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Buy coal for preservation and act strategically on the fuel market *

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Abstract

A coalition of given size fights climate change by purchasing fossil fuel deposits to prevent their exploitation, and it seeks to manipulate the terms of fuel trade in its favor. Harstad (2012, Theorem 1) claims that the trade of deposits internalizes the negative climate externalities and renders non-distortionary the coalition's strategic action on the fuel market. Based on our earlier result that Harstad's 'killing-twobirds-with-one-stone theorem' is flawed, our paper presents the correct outcome within Harstad's analytical framework. We show that the coalition's strategic action is distortionary, if one of two conditions is satisfied in the first-best regime, in which the coalition takes the fuel price as given. Either the coalition imports fuel or it exports fuel and the gain from increasing export revenues via pushing the fuel price up overcompensates the induced climate damage increase.

JEL classification: Q31, Q38, Q55 Key words: climate coalition, fossil fuel, deposits, extraction, fuel caps

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1 Introduction

Compelling scientific evidence suggests that greenhouse gas emissions, notably carbon emissions, generate severe negative climate externalities that can be internalized by global cooperative action. The experience from the Kyoto protocol and the climate change summits of recent years to reach a post-Kyoto agreement are disappointing. It is true that several countries have increased their efforts to curb emissions, notably the (Annex 1) countries that committed to emissions reductions in the Kyoto Protocol. Yet many small and large countries still refrain from taking (strong) action, and most of them have expanded their emissions significantly since 1990. That raises the question of what the chances are of a climate coalition to reduce carbon emissions efficiently by unilateral action.

Environmental economists have intensively analyzed this question. There is a literature that shows that unilateral environmental or trade policy is distortionary in the presence of trade and transboundary pollution (Markusen 1975, Hoel 1994, Copeland 1996).¹ In these second-best settings, the unilateral policy causes carbon leakage, which renders global emissions inefficiently high. The inefficiency aggravates, if the climate coalition implements its environmental policy strategically by influencing the terms of trade to its own favor.

Most of the aforementioned studies investigate demand-side climate policies. Bohm (1993), Harstad (2012) and Asheim (2013) are the only studies we know with an analytical approach to supply-side policies in which countries suffering from climate damage purchase or lease fossil energy deposits ('buy coal') to prevent their extraction. In a stylized parametric model, Bohm (1993) derives conditions under which a special policy mix consisting of the purchase or lease of deposits and a fuel-demand cap implements the emission cap at lower costs than the stand-alone fuel-demand-cap policy. Asheim (2013) makes the case for deposit policies as a distributional instrument in a growth model á la Dasgupta-Heal-Solow-Stiglitz.

Harstad (2012) considers a world economy with non-cooperative countries and a (climate) coalition acting as one agent. The coalition and the countries extract and consume fossil fuel. Carbon emissions from fuel consumption generate climate damage that hits the coalition only. As in Hoel (1994), the coalition exerts - or tries to exert - market power by manipulating the terms of fuel trade in its favor via the choice of fuel demand and supply. Hence, in the absence of climate policy Harstad's economy exhibits two different kinds of distortions: the non-internalized climate damage suffered by the coalition and the distortion

¹Not only unilateral environmental policy is inefficient, but also non-cooperative environmental policy (Ludema and Wooton 1994, Copeland and Taylor 1995, Kiyono and Ishikawa 2013) and the formation of self-enforcing international environmental agreements (Barrrett 1994, Rubio and Ulph 2006, Eichner and Pethig 2013).

caused by the coalition's strategic action on the fuel market. Harstad then allows for international trade in (the right to extract) fossil-fuel deposits. Loosely expressed in our words, his Theorem 1 states that if 'his' deposit market is in equilibrium, embedded in the equilibrium of his three-stage game, both types of distortions are eliminated. Eichner and Pethig (2016) disprove Harstad's Theorem 1. The present paper adopts Harstad's analytical framework and characterizes the outcome of Harstad's three-stage game after having corrected the flaw in the proof of his Theorem 1.

For that purpose Section 2 briefly presents the model, characterizes the social optimum with deposit trading for preservation and decentralizes the social optimum in an economy with a perfectly competitive market for fuel and a deposit market for preservation. Proposition 1 shows that deposit trading internalizes the climate damage. Since strategic effects are absent the economy with a perfectly competitive market for fuel and a deposit market for preservation is efficient.

