes participation. Section 5 concludes and the Appendix contains all the proofs.

2. The basic model

There are two sets of countries: one set, M, participates in the climate treaty while the other set, N, does not. This paper focuses on the interaction between these sets and thus abstracts from internal conflicts or decision-making within M. I will thus treat M as one player or country, perhaps assuming that the participating countries have agreed

whether the factor is to be used for production.

[10] In contrast, the literature on tradable pollution permits (surveyed by Tietenberg, 2006), presumes that all trading countries are participating in the coalition. Trading permits within the coalition is just a way of obtaining a certain emission reduction efficiently and it does not eliminate leakages.

to maximize the sum of their utilities. The nonparticipating countries, N, interact with each other and with M only through markets.

Every country benefits from consuming energy, but fuel is costly to extract. If a country $i \in M \cup N$ consumes y_i units of fuel, i's benefit is given by the function $B_i(y_i)$, which is twice differentiable and satisfies $B_i' > 0 \geq B_i''$. Country i's cost of supplying or extracting x_i units is represented by an increasing and strictly convex function, $C_i(x_i)$. There is a world market for fuel and p measures the equilibrium price. Assuming quasi-linear utility functions, the payoffs are:

$$\begin{aligned} U_i &= B_i(y_i) - C_i(x_i) - p(y_i - x_i) \text{ if } i \in N, \\ U_i &= B_i(y_i) - C_i(x_i) - p(y_i - x_i) - H\left(\sum_{M \cup N} x_i\right) \text{ if } i = M, \end{aligned}$$

where $H(.)$ is the harm experienced by M from the pollution. $H' > 0$ and $H'' \geq 0$. I assume that only M, and not $i \in N$ have environmental concerns. This may be reasonable since $i \in N$ is not participating in the climate treaty, and it may explain this very fact. Alternatively, one could assume that nonparticipants act *as if* they have no environmental concern, for example because domestic forces hinder the implementation of a climate policy unless the government has committed by signing an international treaty.[11] The extension in Section 4.4 allows $i \in N$ to be harmed by pollution. Section 4.3 permits various fuels (such as gas and coal) to differ in their environmental impact.

I assume that $i \in N$ chooses x_i and y_i taking the fuel price as given. This is natural if the decisions to consume and produce are decentralized to agents with little market power. Thus, the assumption does not imply that i, as a country, is tiny. Alternatively, the price-taking assumption would hold if p followed from M's climate policy set earlier in the game.

To cope with the environmental harm, M sets environmental policies. This amounts to setting x_M and y_M if relying on quotas for extraction and consumption. The price for fuel will then adjust to ensure that the market clears:

$$\sum_{M \cup N} y_i = \sum_{M \cup N} x_i.$$

[11] Similarly, liberalizing trade policies may be difficult for political reasons, and being committed by a trade treaty can be help (Hoekman and Kostecki, 2001).

Since the market-clearing condition must hold, and $\sum_N (y_i - x_i) = x_M - y_M$ depends on p, the outcome would be identical if M instead could choose x_M and p and let y_M clear the market. Similarly, M may regulate x_M and y_M by setting a tax τ_x on domestic production, a tax τ_y on consumption, and perhaps even a tariff τ_I on import (or such an export subsidy). Any tax vector $\tau = \{\tau_x, \tau_y, \tau_I\}$ is going to pin down x_M, y_M and p. The outcome is going to be identical no matter how M influences these variables, and the choice between quotas and taxes is therefore immaterial in this model.[12] In any case, the equilibrium fuel price is influenced by M's policies and M does, of course, take this effect into account.

The novel part of the model is that I endogenize $C_i(.)$ by allowing for trade in deposits.[13] There is a continuum of deposits, and the cost function $C_i(.)$ is implicitly ordering a country's deposits according to their extraction costs. This is natural, since a country that is extracting x_i units would always prefer to first extract the deposits that have the lowest possible extraction costs. A small deposit allocated between x_i' and x_i'' is characterized by its size $\Delta \equiv x_i'' - x_i'$ and its marginal extraction cost $c \equiv [C_i(x_i'') - C_i(x_i')]/\Delta$. In the deposit market, M may purchase from $i \in N$ the right to exploit such a deposit. The market is cleared if, and only if, there exists no pair of countries $(i, j) \in (M \cup N)^2$ and no price such that both i and j strictly benefit from transferring the right to exploit a deposit from i to j at that price. If this condition is not satisfied, there are still gains from trade. With this equilibrium concept, I can check whether a particular allocation of deposits, leading to a particular $C_i(.)$ and $C_M(.)$, constitutes an equilibrium.

Note that I do not need to specify a market structure leading to this equilibrium. But, as discussed in Section 4.5, there are several possibilities. For example, one could let $i \in (M \cup N)$ make a take-it-or-leave-it offer to the other countries, conditional on the offer being accepted by everyone.

The timing of the game is given by Figure 1: after the deposit market clears, M sets

[12] This is in line with Weitzman (1974), showing that uncertainty regarding the parameters is necessary to rank quotas and taxes.

[13] Of course, the aggregate world-wide cost function is exogenously given. For any allocation of deposits, we could write it as:

$$C(x) = \min_{\{x_i\}} \sum_{M \cup N} C_i(x_i) \text{ s.t. } \sum_{M \cup N} x_i = x.$$

its policies and, finally, the fossil fuel market clears.[14] The next section solves the game by backwards induction in order to characterize all subgame-perfect equilibria. Several extensions are discussed in Section 4.

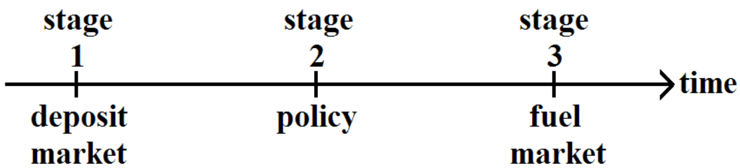

Figure 1: Timing of the game

3. The equilibrium

As a benchmark, note that the first best is given by equalizing every country's marginal benefit of consumption to the marginal cost of production plus the marginal environmental harm. For any given allocation of deposits, this means:

$$\max_{\{x_i\},\{y_i\}} \sum_{M\cup N} U_i \Rightarrow B_j'\left(y_j^*\right) - H'\left(\sum_{M\cup N} x_i^*\right) \in C_i'\left(x_i^*\right)\ \forall i,j \in M\cup N, \tag{3.1}$$

where I let $C_i'\left(x_i\right) \equiv \left[\lim_{\epsilon\uparrow 0} C_i'\left(x_i+\epsilon\right), \lim_{\epsilon\downarrow 0} C_i'\left(x_i+\epsilon\right)\right]$ be an interval if $C_i'\left(x_i\right)$ is discontinuous at x_i (i.e., if $C_i\left(x_i\right)$ has a kink at x_i). Thus, $C_i'\left(.\right)$ may be a correspondence, and not a function.

3.1. The market for fuel

At the third stage, each nonparticipating country, $i \in N$, simply sets its marginal benefit

$$B_i'(y_i) = p \Rightarrow y_i = D_i\left(p\right) \equiv B_i'^{-1}\left(p\right). \tag{3.2}$$

The demand by $i \in N$ is thus given by $D_i\left(p\right)$. On the production side, $C_i'\left(x_i\right) = p$, if $C_i'\left(x_i\right)$ is singular. If $C_i'\left(x_i\right)$ is nonsingular, $p \in C_i'\left(x_i\right)$. Since $C_i\left(.\right)$ is a strictly convex function, the correspondence $C_i'\left(.\right)$ is invertible and its inverse, $x_i = S_i\left(p\right) \equiv C_i'^{-1}\left(p\right)$, is a function. Obviously, if $C_i'\left(x_i\right)$ is nonsingular at x_i, $S_i'\left(p\right) = 0$ at each $p \in C_i'\left(x_i\right)$.

$$p \in C_i'\left(x_i\right) \ \Rightarrow x_i = S_i\left(p\right) \equiv C_i'^{-1}\left(p\right) \forall i \in N. \tag{3.3}$$

[14] I do not allow nonparticipating governments to set policies influencing supply and demand. Allowing for this would complicate the analysis without altering the main result, as argued in Section 4.5.

For the coalition M, supply and demand depends on the policies, determined at the second stage. For example, y_M could be set directly by a consumption quota, while x_M could be set directly by an extraction quota. Alternatively, the government may specify a tax vector τ and redistribute the revenues lump sum within M. If the consumers and suppliers in M are price-takers when trading fuel, x_M and y_M would be given by:

$$\left\{ \begin{array}{c} B_M'(y_M) = p + \tau_y + \tau_I \\ C_M'(x_M) = p - \tau_x + \tau_I \end{array} \right\} \Rightarrow \left\{ \begin{array}{c} y_M = D_M(p + \tau_y + \tau_I) \equiv B_M'^{-1}(p + \tau_y + \tau_I) \\ x_M = S_M(p - \tau_x + \tau_I) \equiv C_M'^{-1}(p - \tau_x + \tau_I) \end{array} \right\}. \tag{3.4}$$

Clearly, x_M and y_M can be implemented by any two of $\{\tau_x, \tau_y, \tau_I\}$. In any case, p is such that the market clears:

$$\begin{aligned} I \equiv y_M - x_M &= S(p) - D(p), \text{ where} \qquad (3.5) \\ S(p) &\equiv \sum_N S_i(p), \\ D(p) &\equiv \sum_N D_i(p). \end{aligned}$$

3.2. Equilibrium policies

At the second stage, M maximizes

$$U_M = B_M(y_M) - C_M(x_M) - H\left(x_M + \sum_N x_i\right) - p(y_M - x_M),$$

subject to (3.2)-(3.5). By choosing τ, the system (3.2)-(3.5) of $2n+3$ equations uniquely determines every x_i, y_i, and p for the third stage. Equivalently, M can directly specify x_M and y_M, and let p, x_i and y_i, $i \in N$, be determined by (3.2)-(3.3) and (3.5). Substituted in (3.4), one can easily derive a set of taxes that can implement this policy. In any case, we can state:

Lemma 1. *M's equilibrium policy implements:*

$$B_M'(y_M) = p + \left(\frac{S'(p)}{S'(p) - D'(p)}\right) H' + \frac{y_M - x_M}{S'(p) - D'(p)}, \tag{3.6}$$

$$C_M'(x_M) \ni p - \left(1 - \frac{S'(p)}{S'(p) - D'(p)}\right) H' + \frac{y_M - x_M}{S'(p) - D'(p)}. \tag{3.7}$$

Compared to the first best (3.1), the equilibrium is generally quite different. Neither marginal benefits nor marginal costs are equalized across countries. M understands that by reducing its supply, p increases, and N extracts more. By reducing M's consumption, p declines, and N consumes more. The conditions (3.6)-(3.7) show how M balances these two types of leakages: Abstracting from the last terms (i.e., if $y_M = x_M$), M would focus on demand-side policies, and reduce y_M, if foreign supply were elastic relative to demand. If demand were more elastic than supply, M would focus on reducing its supply x_M rather than its demand.

In addition, the last terms in (3.6)-(3.7) show that M sets policies considering the impact on its terms of trade. If M is exporting fossil fuel, M prefers to reduce its production and increase its consumption, since both changes increase the price M receives for its export. M's ability to affect the equilibrium price is another reason why the first best is generally not achieved, besides the free riding and the two types of leakages.