Section 3 investigates Harstad's three-stage game with deposit trade for preservation. In that game there emerge two distortions: the non-internalized climate damage and the market power on the fuel market. It turns out that the deposit purchases for preservation again internalize the climate damage. However, whether the distortion from strategic action on the fuel market is eliminated depends on import and export patterns (Proposition 2). Deviating from the efficient fuel caps changes the coalition's welfare via two channels: we identify a *terms-of-trade effect* and a *climate damage effect*. If the coalition's fuel extraction exactly equals its fuel consumption, the terms-of-trade effect vanishes, the climate damage effect is negative and the coalition would loose welfare when deviating from the efficient fuel caps. Hence, the coalition chooses the efficient fuel caps and (strategic) action is nondistortionary. If the coalition imports fuel, the terms-of-trade effect is positive, the climate damage effect vanishes and the coalition gains through strategic action that is distortionary. If the coalition exports fuel, the terms-of-trade effect is positive and the climate damage effect is negative. Strategic action is distortionary if the terms-of-trade effect overcompensates the climate damage effect.

Finally, Section 4 provides a brief assessment of Harstad's Theorem 1. Harstad introduces in addition to deposit trade for preservation further deposit trade for extraction. Eichner and Pethig (2016) point out that additional deposit trade does not change the coalition's fuel exports or imports. Hence, the inefficiency of strategic action for the deposit preservation trade also prevails for Harstad's deposit trade. Section 5 concludes.

2 Buy deposits for preservation and take the fuel price as given

Throughout the paper, we adopt Harstad's (2012) analytical framework. His world economy consists of two groups of countries, M and N. The members of group M participate in an international climate agreement and the group – or coalition – M acts as one agent. Each country $i \in N \cup \{M\} := \Omega$ is endowed with the amount \bar{l}_i of a composite immobile factor ("labor"), and produces fossil fuel x_i with factor input l_{xi} and a consumption good w_i^s ("wheat") with factor input l_{wi} . The simple production functions are $w_i^s = a_i l_{wi}$ and $x_i = X_i(l_{xi})$, with $a_i > 0$ and constant, $X'_i > 0$ and $X''_i < 0$. Combined with the labor supply constraint $l_{xi} + l_{wi} = \bar{l}_i$, the production functions yield the production possibility frontier

$$w_i^s = a_i \bar{l}_i - C_i(x_i) \quad \forall i \in \Omega, \tag{1}$$

where $C_i(x_i) := X_i^{-1}(x_i)$ is country *i*'s strictly convex extraction cost function. Country *i*'s deposits are specified by the fossil fuel in situ ordered according to increasing marginal extraction costs. We denote these fossil fuel deposits by $[0, \infty \Big[_{C'_i}$ and determine the cost of extracting some (small) deposit² $[\underline{x}, \overline{x}]_{C'_i} \in [0, \infty \Big[_{C'_i} \text{ as } C_i(\overline{x}) - C_i(\underline{x})]$. Country *i* is the initial owner of the deposits $[0, \infty \Big[_{C'_i}$ and has both the right to extract and to sell the right to extract the fossil fuel contained in these deposits. The utility of the representative consumer of country *i* is

$$u_i = B_i(y_i) + w_i^d - \delta(i)H\left(\sum_{\Omega} x_j\right) \quad \text{with } \delta(i) = \begin{cases} 1, & \text{if } i = M, \\ 0, & \text{if } i \in N. \end{cases}$$
(2)

 $H(\sum_{\Omega} x_j)$ (with H' > 0) is the climate damage suffered by the coalition and $B_i(y_i)$ is the utility from consuming y_i units of fuel (with $B'_i > 0$ and $B''_i < 0$). Carbon emissions from burning fossil fuel generate climate damage. Since emissions are proportional to fuel output and consumption, x_i denotes both fuel supply and emissions. The scarcity constraints for wheat and fuel,

$$\sum_{\Omega} (x_j - y_j) = 0 \quad \text{and} \quad \sum_{\Omega} (w_j^s - w_j^d) = 0, \tag{3}$$

complete the description of the analytical framework.

In the present section, we assume perfectly competitive international markets for wheat and fuel. Treating all agents and governments as price takers on these markets is in contrast to Hoel (1994) and Harstad (2012) whose focus are economies in which the coalition exerts

 $^{^{2}}$ For the concept of deposit endowments in the formal model see Appendix A1.

market power on the fuel market by manipulating the terms of trade in its favor. We will take up that case in the next section. Throughout the paper, the countries in group N abstain from actions to reduce carbon emissions. If the coalition would not fight climate damage either, the damage would obviously be non-internalized, i.e. excessive. Aiming to avoid that inefficiency, the coalition is supposed to implement the following supply-side climate policy. It purchases (the right to exploit) deposits from the countries outside the coalition for the purpose to prevent their exploitation. We refer to that policy as the introduction of a deposit preservation market (deposit market, for short). By assumption, this market clears, when there is no deal left to purchase deposits for preservation at some price³ that would be strictly beneficial for both the coalition and the selling country.

In the sequel, we follow Eichner and Pethig (2016) and show that an equilibrium in the market economy with competitive international markets for wheat and fuel and with a deposit market as specified above is efficient. It is analytical convenient to establish first the social optimum and then decentralize the social planner's solution. In order to characterize an efficient allocation in case of tradable deposits, imagine a social planner who takes away from the initial deposit endowment $\left[0,\infty\right]_{C'_i}$ of each country $i \in N$ all deposits in some interval $\left[\sigma_i,\xi_i\right]_{C'_i} \neq \emptyset$ and transfers them to the coalition obliging it to preserve the deposits it receives. Then the question arises how to choose the boundary points σ_i and ξ_i of the interval $\left[\sigma_i,\xi_i\right]_{C'_i}$ that maximize global welfare. Denote the 'number' of deposits in the interval $\left[\sigma_i,\xi_i\right]_{C'_i}$ by $z_i^s := \xi_i - \sigma_i$ and the total 'size' of deposits transferred to the coalition by

$$z_M^d = \sum_N z_j^s. \tag{4}$$

The social planner solves the Lagrangean

$$\mathcal{L}(\cdot) = \sum_{N} \left[B_{j}(y_{j}) + a_{j}\bar{r}_{j} - C_{j}(\xi_{j} - z_{j}^{s}) \right] + B_{M}(y_{M}) + a_{M}\bar{r}_{M} - C_{M}(x_{M}) -H\left(x_{M} - z_{M}^{d} + \sum_{N}\xi_{j}\right) + \lambda_{f}\left[x_{M} - y_{M} + \sum_{N}(\xi_{j} - z_{j}^{s} - y_{j})\right] + \lambda_{z}\left(\sum_{N}z_{j}^{s} - z_{M}^{d}\right).$$
(5)

Attach an asterisk superscript to the solution values of (5) and characterize the social optimum by

$$H'\left(\sum_{\Omega} x_j^*\right) = \lambda_z^*, \ B'_i(y_i^*) = C'_i(x_i^*) + H'\left(\sum_{\Omega} x_j^*\right) = \lambda_f^* \quad \forall i \in \Omega,$$
(6a)

$$z_i^{s*} = \xi_i^* - \sigma_i^* = \xi_i^* - x_i^* \quad \forall i \in N.$$
 (6b)

³Note that following Harstad (2012) we do not require a uniform deposit price.

As expected, (6a) implies

$$B'_{i}(y^{*}_{i}) = B'_{j}(y^{*}_{j}) \text{ and } C'_{i}(x^{*}_{i}) = C'_{j}(x^{*}_{j}) \quad \forall i, j \in \Omega.$$
 (6c)

It is easy to see that the equations (6c) also result from the standard solution of the social planner that we obtain when solving the Lagrangean (5) after setting $z_i^s = 0$ and $\xi_i = x_i$ for all $i \in N$.

After having characterized the social planner's solution we turn to decentralize the social optimum. The standard procedure considers perfectly competitive markets for fuel (price = p), wheat (price = 1), and deposits (price = p_z) and determines an equilibrium of that market economy by setting $p = p^* = \lambda^*$ and $p_z = p_z^* = \lambda_z^*$. We need to deviate slightly form that procedure, because the definition of our deposit market allows for deposit deals at different prices.

Proposition 1. Consider an economy (1) - (4) with perfectly competitive international markets for wheat and fuel and with the deposit preservation market as specified above. If the coalition buys the deposits $\bigcup_{j \in N} \left[x_j^*, \xi_j^* \right]_{C'_j}$ defined in (6) at prices that are beneficial for both trading partners and if we set $p^* = \lambda^*$, all markets clear, and the equilibrium of the market economy is efficient.

The message of Proposition 1 is that if the climate damage is the only distortion in the absence of deposit trading, the introduction of deposit trading for the purpose of preservation internalizes the climate damage and thus renders efficient the equilibrium of that market economy. In our model, the coalition's deposit purchases are a climate policy that internalizes the climate damage according to the beneficiary-pays principle.⁴

3 Buy deposits for preservation and manipulate the terms of trade

We now modify the market economy of the last section by assuming, as do Hoel (1994) and Harstad (2012), that the coalition exerts market power on the fuel market by influencing the terms of international fuel trade, i.e. the fuel price, through the strategic choice of its fuel supply and demand. The analysis of the coalition's strategic action on the fuel market requires setting up a game model with three stages. At stage 1, the deposit market clears. The coalition determines its fuel supply and demand at stage 2, and at stage 3, the fuel

⁴Note, however, that this policy would not achieve efficiency, if the countries outside the coalition would also suffer from climate damage.

market equilibrates. In the present section, we analyze and solve that three-stage game applying our concept of the deposit market.⁵ We follow the standard procedure of solving the game via backward induction.