Lemma 1 is, basically, identical to Hoel's (1994) equations (9)-(10). Although Hoel does not allow for a tariff ($\tau_I = 0$), he shows that M's ideal policy can be implemented by taxes on domestic consumption and production:

$$\begin{aligned}
\tau_y &= \left(\frac{S'(p)}{S'(p) - D'(p)}\right) H' + \frac{y_M - x_M}{S'(p) - D'(p)}, \\
\tau_x &= \left(1 - \frac{S'(p)}{S'(p) - D'(p)}\right) H' - \frac{y_M - x_M}{S'(p) - D'(p)}.
\end{aligned}$$

Note that the sum of the taxes is always equal to H', the marginal harm.

Alternatively, (3.6)-(3.7) can be implemented by a production tax and a tariff (while $\tau_y = 0$). The equilibrium policies are then as in Markusen (1975) and Hoel (1996):

$$\begin{aligned}
\tau_I &= \left(\frac{S'(p)}{S'(p) - D'(p)}\right) H' + \frac{y_M - x_M}{S'(p) - D'(p)}, \\
\tau_x &= H'.
\end{aligned}$$

The production tax should be Pigouvian and the emission from M's supply is thus independent of the terms-of-trade effects. This is in line with Copeland and Taylor (1995), Proposition 8. The leakages are dealt with by the tariff. Since the tariff reduces domestic consumption, it should be high if the demand-side leakage is low while the supply-side leakage large. To affect its terms-of-trade, M sets a high tariff if it is importing but a low tariff (or export subsidy) if it is exporting.

3.3. The market for deposits

Consider the first stage of the game. The right to extract each deposit can be traded in a market. The market clears when there exists no pair of countries that would both strictly benefit from trading some of their deposits at some price. This market endogenizes the allocation of deposits, the cost functions $C_i(.)$ and thus the supply curves $S_i(.)$.

The market equilibrium cannot be unique since if each of two countries exploit one deposit, they could easily exchange these two deposits and that would constitute another equilibrium. Nevertheless, I can state the following result:

Theorem 1 (i). *In every equilibrium of the deposit market, M's equilibrium policy (3.6)-(3.7) implements the first best (3.1).*

The result might surprise since (3.6) appears to be substantially different from the first best (3.1). The equilibrium from stage two is generally inefficient because of free-riding, consumption leakage, production leakage, and M's market power. All these problems vanish once the deposit market has cleared.

The theorem follows from Lemmas 2, 3 and 4:

Lemma 2. *In every equilibrium,* $x_i = y_i \ \forall i \in M \cup N$.

When the market for deposits clears, every country expects to rely on neither import nor export of fossil fuel. That this is a feasible equilibrium may not be surprising since M can equally well sell a deposit to i instead of selling the fuel exploited afterwards. Lemma 2 goes further, however, and claims that $x_i = y_i$ always. The intuition is the following. Suppose M is a net exporter and $i \in N$ is an importer. If M sells a small deposit to i, which is such that any owner would exploit it, then M is afterwards exporting a little bit less. By Lemma 1, M finds it optimal to rely less on supply and more on demand side policies, and the equilibrium price is slightly reduced. M is indifferent to this change in the price, since M is always setting the policies such that the price is optimal from M's point of view. For country i, however, the reduced price is beneficial. Thus, i is willing to pay more for the deposit than M requires for giving it up. In equilibrium, therefore, i cannot be importing. For similar reasons, i cannot be exporting, either.

This reasoning assumes that i takes into account that its sale or purchase of deposits may affect the equilibrium price of fuel. This can be consistent with the assumption that i takes the fuel price as given at stage 3: The consumers and suppliers in country i may take the fuel price at stage 3 as given, even if their government realizes that trading national deposits may affect the world price. Alternatively, if the price follows from M's policy at stage 2, it is fixed at stage 3 although i's sale at stage 1 can influence M's policy at stage 2 and thus the price at stage 3.[15]

The next stepping stone for Theorem 1 is:

Lemma 3. *In every equilibrium,* $S_i'(p) = 0 \; \forall i \in N$.

In other words, $C_i'(.)$ is vertical and jumps at the equilibrium x_i, $i \in N$. The reason is, as the proof shows, that M is willing to purchase the deposits that $i \in N$ is almost indifferent to exploit. If the marginal cost c of exploiting a deposit is almost as high as the price p, i is willing to sell the deposit for a low price $(p - c)$. If M purchases this deposit without exploiting it, M's benefit is reduced pollution. This gain is roughly $H' > 0$, certainly larger than the price for the deposit when $c \approx p$. Intuitively, if M considers purchasing, without exploiting, any of i's deposits, it is certainly cheapest to buy deposits that are expensive to exploit. Hence, when the market for deposits clears, the supply of $i \in N$ is locally inelastic.

By combining Lemmas 1-3, $B_M'(y_M) = p = B_i'(y_i) \; \forall i \in N$. Since the supply of country $i \in N$ is locally inelastic, M does not fear supply-side leakage, and it can rely entirely on supply-side politics. Since there is no need to regulate demand, there is no consumption leakage and the marginal benefits of fossil fuel are equalized across countries.

The final stepping stone for Theorem 1 is:

Lemma 4. *In every equilibrium,* $p - H'(.) \in C_i'(x_i)$ *and* $p \in C_i'(x_i) \; \forall i \in N$.

In words, $i \in N$ does not own any deposit with marginal extraction cost between $p - H'(.)$ and p. All such deposits are purchased by M. The reason is that while i would

[15] Instead of maximizing U_M by choosing x_M and y_M at stage 2, suppose M instead choose p and, say, x_M. Also in this case, (3.2)-(3.5) must hold and the first-order conditions for the policy are going to be the same.

benefit from exploiting such deposits, M benefits more by preserving them. Note that Lemma 4 implies $S_i'(\rho) = 0$ for all $\rho \in [p - H'(.), p]$, and Lemma 3 follows as a corollary. Since Lemmas 1-3 also imply that $p - H'(.) \in C_M'(x_M)$, all countries extract the optimal amounts of fossil fuel.

3.4. Implementation

This policy is simple to implement in practice. Instead of calculating taxes for consumption and production, M simply purchases the deposits that are most expensive to exploit. Thereafter, M implements the first best by setting aside these deposits, or by using an extraction tax ($\tau_x = H'$) high enough to make them unprofitable. Finally, the market forces equalize marginal benefits and neither demand nor trade need regulation (i.e., $\tau_y = \tau_I = 0$).

Creating a market for deposits might be the most controversial aspect of this policy. However, note that a rental market suffices: M does not need to purchase the permanent right to exploit deposits. Instead, M can simply pay $i \in N$ for not extracting specified deposits.

3.5. An example

The outcome is particularly simple if $N = \{1\}$, $H(.) = h \sum_{M \cup N} x_i$, and if the supply and demand curves were initially identical and linear in both countries. Without a deposit market, N would consume and supply x' in Figure 2, while M would consume and extract x^*. The area of the triangle $a = (x' - x^*) h/2$ measures the social loss as well as N's private cost of reducing its supply from x' to x^*. With a deposit market, M purchases all deposits with marginal extraction costs between $p^* - h$ and p^*. For this, M must pay a if M makes a take-it-or-leave-it offer but $2a$ if N makes a take-it-or-leave-it offer. In any case, the supply curve of N shifts from C_i' to C_N', while the supply curve of M shifts from C_i' to C_M'. With the extraction tax h in M, both M and N extract x^* and the equilibrium consumption price is p^*.

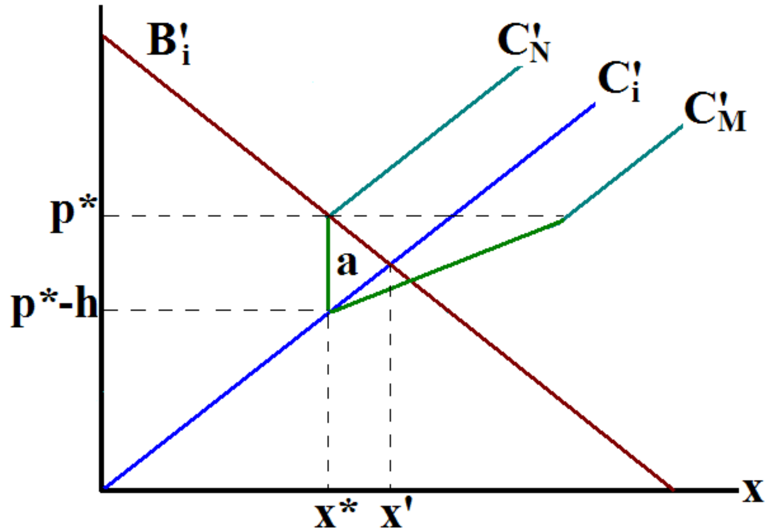

Figure 2: M purchases deposits with marginal costs between $p^* - h$ and p^* and implements the first best.

4. Generalizing the result

4.1. Endogenous technology

Developing new technology is central in the debate on how to cope with climate change. An important extension of the above model is thus to endogenize the technologies, and let countries invest in them. This extension, it turns out, strengthens the case for a market in deposits.

Suppose that every $i \in M \cup N$ can invest r_i in technology at cost $k_i(r_i)$, where $k_i'(.), k_i''(.) > 0$. To simplify, there are no spillovers or trade in technologies. The new technology is a substitute to polluting and it can represent, for example, renewable energy sources.[16] Country i consumes energy from both sources and we may write its total benefit as $\widetilde{B}_i(y_i + r_i)$. Pre-investment policy refers to the case where investments take place between stage 2 and stage 3. Post-investment policy refers to the situation where the investment stage is between stage 1 and stage 2. Solving the game by backwards induction, I first solve the game for a generic distribution of deposits.

[16] Allowing for investments in extraction technologies would be interesting but is omitted to save space.

Assume, to begin, that $i \in M \cup N$ is a price-taker when investing, for example because investments are made by private entities in country i. Then, $\widetilde{B}_i'(.)$ is the willingness to pay for new technology in country i. Whether M's policy has been or is going to be set, in equilibrium:

$$\widetilde{B}_i'(y_i + r_i) = k_i'(r_i) \ \ \forall i \in M \cup N.$$

Is M's investment level r_M optimal? It is, from M's point of view. While a larger r_M decreases the need for fuel and thus the equilibrium fuel price, p is optimally chosen (or influenced) by M at the policy stage. By the envelope theorem, M's marginal value of r_M is simply $\widetilde{B}_M'(.)$. But the lower p, following a larger r_M, is beneficial to the nonparticipants if they are, on average, importing. If $x_M < y_M$, the nonparticipants are, as a group, exporting. The larger r_M would then harm them.

Proposition 1. *The investment level r_M is smaller (larger) than the socially optimal level if and only if $x_M > y_M$ ($x_M < y_M$).*

Are the investments of $i \in N$ optimal? A larger r_i reduces the need to buy fossil fuel, and the price declines. This is good for an importer but, from a social point of view, the sum of these terms-of-trade effects cancel.[17] However, the lower price reduces supply when supply is somewhat elastic (i.e., when $S' > 0$) and, then, emission declines as well. Since this benefit is not internalized by $i \in N$, it invests too little compared to the social optimum when $S' > 0$, no matter the timing of the investments.