Stage 3. At stage 3, M has already chosen its fuel supply and demand, x_M and y_M . The representative consumer of country $i \in N$ determines its fuel demand by maximizing with respect to y_i

$$B_i(y_i) - K_i(x_i, p_a, \pi_z) - p(y_i - x_i) + R_i(p_a, \pi_z) \quad \forall i \in N.$$

 p_a is the fuel price anticipated at stage 1; p is the fuel price prevailing at stage 3; π_z is the marginal climate damage determined at stage 1;⁶ K_i is country *i*'s extraction cost function after the deposit sales at the first stage; and $R_i(p_a, \pi_z)$ is *i*'s revenue from selling deposits at stage 1. The first-order condition readily yields

$$B'_{i}(y_{i}) = p \quad \text{and hence} \quad y_{i} = B_{i}^{-1}(p) =: D_{i}(p) \quad \forall i \in N,$$

$$(7)$$

where B_i^{-1} is the inverse of the marginal benefit function B'_i . Next, consider the fuel supply of country $i \in N$. At stage 3, *i* recalls that it sold at stage 1 the deposits $[\sigma_i(p_a, \pi_z), \xi_i(p_a)]_{C'_i}$, where

$$\xi_i = \xi_i(p_a) = C_i^{\prime - 1}(p_a), \quad \sigma_i = \sigma_i(p_a, \pi_z) := C_i^{\prime - 1}(p_a - \pi_z)$$
(8)

and where $C_i^{\prime -1}$ is the inverse of the marginal cost function C_i^{\prime} . The deposit sale at stage 1 changed *i*'s endowment of deposits such that *i*'s initial marginal cost function C_i^{\prime} turned into the marginal cost function K_i^{\prime} defined by⁷

$$K'_i(x_i, p_a, \pi_z) := \begin{cases} C'_i(x_i) & \text{for } x_i \le \sigma_i, \\ C'_i(\xi_i) - C'_i(\sigma_i) + C'_i(x_i) & \text{for } x_i \ge \sigma_i, \end{cases} \quad \forall i \in N.$$

$$(9)$$

Figure 1 illustrates the marginal cost functions C'_i and K'_i (Figure 1a) and the total cost functions C_i and K_i (Figure 1b). The straight line 0D in Figure 1a is the graph of C'_i . After having sold the deposits $[\sigma_i, \xi_i]_{C'_i}$ at stage 1, country *i*'s marginal cost function K'_i , is represented by the line 0BEF. We derive that line from 0D by shifting the line segment CDto the left by the amount $\xi_i - \sigma_i$ such that CD becomes EF. Thus, country *i*'s endowment

⁵The structure of the three-stage game is the same as in Harstad (2012), but Harstad's concept of deposit market differs from ours. We discuss the consequences of that difference in Section 4 below.

⁶For details of the role and determination of π_z see Lemma 1.

⁷To avoid clutter, we write σ_i , ξ_i etc. for the terms $\sigma_i(p_a, \pi_z)$, $\xi_i(p_a)$ etc. unless it is useful to emphasize their dependence on the variables which were determined at earlier stages of the game.

⁹The line 0BEF in Figure 1a is constructed as in Harstad's (2012) Figure 1.



Figure 1: Marginal and total cost curves of country $i \in N$ before and after deposit trading $[\sigma_i, \xi_i]_{C'_i}$ at stage 1⁹

of deposits changed from 0ABCD to 0ABEF. The function K'_i is discontinuous at $x_i = \sigma_i$, as reflected in the gap BE of the graph 0BEF. In Figure 1b, 0BCD is the graph of the cost function C_i . After the deposit sale at stage 1, the curve 0BF represents country *i*'s new cost function K_i . The curve segment BF of K_i results from moving the curve segment CD from its base point C to the new base point B. The gap BE of the graph of K'_i in Figure 1a translates into a kink of the cost curve 0BF at $x_i = \sigma_i$ (= at point B) in Figure 1b. Figure 1b illustrates that if σ_i is approached from above, the marginal extraction cost is $K'_i(\sigma_i) = \tan \alpha = p_a$, and it is $K'_i(\xi_i) = \tan \beta = p_a - \pi_z < p_a$, if σ_i is approached from below.

The Appendix A2 shows that maximizing with respect to x_i the welfare $U_i = B_i(y_i) - K_i(x_i, p_a, \pi_z) - p(y_i - x_i) + R_i(p_a, \pi_z)$ yields the fuel supply function S_i with the properties

$$S_{i}(p, p_{a}, \pi_{z}) = \begin{cases} C_{i}^{'-1}(p) & \text{for } p \leq p_{a} - \pi_{z}, \\ \sigma_{i} & \text{for } p \in [p_{a} - \pi_{z}, p_{a}], \\ C_{i}^{'-1}[p - C_{i}^{'}(\xi_{i}) + C_{i}^{'}(\sigma_{i})] & \text{for } p \geq p_{a}, \end{cases} \quad (10)$$

In view of (7) and (10), the fuel market clearing condition is

$$x_M + \sum_N S_j(p, p_a, \pi_z) = y_M + \sum_N D_j(p) \,. \tag{11}$$

Equation (11) yields the equilibrium fuel price as a function of x_M , y_M , p_a and π_z , all of which have been determined earlier in the game. We denote that price function as

$$p = P(x_M, y_M, p_a, \pi_z).$$
 (12)

Stage 2. M's deposit purchases at stage 1 does not change its initial extraction cost function C'_M since the coalition only buys deposits for preservation. M chooses its fuel supply and demand by maximizing with respect to x_M and y_M its welfare

$$U_M(x_M, y_M, p_a, \pi_z) = B_M(y_M) - C_M(x_M) - p(y_M - x_M) -H\left[x_M + \sum_N S_j(p, p_a, \pi_z)\right] - R_M(p_a, \pi_z)$$
(13)

subject to (12). The first-order conditions

$$\frac{\partial U_M}{\partial y_M} = B'_M - p - \left(y_M - x_M + H' \sum_N S'_j\right) \frac{\partial P}{\partial y_M} = 0, \tag{14}$$

$$\frac{\partial U_M}{\partial x_M} = -C'_M + p - H' - \left(y_M - x_M + H' \sum_N S'_j\right) \frac{\partial P}{\partial x_M} = 0$$
(15)

coincide with Harstad's (2012) equations (6) and (7). Implicitly, these equations determine M's optimal choice of x_M and y_M as functions of p_a and π_z . We denote the solution of (14) and (15) by

$$x_M = X_M(p_a, \pi_z) \quad \text{and} \quad y_M = Y_M(p_a, \pi_z).$$
(16)

While at stage 3 the equilibrium fuel price depends on x_M , y_M , p_a and π_z , as shown in (12), it now depends on p_a and π_z only,

$$p = P[X_M(p_a, \pi_z), Y_M(p_a, \pi_z), p_a, \pi_z].$$
(17)

Stage 1. We have to determine those deposits $[\underline{x}_i, \overline{x}_i]_{C'_i}$ which each country $i \in N$ sells to the coalition with mutual gains from trade and which clear the deposit market. M aims at buying deposits the preservation of which fully reduces the climate damage. Hence, M only buys some of those deposits, which are profitable, that is, which country i would have extracted in the absence of deposit trading. Given the anticipated fuel price p_a , the interval with profitable deposits is $[0, \xi_i]_{C'_i}$, where $\xi_i = \xi_i(p_a) := C'^{-1}(p_a).^{10}$ Hence M's purchase and subsequent preservation of $[\underline{x}_i, \overline{x}_i]_{C'_i}$ secures full climate damage reduction only if $[\underline{x}_i, \overline{x}_i]_{C'_i} \subset [0, \xi_i]_{C'_i}.^{11}$ Moreover, the inequality $\overline{x}_i \leq \xi_i$ must hold as equality, because there is no other interval of deposits in $[0, \xi_i]_{C'_i}$ of the same size as $[\underline{x}_i, \xi_i]_{C'_i}$, whose economic value is smaller than that of $[\underline{x}_i, \xi_i]_{C'_i}.^{12}$ These considerations make M's purchase (and country i's

¹⁰See equation (8) above.

¹¹Here we presuppose w.l.o.g. that the price p_a is so low that the aggregate fuel supply $X_M(p_a, \pi_z) + \sum_N \xi_j(p_a)$ leads to excessive climate damage.

¹²The economic value of the deposits in the interval $[\underline{x}_i, \xi_i(p_a)]_{C'_i}$ is the profit $p(\xi_i(p_a) - \underline{x}_i) - C_i(\xi_i(p_a)) + C_i(\underline{x}_i)$ that would accrue to country *i* if it would extract and sell the fuel from these deposits instead of selling the unexploited deposits to M.

sale) of deposits equivalent to the choice of \underline{x}_i . To put it differently, we have to determine $z_i^s = \xi_i - \underline{x}_i$, the 'number' of deposits M buys in the interval $[\underline{x}_i, \xi_i]_{C'_i}$. In the Appendix A2 we prove

Lemma 1. (Equilibrium of the deposit market)