Proposition 2. *(i) For every $i \in N$, the investment level r_i is lower than the socially optimal level, and it is* strictly *lower if and only if $S'(p) > 0$. (ii) The benefit for M of i's marginal investment is given by (4.1).*

$$\frac{\partial U_M}{\partial r_i} = \left(\frac{S'(p)}{\sum_N \left(S_i'(p) - 1/B_i''(p)\right)} \right) H' + \frac{y_M - x_M}{\sum_N \left(S_i'(p) - 1/B_i''(p)\right)} \ \forall i \in N. \tag{4.1}$$

The first term at the right-hand side of (4.1) is positive and captures the environmental gain when new technology reduces emissions. The second term is positive unless M is a

[17] In contrast to M, $i \in N$ does not set p and it does indeed care about how r_i affects p. Thus, if $i, j \in N$, $i \neq j$, we can write $\partial U_i / \partial r_i = \widetilde{B}_i'(.) - (y_i - x_i) \partial p / \partial r_i$, $\partial U_j / \partial r_i = -(y_j - x_j) \partial p / \partial r_i$ and $\partial U_M / \partial r_i = -(y_i - x_i) \partial p / \partial r_i - H'(.) \partial \left(\sum_N x_i\right) / \partial r_i$. Summing over these, the terms-of-trade effects cancel since $\sum_{M \cup N} (y_i - x_i) = 0$.

net exporter of fuel. If M were exporting so much that the right-hand side of (4.1) were negative, M would be harmed by a larger r_i, $i \in N$, since that would reduce p and thus M's revenues. But, otherwise, M would like $i \in N$ to invest more.

If M's policies are set after the investments are fixed, $D_i'(.) = 1/B_i''(p)$ and, combining (4.1) and (3.6),

$$\partial U_M / \partial r_i = \widetilde{B}_i (y_i + r_i) - p,$$

which is equal to M's ideal consumption tax, or tariff. When this tax is positive, M strictly benefits from a marginally larger r_i, $i \in N$. If it could, M would then like to share its technology with i, or to invest directly in the nonparticipating countries.

If policies are set before investments, M can indeed influence i's investment. To encourage investments, M sets policies that generate a high fuel price. This can be done by restricting M's supply rather than its demand, for example by having a high supply tax but a low consumption tax (or tariff). Thus, pre-investment policies may rely more on supply-side politics, and less on demand-side politics, than would post-investment policies.

Proposition 3. *The equilibrium policy is given by Lemma 1 whether the policy is chosen before or after the investments. But the demand is more elastic when the policy is chosen first:*

$$\begin{aligned} D_i'(.) &= 1/\widetilde{B}_i''(y_i + r_i) - 1/k_i''(r_i) < 0 \text{ for pre-investment policies,} \\ D_i'(.) &= 1/\widetilde{B}_i''(y_i + r_i) < 0 \text{ for post-investment policies.} \end{aligned}$$

If M sets policies before the investment stage, demand is more elastic. A larger p is then both reducing $y_i + r_i$ and increasing r_i, thus leading to a further decline in y_i. If the right-hand side of (3.6) is positive, it decreases in $|D_i'(.)|$, ceteris paribus. When the right-hand side of (3.6) decreases, x_M must decline while y_M must increase. Since the right-hand side can be interpreted as a consumption tax or a tariff, this tax should thus decrease while the extraction tax should increase.

Proposition 2 implies that M's optimal policy is sensitive to the particular timing. While M would prefer to announce tough supply-side policies before the investment stage, in order to encourage investments, after the investment stage it prefers to rely more on demand-side politics. If a production tax and a tariff is used, M prefers to announce a low tariff before countries invest, but raise it afterwards. The ideal policy of M may thus not be time consistent.

In summary, for a generic distribution of deposits, investments in renewable energy are suboptimal for all countries. Nonparticipants invest too little, amplifying their existing over-pollution. To encourage more investments, M would like to commit to tough supply-side policies rather than demand-side policies, but this policy may not be time consistent.

All these problems are solved if there is a market for deposits at stage 1.

Theorem 1 (ii). *In every equilibrium of the deposit market, M's equilibrium policy implements the first best whether it is chosen before or after investments.*

The result follows, almost as a corollary, from Propositions 1-3 and Lemmas 1-3. *If* the equilibrium in the deposit market is as described in Section 3.3, $y_i = x_i$ and M's investments are optimal, according to Proposition 1. Lemma 3 states that $S_i'(.) = 0 \forall i \in N$, and Proposition 2 then implies that all countries invest optimally. Since the equilibrium policy, given by Lemma 1, does not depend on $D_i'(.)$ when $\sum_N S_i' = 0$, M's policy is the same whether it is set before or after investments, despite Proposition 3. Finally, when combining Lemmas 2 and 3 with Proposition 2, $\partial U_M / \partial r_i = 0$. This implies that M has no interest in influencing r_i, $i \in N$, and the deposit allocation described by Lemmas 1-4 continues to be an equilibrium. The proof that this must be true in all equilibria follows the same steps as before.

As a variant of the model, suppose the r_i's were not chosen by private investors but by governments. For $i = M$, this turned out to be irrelevant since, as noted, r_M is optimal from M's point of view. For $i \in N$, this change would not matter if government i took the price p as given, perhaps because the price has already been set by M at the policy stage. However, if i anticipates that r_i may affect the price, the first-order condition for r_i becomes:

$$k_i'(r_i^*) = \widetilde{B}_i'(y_i^* + r_i^*) - (y_i - x_i)\,\partial p / \partial r_i \;\forall i \in N.$$

Better technology reduces the fuel price ($\partial p / \partial r_i < 0$). The lower price is good for country

$i \in N$ if it imports fuel but bad if it exports. Hence, importers invest more than exporters. If $(y_i - x_i)$ is very large, i may actually invest too much, compared to the social optimum, just as M would have done, according to Proposition 1. With a deposit market, however, $y_i = x_i$ and it does not matter whether i, at the investment stage, takes p as given or not. The first best continues to be an equilibrium whether investments are private or public.

4.2. Multiple periods

A one-period model may well capture a dynamic world. In particular, suppose the environmental damage $H(.)$ is a function of cumulated emissions, no matter at which point in time they take place. Then, the first best is still implemented by the equilibrium above: M only needs to buy and set aside certain deposits at the start of the game, and let the market work out the allocation of consumption. If time is a dimension in this allocation, the equilibrium price path optimally allocates the remaining production and consumption over time.

Without a deposit market, however, difficulties arise. In additional to the inefficiencies already discussed, there will be intertemporal leakages. If M is expected to reduce its future consumption, the expected future price declines. This makes it more attractive for the nonparticipants to extract fuel now. This effect has been referred to as the "green paradox" by Sinn (2008), since a harsher environmental policy (in the future) can actually increase emissions (today). Clearly, the green paradox reduces the value of an anticipated future demand-side policy.[18]

To illustrate this, suppose there are two periods, $t \in \{1, 2\}$, and let $\delta \in (0, 1)$ be the common discount factor. The extraction costs are, as before, associated with the deposits. Thus, if $C_i(.)$ is i's extraction cost function, the cost of extracting $x_{i,1}$ units in period 1 is $C_i(x_{i,1})$, while the cost of thereafter extracting $x_{i,2}$ in period 2 is $C_i(x_{i,1} + x_{i,2}) - C_i(x_{i,1})$. To capture the intuition that climate change is a long-run problem, and its real cost is coming in the future, let the harm $H(.)$ be experienced only in the second period. Since greenhouse-gases have a long-lasting impact on the climate, suppose $H(.)$ is a function

[18] A similar effect is identified by Kremer and Morcom (2000), showing that an anticipated future crackdown on the illegal harvesting of ivory may raise current poaching.

of cumulated emissions. When the prices in periods 1 and 2 are p_1 and p_2, the payoff for $i \in M \cup N$ is:

$$\begin{aligned} U_i &= B_{i,1}(y_{i,1}) - C_i(x_{i,1}) + p_1(x_{i,1} - y_{i,1}) \\ &\quad + \delta\left[B_{i,2}(y_{i,2}) - C_i(x_{i,1} + x_{i,2}) + C_i(x_{i,1}) + p_2(x_{i,2} - y_{i,2})\right] \\ &\quad - \delta H\left(\sum_{t\in\{1,2\}}\sum_{j\in M\cup N} x_{j,t}\right)\Upsilon_i, \end{aligned} \tag{4.2}$$

where the index-function $\Upsilon_i = 0$ for $i \in N$ and $\Upsilon_M = 1$.

If M can commit to future policies, the timing of the game is the following. In the first period, M sets $\{x_{M,1}, y_{M,1}, x_{M,2}, y_{M,2}\}$. Thereafter, the first-period fossil fuel market clears. Finally, the second-period market clears.

Taking the prices as given, the demand in country $i \in N$ is $y_{i,1} = D_{i,1}(p_1) \equiv B_{i,1}'^{-1}(p_1)$ and $y_{i,2} = D_{i,2}(p_2) \equiv B_{i,2}'^{-1}(p_2)$. In the second period, i's cumulated supply is given by $x_{i,1} + x_{i,2} = S_i(p_2) \equiv C_i'^{-1}(p_2)$. In the first period, i must consider whether to extract a marginal deposit now or later. This leads to $x_{i,1} = S_i((p_1 - \delta p_2)/(1-\delta))$.[19] In each period, the market must clear, such that $I_t \equiv y_{M,t} - x_{M,t} = \sum_N (x_{i,t} - y_{i,t})\, \forall t \in \{1,2\}$.[20]

Anticipating all this, the Appendix derives M's optimal policy for both periods, and taxes implementing this policy. Just as before, the sum of the taxes must equal the marginal environmental harm.

Proposition 4. *If M can commit, its second-period policies is given by:*

$$B_{M,2}'(y_{M,2}) = p_2 + \left(\frac{dp_2}{dI_2}S'(p_2)\right)H' + \frac{dp_1}{dI_2}\frac{I_1}{\delta} + \frac{dp_2}{dI_2}I_2, \tag{4.3}$$

$$C_M'(x_{M,1} + x_{M,2}) \ni p_2 - \left(1 - \frac{dp_2}{dI_2}S'(p_2)\right)H' + \frac{dp_1}{dI_2}\frac{I_1}{\delta} + \frac{dp_2}{dI_2}I_2, \tag{4.4}$$

where :

$$\frac{dp_2}{dI_2} = \frac{S'([p_1 - \delta p_2]/[1-\delta]) - (1-\delta)D_1'}{[S'(p_2) - D_2'][S'([p_1 - \delta p_2]/[1-\delta]) - (1-\delta)D_1'] - \delta S'([p_1 - \delta p_2]/[1-\delta])D_1'},$$

$$\frac{dp_1}{dI_2} = \frac{\delta S'([p_1 - \delta p_2]/[1-\delta])}{[S'(p_2) - D_2'][S'([p_1 - \delta p_2]/[1-\delta]) - (1-\delta)D_1'] - \delta S'([p_1 - \delta p_2]/[1-\delta])D_1'}.$$

[19] Too see this, take a small deposit with marginal cost c. It is extracted in period 1 rather than period 2 if this gives a higher present discounted value of the profit: $p_1 - c \geq \delta(p_2 - c) \Rightarrow c \leq (p_1 - \delta p_2)/(1-\delta)$.

[20] This would hold even if fossil fuel could be stored, since rather than storing fossil fuel it would be cheaper to delay exploiting it.