Suppose p_a , π_z , $\xi_i(p_a)$, $\sigma_i(p_a, \pi_z)$ from (8) and $x_M = X_M(p_a, \pi_z)$ from (16) are given and define

$$\hat{\sigma}_i(p_a) := \sigma_i(p_a, \pi_z(p_a)) = C_i^{\prime - 1}(p_a - \pi_z(p_a)),$$
(18)

where $\pi_z = \pi_z(p_a)$, if and only if

$$\pi_z = H' \left[X_M(p_a, \pi_z) + \sum_N \sigma_j(p_a, \pi_z) \right].$$
(19)

Contingent on the anticipated fuel price p_a , the deposit market is in equilibrium, if and only if the coalition purchases the deposits $\{[\hat{\sigma}_i(p_a), \xi_i(p_a)]_{C'_i}\}_{i \in N}$.

Lemma 1 establishes that the deposit market is cleared,¹³ if $\underline{x}_i = \hat{\sigma}_i(p_a)$ and therefore $z_i^s = \xi_i(p_a) - \hat{\sigma}_i(p_a)$ is satisfied for all $i \in N$. Equation (19) provides the reason for our interpretation of π_z as the shadow price of climate damage and it implicitly specifies the shadow price π_z , which we treated as given up to now, as a function of p_a .¹⁴ The specification of π_z by $\pi_z(p_a)$ in (18) not only yields (19), but also determines the equilibrium values

$$x_M = X_M(p_a, \pi_z(p_a)) := \hat{X}_M(p_a), \quad y_M = Y_M(p_a, \pi_z(p_a)) := \hat{Y}_M(p_a)$$

and $p = \hat{P}(p_a) := P\left[X_M(p_a, \pi_z(p_a)), Y_M(p_a, \pi_z(p_a)), p_a, \pi_z(p_a)\right].$ (20)

Consistency requires equality of the fuel price p_a that is anticipated at stage 1 and the fuel price p that clears the fuel market at stage 3. Assuming that the price function \hat{P} from (20) possesses a fixed point, we set $p = p_a$. That completes the characterization of the solution to the three-stage game.

It remains to examine the efficiency properties of the outcome. According to (6), efficiency requires $B'_i = B'_j$ for all $i, j \in \Omega$ and $B'_i - K'_i - H' = 0$ for all $i \in N$ and $B'_M - C'_M - H' = 0$. These equations are satisfied for all $i \in N$ due to $p = p_a$, (7), (8) and

¹³The countries in group N are price takers on the fuel market. They leave the decision about which and how many deposits to buy to the coalition, but they do not sell deposits unless the sales price exceeds the profits they could have made from exploiting instead of selling their deposits (profits foregone). If a deal enhances the joint welfare of the trading partners, an agreement about their shares of the surplus is always reached.

¹⁴Obviously, $\pi_z = \pi_z(p_a)$ is the equilibrium deposit price of a perfectly competitive deposit market (contingent on the anticipated fuel price p_a).

(19). In view of (14) and (15), the equation $B'_M - C'_M - H' = 0$ is also satisfied, if and only if

$$\left(y_M - x_M + H' \sum_N S'_j\right) \frac{\partial P}{\partial y_M} = 0.$$
(21)

This equation is satisfied, in turn, if and only if either $\frac{\partial P}{\partial y_M} = 0$ or the bracketed term is zero. Since we consider here a coalition that acts strategically on the fuel market, we have $\frac{\partial P}{\partial y_M} = -\frac{\partial P}{\partial x_M} > 0$ such that efficiency requires

$$y_M - x_M + H' \sum_N S'_j = 0.$$
 (22)

Before we investigate the conditions under which (22) is satisfied, we briefly consider the special case of the game, in which the coalition is a price taker on the fuel market along with all other countries. Technically speaking, we drop the second stage of the game by simply setting $\frac{\partial P}{\partial y_M} = -\frac{\partial P}{\partial x_M} = 0$ in (14) and (15) to obtain the efficiency condition $B'_M - C'_M - H' = 0$. We conclude that the outcome is efficient if the coalition acts as a price taker on the fuel market in the game in which the competitive fuel market clears after the deposit market. That conclusion is in line with our result in Proposition 1.

Returning to the case of strategic action on the fuel market, we characterize the equilibrium of the three-stage game as follows.

Proposition 2. Consider the world economies (1) - (4) with a deposit market, with a perfectly competitive wheat market, and with a fuel market, on which the coalition acts strategically while all other countries are price takers. The equilibrium of the three-stage game satisfies:

- (i) The deposit market equilibrium internalizes the climate damage. The coalition's equilibrium deposit purchases are $\bigcup_{j \in N} \left[\hat{\sigma}_j(p), \hat{\xi}_j(p) \right]_{C'_i}$.
- (ii) The coalition's strategic action on the fuel market is distortionary, if and only if^{15}

either
$$\langle y_M^* - x_M^* > 0 \rangle$$
 or $\langle y_M^* - x_M^* < 0$ and $y_M^* - x_M^* + H' \sum_N \underbrace{S'_j}_{+} < 0 \rangle$ (23)

¹⁵We conducted a two-country numerical example with the help of the computer programme Mathematica. For the functions $B_j(y_j) = 9y_j - \frac{y_j^2}{2}$ for $j = M, N, C_M(x_M) = x_M^2, C_N(x_N) = \frac{x_N^2}{2}, H(x_M + x_N) = x_M + x_N$ the efficient allocation is characterized by fuel consumption, extraction and welfare levels $y_M^* = 3.429 > x_N^* = 2.286, u_M^* = 6.031$ and $u_N^* = 21.398$. Strategic action on the fuel market (S' > 0) yields $\tilde{u}_M = 6.375$ and $\tilde{u}_N = 20.813$. We also have determined the laissez-faire scenario without buying any deposits which is characterized by $B'_M = B'_N, B'_M = C'_M + H', B'_N = C'_N, y_M + y_N = x_M + x_N$. The associated welfare levels are $u_M^o = 6.204$ and $u_N^o = 21.398$. Comparing the three scenarios we obtain the ranking $\tilde{u}_M > u_M^o > u_M^*$, $u_N^* > u_N^o > \tilde{u}_N$ and $u_M^* + u_N^* > \tilde{u}_M + \tilde{u}_N > u_M^o + u_N^o$. Further details are available from the authors upon request.

where the letters marked by an asterisk denote the values of variables and functions in an efficient equilibrium of the market economy in Proposition 1.

In the absence of deposit trading non-coalition countries extract fuel without accounting that their fuel extraction harms the coalition. In other words the coalition suffers a noninternalized climate damage distortion. With deposit trading the coalition purchases deposits for preservation and internalizes the negative externalities generated by non-coalition countries (see Proposition 2(i)).

Proposition 2(ii) answers the question whether and when it is in the coalition's interest to act strategically on the fuel market. To get an intuition for (23) we investigate how the coalition's welfare changes when fuel caps x_M or y_M are marginally increased, formally

$$dU_{M} = \frac{\partial U_{M}^{*}}{\partial q_{M}} dq_{M} := -\left(y_{M}^{*} - x_{M}^{*} + H^{'*} \sum_{N} S_{j}^{'*}\right) P_{q_{M}}^{*} dq_{M}$$
$$= \underbrace{-\left(y_{M}^{*} - x_{M}^{*}\right) P_{q_{M}}^{*} dq_{M}}_{dw_{F}} \underbrace{-\left(H^{'*} \sum_{N} S_{j}^{'*}\right) P_{q_{M}}^{*} dq_{M}}_{dw_{H}}$$
(24)

The term dw_F in (24) represents the coalition's welfare change due to the change of fuel exports or imports which is induced through its variation of the fuel supply or fuel demand $(dq_M \neq 0)$. dw_F is the terms of trade effect of strategic action. The term dw_H captures the welfare change due to the change in climate damage which is induced by the coalition through its variation of the fuel supply or fuel demand $(dq_M \neq 0)$. dw_H is the climate damage effect of strategic action.

We explain the welfare changes exemplarily for a fuel importing coalition $(y_M^* > x_M^*)$. If the coalition refrains from strategic action, the fuel supply and the marginal extraction costs of country $i \in N$ are characterized by point E in Figure 1a. To figure out whether strategic action pays the coalition marginally increases¹⁶ x_M . The consequence is a reduction of the fuel price $(P_{x_M}^* < 0)$ which yields a positive terms-of-trade effect of strategic action $(-(y_M^* - x_M^*)P_{x_M}^* > 0)$. Reducing the fuel price (the movement from point E in the direction of point B in Figure 1a) does not change the fuel supply of country $i \in N$, formally $S'_i = 0$ due to $p \in [p_a - \pi_z, p_a]$ in (10), and hence the climate damage effect of strategic action vanishes. To sum up, increasing x_M enhances the coalition's welfare and strategic action pays. For sake of completeness, we also investigate the welfare effects of reducing the fuel cap x_M . Decreasing x_M raises the fuel price and the terms-of-trade effect of strategic action is negative. Country $i \in N$ increases its fuel supply $(S'_i > 0)$ upon the fuel price hike (the movement from point E in Figure 1a in the direction of point F implies $p > p_a$ in (10)) and

¹⁶The same arguments also hold for reducing y_M .

the climate damage effect $-H' \sum_N S'_j P^*_{x_M} dx_M$ is also negative. Reducing x_M diminishes the coalition's welfare. However, the relevant result is that the coalition gains welfare through increasing x_M . To conclude, if $y^*_M > x^*_M$ the coalition's strategic action is distortionary, because there is a strategic action that has a positive terms-of-trade effect ($dw_F > 0$) and a zero climate damage effect ($dw_H = 0$).