On the other hand, if M cannot commit to future policies, its second-period policy is given by Lemma 1, above. By comparison, the two are, in general, quite different. First, when committing to second-period policies, M would like to consider the effect on its terms-of-trade not only for the second period, but also for the first. Once the second period has arrived, this effect is sunk and M can ignore it. This implies that M's ideal tax policy is not time consistent, also if there are no environmental harm.[21]

Second, even abstracting from the terms-of-trade effects, M's preferred policy under commitment is generally different from the equilibrium policy when it cannot commit. By comparing (4.3)-(4.4) to (3.6)-(3.7) for $I_1 = I_2 = 0$, M would prefer to commit to rely more on supply-side policies, and less on demand-side policies, than what it is going to find optimal in period 2. By doing this, M minimizes the intertemporal consumption leakage and the problems of the "green paradox," discussed above.[22] Unfortunately, if M cannot commit, this policy is not time consistent.

Consider now a deposit market at the beginning of period 1. For the same reason as before, Lemma 2 continues to hold and $x_{M,t} = y_{M,t}$, $\forall t \in \{1, 2\}$. M purchases from country $i \in N$ the deposits that are most costly to extract. Thus, Lemmas 3 and 4 continue to hold for the second period (i.e., for $p = p_2$). This does not imply that i's supply is inelastic in period 1, but it becomes locally inelastic in period 2. By substituting $S_i'(p_2) = 0$ in (4.3)-(4.4), M relies entirely on supply-side policies in period 2 whether it can commit or not. M's policy is thus time consistent.

Once the deposit market clears, the Appendix shows that M relies on supply-side policies also in the first period, and that intertemporal efficiency is ensured.

Theorem 1 (iii). *With a deposit market in the beginning of the game, the first best is implemented by M's equilibrium policies whether or not M can commit to future policies.*

M's policy is simple to implement once the deposit market clears. It can just set aside the costliest deposits and thereafter let the market clear, or it can set an extraction taxes,

[21] This result is known from Newbery (1976) and the subsequent literature (surveyed by Karp and Newbery, 1993).

[22] By instead committing to reducing its future supply, the future fossil fuel price increases, and non-participants find it optimal to extract less in period 1 (but, as before, more in period 2). Thus, while the intertemporal effect of the second-period policy increases consumption leakage, it does not increase extraction leakage.

$\tau_{x,t}$, $t \in \{1,2\}$, high enough to make the marginal deposits unprofitable. As shown in the Appendix, these taxes should be Pigouvian:

$$\tau_{x,1}/\delta = \tau_{x,2} = H'(.) .$$

Note that the tax should be positive in both periods. If there were an extraction tax only in the second period, the private suppliers would prefer to extract in period 1 rather than in period 2, just to avoid paying this tax. This would generate the green paradox, discussed above, and the outcome would be dynamically inefficient. To avoid this, the present-discounted value of the tax should be the same across periods.

The reasoning above continues to hold if there are more than two periods. In any case, a deposit market at the beginning of the game implements the first best. Things would be more complicated, however, if M not only cared about the aggregate emissions, but the time at which they took place. M may then have an incentive to trade deposits at the beginning of every period. Whether this would ensure efficiency would depend on the structure of the deposit market. For example, if M could influence the future price it would pay for deposits by extracting less today, it would distort its extraction path in order to influence its future terms-of-trade. For similar reasons, a rental market for the right to extract deposits may not guarantee the first best, if the future rental price can be influenced by M's extraction path.

4.3. Heterogeneous fuels

The analysis above assumed that consuming one unit of fossil fuel created one unit of pollution. In reality, fuel types differ in their carbon content: natural gas pollutes less than oil which, in turn, pollutes less than coal. Oil fields themselves differ widely: exploiting Canadian oil sands pollutes more than extracting North-Sea oil, for instance.

The model can accommodate heterogeneous fuels both within and between countries. For a small deposit of size Δ, let c be its marginal production cost and e its marginal emission content. Thus, the cost and emissions from exploiting this deposit are $c \cdot \Delta$ and $e \cdot \Delta$. As before, the deposits belonging to $i \in N$ are ordered according to their extraction costs.[23] If country $i \in N$ supplies x_i units, its total emission is $E_i(x_i)$, where $E_i'(x_i)$ is the marginal emission content of a deposit located at x_i. If $E_i'(x_i)$ is increasing (decreasing), the fuel that is most costly to extract is most (least) polluting. Assume that $E_i'(.)$ is continuous at x_i if $C_i'(.)$ is continuous at x_i,[24] and that $E_i'(x_i) \geq \overline{e}$ for all i and x_i, for some $\overline{e} > 0$. If $i \in M \cup N$ supplies x_i units, the total emissions level is $\sum_{M\cup N} E_i(x_i)$, and the harm, experienced by M, is $H\left(\sum_{M\cup N} E_i(x_i)\right)$.

Optimally, marginal benefits should be equalized across countries and a marginal deposit should be extracted if and only if:

$$c + eH'(.) \leq B_j'(y_j) = B_i'(y_i)\, \forall i, j \in M \cup N. \tag{4.5}$$

To find the equilibrium, note that stage 3 has the same outcome as in Section 3.1. At stage 2, M sets policies taking into account leakages and their emission content.

Lemma 5. *M's equilibrium policy implements:*

$$\begin{aligned} B_M'(y_M) &= p + \frac{\sum_N E_i'(x_i)\, S_i'(p)}{S'(p) - D'(p)} H' + \frac{y_M - x_M}{S'(p) - D'(p)} & (4.6) \\ C_M'(x_M) &\ni p - \left(E_M'(x_M) - \frac{\sum_N E_i'(x_i)\, S_i'(p)}{S'(p) - D'(p)} \right) H' + \frac{y_M - x_M}{S'(p) - D'(p)} & (4.7) \end{aligned}$$

Note that M focuses more on reducing its demand, and less on reducing its supply, if fuel abroad tends to be dirtier than domestic fuel, particularly if this is true for foreign countries with a very elastic supply function. Just as before, one can easily find taxes implementing this policy. If E_M' is much smaller than E_i', M may find it optimal to subsidize domestic extraction ($\tau_x < 0$). This may be the case, for example, if the participants possess gas while the nonparticipants rely on coal. The lemma generalizes the result by Golombek et al. (1995), who extend the model by Hoel (1994) to allow for three types of fuel.

Although Lemma 5 describes M's best policy to cope with free-riding and leakages, the outcome is not first best for a generic allocation of deposits. In addition to the

[23] The deposits belonging to M are ordered according to $c + eH'(.)$, where $H'(.)$ is evaluated at the equilibrium pollution level. The reason is that M is always exploiting the deposits with the smallest $c + eH'(.)$.

[24] This requires that deposits having almost identical extraction costs also have similar emission content. This assumption saves a step in the proof.

inefficiencies discussed already, country $i \in N$ tends to exploit the wrong deposits. Since $i \in N$ does not internalize the environmental harm, it might exploit deposits that have higher emission contents and larger social costs than some other deposit that it find too costly to exploit. For this reason, a deposit market is even more important than before.

Theorem 1 (iv). *In every equilibrium of the deposit market, M's equilbrium policy (4.6)-(4.7) implements the first best (4.5) even if fuels vary in their emission content.*

Just as before, Lemma 2 and 3 continue to hold: Deposits are sold to importers and there is no trade in fuel in equilibrium. Because every marginal deposit is polluting at least $\overline{e} > 0$, M purchases every marginal deposit from $i \in N$, who ends up with a locally inelastic supply curve.

However, Lemma 4 is no longer sufficient to reach the first best (4.5), since some deposits might be cheap to exploit even if they are highly polluting. In equilibrium, it turns out, M is purchasing these deposits.

Lemma 6. *In equilibrium, there exists no $\widetilde{x}_i$ such that:*

$$C_i'(\widetilde{x}_i) \subset (p - E_i'(\widetilde{x}_i) H', p), \, i \in N.$$

In other words, $i \in N$ cannot own a deposit with marginal cost c and marginal emission content e such that $p - eH' < c < p$. If i did own such a deposit, i would exploit it and its marginal benefit would be $p - c$. The marginal harm to M, however, would be $eH'(.)$, which is larger than i's gain. Therefore, M is purchasing all such deposits in equilibrium. Lemma 6 ensures that $i \in N$ does not exploit deposits violating (4.5). M does not exploit such deposits, either, according to (4.7) when substituting $S'(p) = y_M - x_M = 0$.

4.4. Shared harm and shared ownership

So far, I have assumed that nonparticipants do not experience any harm from pollution. This assumption may approximate reality if the nonparticipants' harm is only a small fraction of the total harm. Moreover, if signing an international agreement is necessary to overcome domestic resistance for a climate policy, the nonparticipants' harm would not affect the equilibrium derived above. However, the above equilibrium would no longer implement the first best, since M would not internalize the nonparticipants' harm when deciding how many deposits to set aside.

While $H(.)$ measures the total harm, as before, let $H_i(.)$ measure the harm experienced by country i. Clearly, $H(.) \equiv \sum_{M \cup N} H_i(.)$. The optimal x_i^*s can be derived as before. Then, define:

$$\alpha_i \equiv H_i'\left(\sum x_i^*\right)/H'\left(\sum x_i^*\right).$$

Parameter $\alpha_i \in [0,1]$ measures i's marginal harm as a fraction of the total marginal harm at the optimal emission levels.

Oil companies often share the ownership of oil fields. Similarly, suppose that ownership of fossil fuel deposits can be shared by countries. If a country owns a certain fraction of a given deposit, and this deposit is exploited, then the country receives a share of the profit equal to its ownership-share.

Theorem 1 (v). *There exist an equilibrium in the deposit market where i owns α_i of every deposit satisfying (4.8). This equilibrium implements the first best.*

$$c \in \left(\rho - H'\left(\sum_N x_i^*\right), \rho\right), \ \rho \equiv B_i'(y_i^*) \, \forall i \in M \cup N. \tag{4.8}$$

Take a small deposit of size Δ with marginal extraction cost c satisfying (4.8). If exploited, i's benefit would be $\alpha_i [B_i'(y_i^*) - c - H'(.)] \Delta < 0$, and every i would thus prefer to not exploit such a deposit. This is socially optimal, since a deposit should only be exploited if $c \leq B_i'(y_i^*) - H'(\sum_N x_i^*)$. Deposits satisfying $c > B_i'(y_i^*)$ are not exploited by any owner. Hence, when i owns α_i of every deposit satisfying (4.8), the first best is implemented, no matter whether the owners make decisions by unanimity or majority rule. Lemma 2 continues to hold and, besides setting aside deposits satisfying (4.8), further regulation is neither necessary nor desired. It follows that $B_i'(y_i^*)$ is equalized across countries.

The shares α_i constitute an equilibrium since no two owners would benefit by trading such a deposit share. If the consequence following such a transaction would be that a marginal deposit would be exploited, the new owner j would benefit $\alpha_i (p - c) - H_j'(.)$, which is less than the harm experienced by the previous owner i.

This is not a unique equilibrium when $|N| > 1$, however. If a deposit is owned and exploited by a single owner, it might not pay any individual country to step in and purchase a fraction of this deposit with the aim at preserving it. If the multiple potential owners cannot coordinate such a takeover, other equilibria exist which fail to implement the first best.

4.5. An example

Building on Section 3.5, this subsection presents an example to further illustrate the main results. Let m measure the number of participants in M, $n \equiv |N|$, and suppose all countries have identical demand and supply curves before any trade in deposits. Let these functions be linear, such that demand is given by $B_i(.) = by_i - ay_i^2/2$ and $C_i(.) = cx_i^2/2$, $i \in \{1, M\}$. Finally, let $H(.) = mh \cdot (x_M + x_1)$, since each of the participating countries face the marginal harm h.

If there is no market for deposits, (3.6) implies that

$$\begin{aligned} t_S &= \frac{chm}{a+c} \text{ and } t_D = \frac{ahm}{a+c}, \\ x_i &= y_i = \frac{b-hm}{a+c} \ \forall i \in M, \\ x_i &= y_i = \frac{b}{a+c} \ \forall i \in N. \end{aligned}$$

The demand and supply for one country is illustrated in Figure 3. Each coalition-partner produces and consumes f, in the figure, while nonparticipants would produce and consume y, if there were no market for deposits. M reduces its supply and demand by the same amount, and its policies do not affect the non-participating countries. The nonparticipating countries are, however, polluting too much. This creates a social welfare loss of $h^2mn/2(a+c)$, measured by the green and yellow triangles (ksv) in the figure.

With a deposit market, the equilibrium is as follows. M is purchasing all deposits between f and g, with marginal extraction costs between e and d (or, in the equations, between $(bc - hmc)/(a+c)$ and $(bc + hma)/(a+c)$). The supply curve of $i \in N$ shifts to the red line ($0ksw$), while the supply curve in M shifts to the blue line ($0kz$). With the supply tax hm in M, all countries supply (and consume) the optimal amount f. There is no tax on consumers, who face the price d.

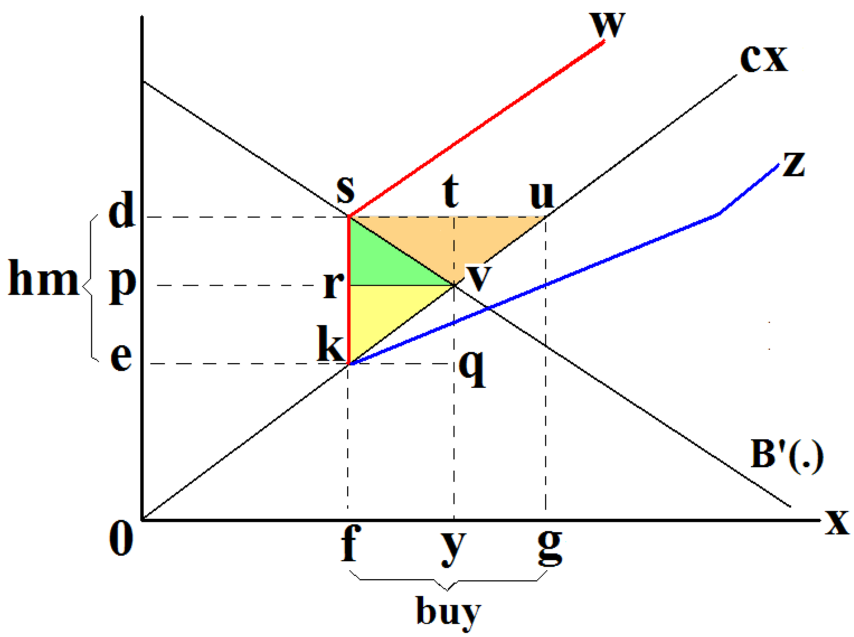

Figure 3: Purchasing g-f in country i changes the supply curves and improves efficiency by ksv.

4.6. The price to pay

It has been assumed that the deposit market clears where there exists no pair of countries, and no price, such that one country can sell a deposit to the other at that price and make both strictly better off. If this condition is violated, there are still gains from trade. The condition is actually stronger than necessary, since the proofs only consider trade between M and $i \in N$. I do not need to allow for trade between i and j, if $i, j \in N$.

Relying on this definition, there has been no need to specify how this equilibrium may be achieved. But there are several possibilities. A simple example is to suppose that country i can make a conditional take-it-or-leave-it offer to all the other countries, specifying a new allocation of deposits (thus, implicitly specifying a vector of transactions) and a vector of payments to be made. If every country can veto this proposal, the outcome gives Lemma 2-4, and thus the above outcome.[25] This procedure is referred to

[25]To see this, suppose that if there is no trade in the deposit market, country j gets utility $\overline{U}_j$. With a deposit market, j gets U_j, which depends on the allocation of deposits, minus q_j, the payment it must make. If $i \in M \cup N$ can make a take-it-or-leave-it offer to the rest, it maximizes $U_i + \sum_{M \cup N \setminus i} q_j$ s.t. $U_j - q_j \geq \overline{U}_j \; \forall j \in M \cup N \setminus i$. The constraints will certainly bind in equilibrium and i thus maximizes $U_i + \sum_{M \cup N \setminus i} \left(U_j - \overline{U}_j\right)$, and therefore $\sum_{M \cup N} U_j$, the aggregate surplus. Sufficient conditions for the

as "conditional bids" by Segal (1999) and as "no free riding" by Joskow and Tirole (2000).

However, as these papers show, other market structures fail to implement the efficient equilibrium. For example, if M makes observable non-conditional take-it-or-leave-it offers to the other countries, then M may prefer to restrict trade in deposits below the efficient level in order to affect its terms-of-trade.[26]

Referring to Figure 3, a first guess for M's expenditures on deposit-purchases might be the colored triangle ksu in Figure 3. When d is the equilibrium price for coal and M purchases all deposits between f and g in country $i \in N$, then M may have to pay each marginal deposit-owner the distance between d and its marginal cost, returning this area as the total price to pay.

However, the triangle ksu can be larger than M's gain from i's reduction in pollution. M's gain is the rectangle $kstq$, which has a smaller area that ksu if the supply curve is steeper than the demand curve ($c > a$). M would then be better off not buying any of these deposits, precluding this as an equilibrium. This possibility arises because purchasing $g - y$ is a complement to purchasing $y - f$. As for other complementary goods, such as left-shoes and right-shoes, the buyer cannot be expected to pay its marginal benefit for each.

Hence, if the owners of deposits are making take-or-leave-it offers to M, they cannot require more than $kstq$ in total - and they are likely to demand exactly this amount.

If M has all the bargaining power, on the other hand, it prefers to propose a price for each deposit and let the offers be conditioned on all of them being accepted. If all the deposits are nationally owned in country $i \in N$, M must offer ksv to compensate the country for the welfare loss associated with the implied reduction in supply and demand.

But if the deposits are privately owned in country i, M may be able to pay even less than this amount. If each marginal deposit has a separate owner who does not internalize

maximum are given by Lemma 2-4. In all equilibria of this game, $x_M = y_M$, but in some equilibria, $x_i \neq y_i$ for some $i \in N$. Thus, this game has equilibria that does not necessarily clear the market the way the equilibrium is defined, but Theorem 1 continues to hold, nevertheless (since it only requires $x_M = y_M$ and not $x_i = y_i \forall i \in N$). This implies that the definition of a market equilibrium, used above, is stronger than necessary.

[26] For instance, if M is going to be a net purchaser of deposits, $i \in N$ requires a higher price for selling if M is purchasing a larger number of deposits, since the equilibrium fossil fuel price is then expected to be high. To pay a lower price, M would then prefer to commit to buy less deposits, and it can do this by offering to buy less. This market structure is therefore not implementing the equilibrium above.

the consumer surplus, it suffices to pay the yellow triangle (krv) and make the offer conditional on all offers being accepted. Alternatively, if there is a single private owner, M must pay the yellow triangle minus the rectangle $dprs$. This sum may well be negative, since the buyer is then glad to give up some of its deposit when it anticipates that, as a consequence, the price-setter M is going to increase the price on oil to d. In sum, M is likely to pay less if it has more bargaining power, if the deposits are privately owned and if there are just a few owners.

4.7. Participation

This paper has focused exclusively on a climate coalition's best policy, without any concern for how to build the coalition in the first place. While analyzing coalition formation must be treated elsewhere, participation is such an important problem that it is worth to at least mention how a deposit market may influence the incentive to participate.

There is no consensus on how to model participation the most reasonable way. A common method (see the survey by Barrett, 2005), is to introduce a stage zero in the game, where every country first decides whether to participate. Otherwise, the game unfolds as described in Section 2. To simplify, take the example above, but let every country face the same marginal harm h from pollution. Define $l \equiv m + n = |M \cup N|$. Furthermore, suppose nonparticipating countries implement policies neither on demand nor supply. This might be reasonable if an international treaty is necessary to overcome domestic political resistance. In any case, the following results would not change substantially by relaxing this assumption.

This participation game tends to create a lot of free-riding and incentives to abstain, since abstaining does not affect whether other countries participate. Without a deposit market, each country faces the following trade-off: participating is costly since consumption and production declines from y to f in Figure 3. On the other hand, every other participant reduces its own pollution by $h/(a+c)$ units. As in Barrett (2005), the equilibrium number of participants is just 3!

Adding a deposit market can either raise or reduce participation. On the one hand, the participating members are always better off with a deposit market. Joining this coalition, moreover, reduces the pollution by $h/(a+c)$ units not only for the participants, but for every country. On the other hand, nonparticipants are also better off compared to the situation without a deposit market. The coalition is successful in reducing emissions from every country. Paying for this is costly, however, and by joining the coalition country i is expected to share these costs. Ultimately, whether participation is more or less attractive with a deposit market depends on the price one has to pay for such deposits. Even if M can make take-it-or-leave-it offers, the price depends on whether it is dealing with countries or private suppliers.

Proposition 5. *(i) Without a deposit market, $m = 3$. (ii) If M purchases deposits from countries, $m = 2$. (iii) If M purchases deposits directly from the producers,*

$$\begin{aligned} m &= \max\left\{l, \left\lfloor \frac{2l(a+c)+a}{lc+2a} \right\rfloor\right\} \\ &= l \text{ if } a/c \geq l(l-2). \end{aligned}$$

The function $\lfloor x \rfloor$ calculates the largest integer weakly smaller than x.

If M makes take-it-or-leave-it offers to countries, it must pay each nonparticipating country the yellow and the green triangle (ksv) in Figure 3. This price is so high that the motivation to participate declines compared to the situation without a deposit market. If this is important, potential members would thus like to commit, before the first stage, to not use a deposit market later on. Such a decision is not time consistent, however. After the participation stage, M would always prefer to purchase deposits.

On the other hand, if M only needs to compensate the *producers* of fossil fuel, paying the yellow area (krv) suffices. This price is lower, making participation more attractive. If a is small compared to c, the yellow area dominates the green area, and $m = 2$ also in this case. But if $a \approx c$, participation is always larger with a deposit market than without. If $a/c \geq l(l-2)$, full participation is possible.

4.8. Domestic opposition and lobbying

A tough climate policy might be supported by citizens and environmentalists, but producers as well as consumers are harmed when introducing taxes on demand and supply.

Deposit-owners are stuck and unable to move from one country to another, however, and this may reduce their political clout. Industries relying on energy, on the other hand, may credible threaten to move.

Without a deposit market, such consumers can benefit a lot from moving from a coalition member to a nonparticipant. In the example above, the price is $bhm/(a+c)$ units higher in M than in N. With a deposit market, however, the price is equalized across participants and nonparticipants. Consumers have then no incentive to move, and this reduce their political clout if lobbying against a climate treaty.

Moreover, the incentive to lobby against a climate treaty is much smaller when there is a deposit market. If a country i joins, the coalition reduces supply further and the equilibrium price on fossil fuel increases by $bh/(a+c)$ in every country. This price increase is only a fraction $(1/m)$ of the price increase for i's consumers if i joined M and there were no deposit market.

In sum, with a market for deposits, industries relying on energy have less incentives to lobby against memberships in a climate treaty and they have, in any case, less credibility when threatening to move. Participation in a climate treaty is thus meeting less resistance if there is a deposit market.[27]

4.9. Other extensions

Nonparticipants' policies: Even a country outside the coalition may have market power to influence the fuel price, and it generally has an interest in regulating its supply and demand in order to improve its terms-of-trade. Allowing for this would change the game somewhat and perhaps also the outcome, if there were no deposit market. With a deposit market, however, it would still be the case that every country would be self-sufficient with fuel, in equilibrium, and it would thus have no incentive to affect the world price by regulating its consumption, supply, or trade.

Mobility of firms: While I have abstracted from firms and thus their mobility, Babiker (2005) shows that leakage can be much larger if firms can exit and enter. With a market

[27] Analogously, Grossman and Helpman (1995) study industry groups lobbying for or against the participation in a free-trade area.

for deposits, however, firms using fossil fuel as an input has no incentive to relocate since the fuel price is the same whether they are inside or outside of the coalition. Thus, if leakage is driven by firms relocating, the results above would not weaken.

Information structure: Uncertainty regarding the environmental harm or the cost of exploiting a deposit would not change the model much. The parameters above can measure the expected values. If the buyer or the seller of a deposit had private information regarding its cost, the model would be more complicated, and the proposal-maker may want to design a mechanism to elicit this information. It would be more interesting, in my view, to endogenize the information structure. A country may own unknown or potential deposits, and with some effort one can detect whether these deposits contain fossil fuel. Since the incentive to search for new deposits is stronger if the price of fuel is high, countries may search more if there is a deposit market than if there is not. The effort to search in country $i \in N$ is then suboptimally high, since it does not take into account the environmental consequence if a new deposit is detected and exploited, or it may gain from selling such a deposit to M even if it is not exploited and thus have no social value. In principle, the climate coalition has an incentive to purchase potential deposits, or to pay $i \in N$ for not searching. If such contracts cannot be made, the possibility to search for new deposits would weaken the efficiency result above.

To buy or to rent? As discussed in Section 3.4, the outcome is efficient whether the coalition can buy deposits or just pay $i \in N$ for not exploiting them. Buying and leasing are thus having identical outcomes in the one-period model. In reality, however, this choice may be important. If a potential deposit is rented, the owner $i \in N$ has a strong incentive to prove that it does contain fossil fuel and that its extraction cost is low. Doing so would raise the subsequent rental price.[28] This moral hazard would disappear if the deposit were instead sold to M. On the other hand, if M purchased deposits located within the national boundary of country $i \in N$, i may have a strong incentive to nationalize the deposit and recapture its value. If nationalization is a bigger treat than the moral hazard of continued search, M would prefer to lease rather than purchase the right to exploit deposits.

[28] In addition, in a dynamic model M may try to influence the terms of its future leasing contract by extracting less fuel today. This strategy may violate dynamic efficiency.

5. Conclusions

A climate coalition faces several dilemmas. Not only are nonparticipants polluting too much. If the coalition reduces its consumption of fossil fuel, the world price declines and nonparticipants consume more. By reducing its supply, nonparticipants extract more from their deposits. Furthermore, nonparticipants invest too little in renewable energy sources. In response, the coalition's best policy distorts trade and it is not time consistent.

A market for fossil fuel deposits solves all these problems. In equilibrium, the coalition purchases the right to exploit deposits that are costly or polluting to exploit. This eliminates the supply-side leakage, and the coalition implements its ideal policy simply by reducing its supply of fuel. There is no need to regulate trade or consumption, and there is thus no consumption leakage. The fossil fuel price is equalized across countries, inducing optimal investments in technology. The first best is thus implemented, even if some countries do not participate in the coalition.

Normatively, the result suggests that rather than focusing on reducing consumption, climate policies should focus on the supply side - including the supply of other countries.

More generally, the result shows that efficiency can be obtained without Coasian bargaining ex post, if crucial input factors are tradable ex ante. This insight can be applied to other contexts. For example, boycotting timber from tropical forests would decrease the world price and lead other countries to raise their demand. To prevent such leakage, a wiser strategy may be to purchase the forest or pay countries to let their forests remain. The recent emergence of REDD funds is thus consistent with the prediction of this paper.

However, such crucial inputs may not always exist. Suppose the emission from a deposit depends on the extractor's carefulness (or method of extraction) as well as the deposit itself. If such carefulness is noncontractible, moral hazard arises whenever the coalition is not purchasing every single deposit. Future research should investigate the best role for deposit trading in such settings.

6. Appendix

Proof of Lemma 1: Differentiating (3.2), (3.3), and (3.5) gives:

$$\left\{ \begin{array}{c} dx_i = S_i'(p)\, dp \ \forall i \in N \\ dy_i = D_i'(p)\, dp \ \forall i \in N \\ dx_M - dy_M = \sum_N (dy_i - dx_i) \end{array} \right\} \Rightarrow$$

$$\begin{aligned} \frac{dp}{dI} &= \frac{1}{S'(p) - D'(p)}, \\ \frac{dx_i}{dI} &= \frac{S_i'(p)}{S'(p) - D'(p)}, \\ \frac{dy_i}{dI} &= \frac{D_i'(p)}{S'(p) - D'(p)}. \end{aligned} \tag{6.1}$$

Maximizing U_M w.r.t. x_M and y_M s.t. (6.1) gives (3.6) as the first-order conditions. The second-order conditions hold if C_M and H are sufficiently convex, and they always hold in equilibrium.

To see this, note that the first-order conditions when maximizing w.r.t. x_M and p becomes:

$$\begin{aligned} B_M'(y_M) - C_M'(x_M) - H'(.) &= 0, \\ (B_M'(y_M) - p)\sum_N (S_i'(p) - D_i'(p)) - H'\sum_N S_i'(p) - (y_M - x_M) &= 0. \end{aligned}$$

The second-order conditions require that $\partial^2 U_M(x_M, p)/(\partial x_M)^2 \leq 0$, $\partial^2 U_M(x_M, p)/(\partial p)^2 \leq 0$ and $\left[\partial^2 U_M(x_M, p)/(\partial x_M)^2\right]\left[\partial^2 U_M(x_M, p)/(\partial p)^2\right] - \left[\partial^2 U_M(x_M, p)/\partial p \partial x_M\right]^2 \geq 0$. The first two conditions are, respectively:

$$B_M''(y_M) - C_M''(x_M) - H''(.) \leq 0,$$

$$\begin{aligned} &(B_M'(y_M) - p)\sum_N (S_i''(p) - D_i''(p)) - 2\sum_N (S_i'(p) - D_i'(p)) \\ &+ B_M''(y_M)\left[\sum_N (S_i'(p) - D_i'(p))\right]^2 - H''(.)\left[\sum_N S_i'(p)\right]^2 \\ &- H'(.)\sum_N S_i''(p) \leq 0 \quad . \end{aligned}$$

Of the two conditions above, the first always hold. The second holds if H is sufficiently convex. However, once the deposit market clears ($x_i = y_i$), the second condition boils down to:

$$2\sum_N D_i'(p) + B_M''(y_M)\left[\sum_N D_i'(p)\right]^2 \leq 0,$$

which always hold.

The cross derivative is:

$$\frac{\partial^2 U_M(x_M,p)}{\partial p \partial x_M} = B''_M(y_M)\sum_N (S'_i(p) - D'_i(p)) - H''(.)\sum_N S'_i(p),$$

which is smaller if H is very convex. When the deposit market clears, this boils down to:

$$\frac{\partial^2 U_M(x_M,p)}{\partial p \partial x_M} = -B''_M(y_M)\sum_N 1/B''_i.$$

so the third condition (for the second-order condition to hold) becomes:

$$[B''_M - C''_M - H'']\left[2\sum_N D'_i(p) + B''_M(y_M)\left[\sum_N D'_i(p)\right]^2\right] - \left[B''_M(y_M)\sum_N D'_i\right]^2 \geq 0 \Rightarrow$$

$$[B''_M - C''_M - H'']\left[2\sum_N 1/B''_i + B''_M(y_M)\left[\sum_N 1/B''_i\right]^2\right] - \left[B''_M(y_M)\sum_N 1/B''_i\right]^2 \geq 0 \Rightarrow$$

$$-\left[2 + \sum_N B''_M/B''_i\right]\sum_N [C''_M + H'']/B''_i + 2\sum_N B''_M/B''_i \geq 0,$$

which always hold.

Proof of Lemma 2: Consider an equilibrium allocation of deposits giving cost functions $C_i(.)$ and equilibrium productions $x_i \forall i$, and $x_i = S_i(p) = C_i'^{-1}(p)\, \forall i \in N$. Take a small deposit of size Δ with a marginal exploitation cost c, small enough to make the deposit profitable to exploit whether owned by i or M. If the deposit market clears, i cannot own such a deposit if M would value it more than i. If the right to exploit Δ is transferred from i to M, i's utility becomes:

$$U_i = \max_{x_i,y_i} B_i(y_i) - C_i(x_i) + c\Delta - p(y_i - x_i) - p\Delta. \tag{6.2}$$

Whether or not $C'_i(.)$ is singular at x_i, we can use the envelope theorem to differentiate (6.2). This gives:

$$\frac{dU_i}{d\Delta} = c - p - (y_i - x_i)\frac{dp}{d\Delta}. \tag{6.3}$$

After the transaction, M's utility becomes:

$$U_M = \max_{p,x_M} B_M(y_M) - C_M(x_M) - c\Delta - H(x_M + \Delta + S(p) - \Delta) + p(x_M + \Delta - y_M), \tag{6.4}$$

where I let M maximize w.r.t. p and x_M instead of, for example, y_M and x_M. In any case, (3.2)-(3.5) must be satisfied, implying

$$y_M = x_M + \Delta + S(p) - \Delta - D(p),$$

thus a function of p and x_M but not Δ. Using the envelope theorem when differentiating (6.4), we get simply

$$\frac{dU_M}{d\Delta} = p - c. \tag{6.5}$$

Note that $dp/d\Delta > 0$ follows when differentiating U_M in (6.4) w.r.t. p and the second-order condition holds. Thus, if $y_i < x_i$, the sum of (6.3) and (6.5) is positive, implying that there exist some price which makes both i and M better off following the transaction. If $y_i > x$, both i and M could be better off by the reverse transaction.

Proof of Lemma 3: To prove the lemma by contradiction, suppose that, for some $i \in N$, $C_i'(x_i)$ were singular at the equilibrium deposit allocation and x_i. Then $C_i'(x_i) = B_i'(y_i)\, \forall i \in N$, and there exists some deposit of size $\Delta > 0$ with marginal cost $c \leq C_i'(x_i) = B_i'(y_i) = p$ and

$$c > p - H'(.) \left(1 - \frac{S'(p)}{S'(p) - D'(p)}\right). \tag{6.6}$$

If the right to exploit this deposit were transferred from i to M, i's utility gain would be (6.3), as before. But M would not produce from this deposit when $x_M = y_M$, according to Lemma 1, and after the transaction M's utility would be:

$$U_M = \max_{p, x_M} B_M(y_M) - C_M(x_M) - H(x_M + S(p) - \Delta) - p(y_M - x_M), \tag{6.7}$$

where the variables must satisfy (3.2)-(3.5), implying

$$y_M = x_M + S(p) - \Delta - D(p),$$

since i's supply is reduced by Δ relative to the initial $S_i(p)$. Using the envelope theorem when differentiating (6.7), we get

$$\frac{dU_M}{d\Delta} = -B_M'(.) + H'(.) + p. \tag{6.8}$$

Substituting $y_i = x_i$, the sum of (6.3) and (6.8) is

$$-B_M'(.) + H'(.) + c > -B_M'(.) + p + H'(.) \frac{S(p)}{S'(p) - D'(p)} = 0,$$

where I first used (6.6) and then Lemma 1 and 2. Since the total gain is strictly positive, there exist some price which makes both i and M better off following the transaction, implying that the initial allocation cannot be an equilibrium. It follows that for every $i \in N$, $C_i'(x_i)$ is nonsingular and, hence, $S_i'(p) = 0$.

It is possible that $\lim_{\epsilon \downarrow 0} S_i'(p + \epsilon) > 0$ but we must still have $B_i'(y_i) = B_M'(y_M)$ since, if $B_M'(y_M) < p = B_i'(y_i)$, M would strictly benefit by increasing y_M while simultaneously obtaining i's deposits with marginal cost $c > p$ (such that i would not increase its production following the increase in y_M). Since neither p nor unused deposits matter for $i \in N$ when $x_i = y_i$, i would be indifferent to such a transaction.

Proof of Lemma 4: The transaction described in the previous proof would be stricly beneficial for all $c \in (p - H'(.), p]$, when substituting $S'_i(.) = 0$ in (6.6). Thus, $i \in N$ cannot in equilibrium own such a deposit, $S'_i(.) = 0$ on the interval $(p - H'(.), p]$, implying the lemma.

Proof of Proposition 2: (i) Note that $\partial U_j/\partial r_i = (x_j - y_j)\,\partial p/\partial r_i$ if $i, j \in N$, $i \neq j$, while $\partial U_i/\partial r_i = p + (x_j - y_j)\,\partial p/\partial r_i$ if $i \in N$. Since

$$\begin{aligned}
U_M &= \max_{x_M, y_M, r_M} \widetilde{B}_M(y_M + r_M) - C_M(x_M) - H(x_M + S(p)) - p(y_M - x_M), \\
\frac{\partial U_M}{\partial r_i} &= [-H'(.)\,S'(p) - (y_M - x_M)]\,\frac{\partial p}{\partial r_i} \forall i \in N \Rightarrow \\
& \sum_{j \in M \cup N} \frac{\partial U_j}{\partial r_i} = p - H'(.)\,S'(p)\,\frac{\partial p}{\partial r_i}.
\end{aligned} \tag{6.9}$$

By differentiating the first-order conditions (as in the proof of Lemma 1), we find $\partial p/\partial r_i = -1/\sum_N \left[S'_j(p) - 1/B''_j(p)\right] < 0$ for pre-investment policies, while after the investment stage, $\partial p/\partial r_i < 0$ follows from the second-order condition when maximizing U_M w.r.t. p. Thus, if $S'(p) > 0$, socially optimal investments are given by $k'_i(r^*_i) = p - H'(.)\,S'(p)\,\partial p/\partial r_i > p = k'_i(r_i)$, so the equilibrium investment r_i is strictly smaller than the optimal r^*_i. (ii) At the policy stage, it must hold for M in (6.9) that $\partial p/\partial r_i = -1/\sum_N \left[S'_j(p) - 1/B''_j(p)\right]$, whether x_M and y_M are sunk or yet to be optimally chosen. Substituting in (6.9) concludes the proof. Alternatively, for post-investment policies, it follows from the envelope theorem (when maximizing U_M w.r.t. x_M and p) that $\partial U_M/\partial r_i = \widetilde{B}'_M - p$, which can be written as (4.1), given (3.6).

Proof of Proposition 3: Lemma 1 continues to hold given the demand function $D_i(p)$ and the supply function $S_i(p)$.When r_i is sunk, demand is given by:

$$y_i = D_i(p) = \widetilde{B}'^{-1}_i(p) - r_i \Rightarrow \partial y_i/\partial p = D'_i(p) = 1/\left(\widetilde{B}'^{-1}_i\right)'(p) = 1/\widetilde{B}''_i(y_i + r_i).$$

Suppose now that r_i is decided after M's policy is set. The first-order condition for r_i, $i \in N$, is $p = k'_i(r_i)$. Differentiating this, we get $dr_i/dp = 1/k''_i(r_i)$. Thus, demand is now given by

$$\begin{aligned}
D_i(p) &= y_i = \widetilde{B}'^{-1}_i(p) - r_i \Rightarrow \\
D'_i(p) &= \partial y_i/\partial p = \left(\widetilde{B}'^{-1}_i\right)'(p) - 1/k''_i(r_i) = 1/\widetilde{B}''_i(y_i + r_i) - 1/k''_i(r_i).
\end{aligned}$$

The proofs below for Lemmas 1-3 and 5 permit heterogeneous fuels, as discussed in Section 4.3. Lemmas 1-3 are obtained by setting $E_i(x_i) = x_i$.

Proof of Lemma 1' and 5: Differentiating (3.2), (3.3), and (3.5) gives:

$$\left\{ \begin{array}{c} dx_i = S'_i(p)\,dp \;\forall i \in N \\ dy_i = D'_i(p)\,dp \;\forall i \in N \\ dx_M - dy_M = \sum_{i \in N}(dy_i - dx_i) \end{array} \right\} \Rightarrow$$

$$\begin{aligned}\frac{dp}{dx_M - dy_M} &= \frac{-1}{\sum_{i\in N}\left(S_i'(p) - D_i'(p)\right)}, \\ \frac{dx_i}{dx_M - dy_M} &= \frac{-S_i'(p)}{\sum_{i\in N}\left(S_i'(p) - D_i'(p)\right)}, \\ \frac{dy_i}{dx_M - dy_M} &= \frac{-D_i'(p)}{\sum_{i\in N}\left(S_i'(p) - D_i'(p)\right)}.\end{aligned} \tag{6.10}$$

M's problem is:

$$\max_{x_M, y_M} B_M(y_M) - C_M(x_M) - H\left(E_M(x_M) + \sum_N E_i(S_i(p))\right) + p(x_M - y_M),$$

giving the first-order conditions for x_M and y_M:

$$\begin{aligned}-C_M'(x_M) - H'(.)\left[E_M'(.) + \sum_N E_i'(.)\, S_i'(p)\frac{\partial p}{\partial x_M}\right] + p + (x_M - y_M)\frac{\partial p}{\partial x_M} &= 0, \\ B_M'(y_M) - H'(.)\left[\sum_N E_i'(.)\, S_i'(p)\frac{\partial p}{\partial y_M}\right] - p + (x_M - y_M)\frac{\partial p}{\partial y_M} &= 0.\end{aligned}$$

Substituting $\partial p/\partial y_M = -\partial p/\partial x_M = 1/\left[\sum_{i\in N}\left(S_i'(p) - D_i'(p)\right)\right]$ from (6.10) gives (4.6)-(4.7).

Proof of Lemma 2': Consider an equilibrium allocation of deposits giving cost functions $C_i(.)$ and equilibrium productions $x_i \forall i$, and $x_i = S_i(p) = C_i'^{-1}(p)\,\forall i \in N$. Take a small deposit of size Δ with a marginal exploitation cost c and emission content e, both small enough to make the deposit profitable to exploit whether owned by i or M. If the right to exploit Δ is transferred from i to M, i's utility becomes:

$$U_i = \max_{x_i, y_i} B_i(y_i) - C_i(x_i) + c\Delta - p(y_i - x_i) - p\Delta. \tag{6.11}$$

Whether or not $C'(.)$ is singular at x_i, we can use the envelope theorem to differentiate (6.11). This gives:

$$\frac{dU_i}{d\Delta} = c - p - (y_i - x_i)\frac{dp}{d\Delta}. \tag{6.12}$$

After the transaction, M's utility becomes:

$$\begin{aligned}U_M = {} & \max_{p, x_M} B_M(y_M) - C_M(x_M) - c\Delta + p(x_M + \Delta - y_M) \\ & -H\left(E_M(x_M) + e\Delta + \sum_N E_i(S_i(p)) - e\Delta\right),\end{aligned} \tag{6.13}$$

where I let M maximize w.r.t. p and x_M instead of, for example, y_M and x_M. In any case, (3.2)-(3.5) must be satisfied, implying

$$y_M = x_M + \Delta + \sum_N S_i(p) - \Delta - \sum_N D_i(p),$$

thus a function of p and x_M but not Δ. Using the envelope theorem when differentiating (6.13), we get simply

$$\frac{dU_M}{d\Delta} = p - c. \tag{6.14}$$

Note that the first-order condition of (6.13) w.r.t. p is:

$$\left(B'_M(.) - p\right)\left[\sum_N S'_i(p) - \sum_N D'_i(p)\right] - H'(\cdot)\left(\sum_N E'_i\left(S'_i(p)\right)\right) + \left(x_M + \Delta - y_M\right) = 0. \tag{6.15}$$

Since (6.15) must decrease in p for the second-order condition to be satisfied, and since (6.15) is increasing in Δ, it follows that $dp/d\Delta > 0$.

Thus, if $y_i < x_i$, the sum of (6.12) and (6.14) is positive, implying that there exist some price which makes both i and M better off following the transaction. If $y_i > x$, both i and M could be better off by the reverse transaction. *QED*

Proof of Lemma 3': The prove the lemma by contradiction, suppose that, for some $i \in N$, $C'_i(x_i)$ were singular at the equilibrium deposit allocation and x_i. Then $E'_i(.)$ is continuous at x_i, and there are generically two possibilities.

(i) If

$$p - C'_i(x_i) < H'(.)\left(E'_i(x_i) - \frac{\sum_N E'_j(x_j)\, S'_j(p)}{\sum_N \left(S'_j(p) - D'_j(p)\right)}\right),$$

then i owns a deposit of size Δ with marginal cost c and emission factor $e\Delta$ such that $p > c$ but

$$p - c < H'(.)\left(e - \frac{\sum_N E'_j(x_j)\, S'_j(p)}{\sum_N \left(S'_j(p) - D'_j(p)\right)}\right). \tag{6.16}$$

If the right to exploit this deposit were transferred from i to M, i's utility gain would be (6.12), as before. But M would not produce from this deposit when $x_i = y_i$, according to (4.7), and after the transaction M's utility would be:

$$U_M = \max_{p, x_M} B_M(y_M) - C_M(x_M) - H\left(E_M(x_M) + \sum_N E_i\left(S_i(p)\right) - e\Delta\right) - p\left(y_M - x_M\right), \tag{6.17}$$

where the variables must satisfy (3.2)-(3.5), implying

$$y_M = x_M + \sum_N S_i(p) - \Delta - \sum_N D_i(p),$$

since i's supply is reduced by Δ relative to the initial $S_i(p)$. Using the envelope theorem when differentiating (6.17), we get

$$\frac{dU_M}{d\Delta} = -B'_M(.) + eH'(.) + p. \tag{6.18}$$

Substituting $y_i = x_i$, the sum of (6.12) and (6.18) is

$$-B'_M(.) + eH'(.) + c > -B'_M(.) + p + H'(.)\,\frac{\sum_N E'_j(x_j)\, S'_j(p)}{\sum_N \left(S'_j(p) - D'_j(p)\right)} = 0,$$

where I first used (6.16) and then Lemma 1 and 2. Since the total gain is strictly positive, there exist some price which makes both i and M better off following the transaction, implying that the initial allocation cannot be an equilibrium.

(ii) If instead

$$p - C_i'(x_i) > H'(.)\left(E_i'(x_i) - \frac{\sum_N E_j'(x_j) S_j'(p)}{\sum_N \left(S_j'(p) - D_j'(p)\right)}\right),$$

then i owns a deposit of size Δ with marginal cost c and emission factor $e\Delta$ such that $p < c$ but

$$p - c > H'(.)\left(e - \frac{\sum_N E_j'(x_j) S_j'(p)}{\sum_N \left(S_j'(p) - D_j'(p)\right)}\right). \tag{6.19}$$

The deposit is not exploited by i and i is indifferent to transferring it to M. If M owned it, M would exploit it according to (4.7) and thus benefit from obtaining it. Thus, the initial allocation cannot be an equilibrium.

It is possible that $\lim_{\epsilon\downarrow 0} S_i'(p+\epsilon) > 0$ but we must still have $B_i'(y_i) = B_M'(y_M)$ since, if $B_M'(y_M) < p = B_i'(y_i)$, M would strictly benefit by increasing y_M while simultaneously obtaining i's deposits with marginal cost $c > p$ (such that i would not increase its production following the increase in y_M). Since neither p nor unused deposits matter for $i \in N$ when $x_i = y_i$, i would be indifferent to such a transaction.

Proof of Proposition 4: The first-order conditions for $i \in N$ are, together with the budget constraints:

$$\begin{aligned}
y_{i,t} &= D_{i,t}(p_t), \\
x_{i,1} + x_{i,2} &= S_i(p_2), \\
x_{i,1} &= S_i\left(\frac{p_1 - \delta p_2}{1-\delta}\right), \\
\sum_N (x_{i,1} - y_{i,1}) &= I_1 \equiv y_{M,1} - x_{M,1}, \\
\sum_N (y_{i,2} - x_{i,2}) &= I_2 \equiv y_{M,2} - x_{M,2}.
\end{aligned}$$

This system of $4n+2$ equations pins down p_t, $x_{i,t}$ and $y_{i,t}$ for all $i \in N$, $t \in \{1,2\}$ as a function of I_1 and I_2. Differentiating these equations gives:

$$\begin{aligned}
dy_{i,t} &= dp_t D_{i,t}', \\
dx_{i,1} + dx_{i,2} &= dp_2 S_i'(p_2), \\
dx_{i,1} &= \left(\frac{dp_1 - \delta dp_2}{1-\delta}\right) S_i'\left(\frac{p_1 - \delta p_2}{1-\delta}\right), \\
\sum_N (dx_{i,1} - dy_{i,1}) &= dI_1, \\
\sum_N (dx_{i,2} - dy_{i,2}) &= dI_2.
\end{aligned}$$

By substitution, we get:

$$
\begin{aligned}
\sum_N \left(\left(\frac{dp_1 - \delta dp_2}{1-\delta} \right) S_i' \left(\frac{p_1 - \delta p_2}{1-\delta} \right) - dp_1 D_{i,1}' \right) &= dI_1, \\
\sum_N \left(dp_2 S_i' (p_2) - \left(\frac{dp_1 - \delta dp_2}{1-\delta} \right) S_i' \left(\frac{p_1 - \delta p_2}{1-\delta} \right) - dp_2 D_{i,2}' \right) &= dI_2.
\end{aligned}
$$

Set $S_1' \equiv \sum_N S_i' ([p_1 - \delta p_2] / [1-\delta])$, $S_2' \equiv \sum_N S_i' (p_2)$, $D_1' \equiv \sum_N D_{i,1}' (p_1)$, $D_2' \equiv \sum_N D_{i,2}' (p_2)$, and solve for dp_1 and dp_2:

$$
\begin{aligned}
dp_2 &= \frac{dI_2 + dI_1 S_1' / (S_1' - D_1' (1-\delta))}{S_2' - D_2' - \delta D_1' S_1' / (S_1' - D_1' (1-\delta))}, \\
dp_1 &= \frac{dI_1 (1-\delta)}{S_1' - D_1' (1-\delta)} + \delta \frac{S_1'}{S_1' - D_1' (1-\delta)} \left(\frac{dI_2 + dI_1 S_1' / (S_1' - D_1' (1-\delta))}{S_2' - D_2' - \delta D_1' S_1' / (S_1' - D_1' (1-\delta))} \right).
\end{aligned}
$$

At the policy-stage, M chooses $\{x_{M,1}, y_{M,1}, x_{M,2}, y_{M,2}\}$ to maximize (4.2) for $i = M$. The first-order conditions for $x_{M,2}$ and $y_{M,2}$ give:

$$
\begin{aligned}
-\left(1 - S_2' \frac{dp_2}{dI_2}\right) H' + p_2 + \frac{dp_1}{dI_2} \frac{I_1}{\delta} + \frac{dp_2}{dI_2} I_2 &\in C_M' (x_{M,1} + x_{M,2}), \qquad (6.20) \\
-\left(S_2' \frac{dp_2}{dI_2}\right) H' + B_{M,2}' - p_2 - \frac{dp_1}{dI_2} \frac{I_1}{\delta} - \frac{dp_2}{dI_2} I_2 &= 0,
\end{aligned}
$$

This policy can be implemented by, for example, the following taxes on production and consumption:

$$
\begin{aligned}
\tau_{x,2} &= \left(1 - S_2' \frac{dp_2}{dI_2}\right) H' - \frac{dp_1}{dI_2} \frac{I_1}{\delta} - \frac{dp_2}{dI_2} I_2, \\
\tau_{y,2} &= \left(S_2' \frac{dp_2}{dI_2}\right) H' + \frac{dp_1}{dI_2} \frac{I_1}{\delta} + \frac{dp_2}{dI_2} I_2.
\end{aligned}
$$

The first-order conditions for the first period gives (we can ignore the effect of $x_{M,1}$ on $x_{M,1} + x_{M,2}$ using the envelope theorem since the f.o.c. w.r.t. $x_{M,2}$ is equivalent to the f.o.c. w.r.t. $x_{M,1} + x_{M,2}$):

$$
\begin{aligned}
-\delta \left(\frac{dp_2}{dI_2} - \frac{dp_2}{dI_1} \right) S_2' H' - (1-\delta) C_M' (x_{M,1}) + p_1 - \delta p_2 & \qquad (6.21) \\
+ \frac{dp_1}{dI_1} I_1 + \delta \frac{dp_2}{dI_1} I_2 - \frac{dp_1}{dI_2} I_1 - \delta \frac{dp_2}{dI_2} I_2 &= 0, \\
-\delta \left(\frac{dp_2}{dI_1} S_2' \right) H' + B_{M,1}' - p_1 - \frac{dp_1}{dI_1} I_1 - \delta \frac{dp_2}{dI_1} I_2 &= 0.
\end{aligned}
$$

For a given set of taxes, $x_{M,1}$ would be given by

$$
p_1 - C_M' (x_{M,1}) - \tau_{x,1} = \delta (p_2 - C_M' (x_{M,1}) - \tau_{x,2}).
$$

By combining the last five equations, M's first-period policy can be implemented by:

$$\begin{aligned}\tau_{x,1} &= \delta\left(1-\frac{dp_2}{dI_1}S_2'\right)H' - \frac{dp_1}{dI_1}I_1 - \delta\frac{dp_2}{dI_1}I_2,\\ \tau_{y,1} &= \delta\left(\frac{dp_2}{dI_1}S_2'\right)H' + \frac{dp_1}{dI_1}I_1 + \delta\frac{dp_2}{dI_1}I_2.\end{aligned}$$

Note that $\tau_{x,1}/\delta > \tau_{x,2}$ if $I_1 = I_2 = 0 < S_2'$. The reason is that i's aggregate production is increasing in p_2 which, in turn, increases more in $\tau_{x,2}$ than in $\tau_{x,1}$.

Proof of Theorem 1 (iii): Lemmas 2-4 hold for the same reasons as before and their proofs are thus omitted. Substituted in Proposition 4, the second-period policies remain the same whether or not M can commit to future policies. In either case, M relies only on supply-side politics in the second period and $B_{M,2}' = p_2 = B_{i,2}' \forall i \in N$. In the first period, M's policy is given by (6.21) if M can commit. If M cannot commit to future policies, M may also want to take into account how first period policies affect second period policies. But since the second-period policy, given by Lemma 1, is identical to M's ideal policy (described by Proposition 4) if M can commit and $I_1 = I_2 = S_2' = 0$, this effect can be ignored (using the envelope theorem). In either case, (6.21) describes M's optimal policy for the first period. Substituting $I_1 = I_2 = S_2' = 0$ in (6.21) implies $B_{M,1}' = p_1 = B_{i,1}'$. M extracts the optimal amount since (6.20) implies $p_2 + H' \in C_M'(x_{M,1} + x_{M,2})$, and $i \in N$ extracts the optimal amount by Lemma 4. In addition, dynamic efficiency requires $x_{i,1} = C_i'^{-1}\left(\left[B_{j,1}' - \delta B_{j,2}'\right]/\left[1-\delta\right]\right)$. It is easily checked that this is satisfied for all $i \in M \cup N$.

Proof of Lemma 6: Suppose $i \in N$ owned a deposit x_i such that $p - eH'(.) < c < p$, thus satisfying (6.16). As in the proof of Lemma 3′, case (i), the joint surplus of M and i would increase if M obtained the ownership of this deposit. A price exists such that both i and M would be better off, implying that this cannot be an equilibrium.

Proof of Proposition 5: (i) is in line with previous results and its proof thus omitted. (ii): The environmental benefit of joining is $h^2 l/(a+c)$ since every country is reducing pollution by $h/(a+c)$ compared to when i did not join. But participation implies that i looses the consumer and producer surplus $h^2 m^2/2(a+c)$. In addition, i must share $1/m$ of the expenditures when compensating each of the $n = l - m$ nonparticipating producers $h^2 m^2/2(a+c)$. Summing up, participation is beneficial if

$$\frac{h^2}{a+c}\left[l - \frac{m^2}{2} - \frac{m(l-m)}{2}\right] \geq 0 \Rightarrow m \leq 2.$$

Proof for (iii): The environmental benefit of joining is $h^2 l/(a+c)$, since every country is reducing pollution by $h/(a+c)$ compared to when i did not join. But while i without participating would only loose the consumer surplus $ah^2(m-1)^2/2(a+c)^2$, by participation it looses its consumer and producer surplus $h^2 m^2/2(a+c)$. In addition, i must share $1/m$ of the expenditures when compensating each of the $l - m$ nonparticipating producers $ch^2 m^2/2(a+c)^2$. Summing up, and defining $\gamma \equiv a/(a+c)$, participation is beneficial if

$$\frac{h^2}{a+c}\left[l + \frac{\gamma}{2}(m-1)^2 - \frac{m^2}{2} - \frac{(1-\gamma)m(l-m)}{2}\right] \geq 0 \Rightarrow \frac{2l+\gamma}{l(1-\gamma)+2\gamma} \geq m.$$

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