A detailed analysis of all possible case for a non-importing coalition $y_M^* \leq x_M^*$ can be found in the Appendix A3. The results are as follows: If the coalition neither imports nor exports fuel in the social optimum $(y_M^* = x_M^*)$, its strategic action is non-distortionary, because all feasible strategic actions have a zero terms-of-trade effect $(dw_F = 0)$ and a non-positive climate damage effect $(dw_H \leq 0)$. If the coalition exports fuel in the social optimum $(y_M^* < x_M^*)$, its strategic action is distortionary, if and only if the positive termsof-trade effect of reducing x_M and/or increasing y_M $(dw_F > 0)$ overcompensates the negative climate-damage effect of reducing x_M and/or increasing y_M $(dw_H < 0)$.

4 An assessment of Harstad's (2012) Theorem 1

The game model of the last section is the same as Harstad's (2012) game model except that Harstad's concept of deposit market differs from the concept we applied. Specifically, Harstad's deposit market allows for bilateral deposit trades at prices that may differ between each pair of traders, as does our concept of deposit market. However, purchases on his deposit market are not restricted to the purpose of preservation. The market "... clears when there exists no pair of countries that would both strictly benefit from trading some of their deposits at some price" (Harstad 2012, p. 92).

According to Harstad, the difference in outcome of the three-stage game with our and his deposit market is significant. Expressed in our words, his Theorem 1 states that in any equilibrium of the three-stage game his deposit market accomplishes two things. It internalizes the climate damage, as does our deposit market, but it also prevents allocative distortions through the coalition's strategic action in *all economies*, whereas our deposit market prevents such distortions *only in the subset of economies satisfying (21)*.

Harstad's Theorem 1 must rely on purchases of deposits for exploitation made in addition to the transactions $(z_i^{s*})_{i\in N}$, because the transactions $(z_i^{s*})_{i\in N}$ are necessary in the equilibrium of the market economy of Proposition 1 as well as in the first-best outcome of Harstad's three-stage game to secure the internalization of climate damage. Harstad adopts the following strategy to prove that the coalition's strategic action is non-distortionary in all economies. He aims to show that there exist suitable transactions on his deposit market

in addition to the transactions $(z_i^{s*})_{i\in\mathbb{N}}$ that close the gap $y_M^* - x_M^* \neq 0$ in all economies satisfying (22). His Lemma 2 claims that $x_i = y_i$ for all $i \in \Omega$ holds whenever his deposit market is in equilibrium.

Eichner and Pethig (2016) prove that it is impossible to attain $x_i = y_i$ for all $i \in \Omega$ through deposit market transactions economies characterized by $y_M^* - x_M^* \neq 0$. The economic argument is simple. Further trade of deposits for the purpose of extraction changes the property rights of these deposits but not the location of extraction and hence does not change any fuel exports or imports. For a formal proof of this argument we refer to Eichner and Pethig (2016, Result 4). We summarize these results in

Proposition 3. Proposition 2 is still satisfied if we replace our by Harstad's concept of deposit market.

5 Concluding remarks

The paper has analyze the performance of deposit trading to reduce carbon emissions efficiently by unilateral action in the model of Harstad (2012). The efficiency result we attained in the case that all agents are price-takers both on the fuel market and on the deposit market is an interesting benchmark. Through the purchase of deposits for preservation the coalition reduces the non-coalition countries' – and its own – fuel supply by an appropriate amount and thus fully internalizes the negative externalities generated by non-coalition countries.

In case of strategic action on the fuel market, the present paper corrects the flaw in the proof of Harstad's Theorem 1 and shows that strategic action is distortionary if the coalition imports fuel and non-distortionary if the coalition neither exports nor imports fuel. A subglobal climate coalition likely does not consist of the big fuel exporting countries, i.e. it likely is a fuel importer. Under this condition, the prediction of our model is that the coalition's strategic action is distortionary. Consequently, internalizing the climate externality is less costly for the coalition than it would be if its strategic action would be non-distortionary. Our results obfuscate the performance of deposit trading. To judge whether deposit trading is indeed a valuable unilateral climate policy option a cost-benefit analysis with realistic calibration is an important item on the agenda of future research.

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Appendix

A1: Extraction costs and endowment of deposits

For analytical convenience, we assume that each deposit contains a single (small) unit of fuel. The ordering of country *i*'s deposits according to costs results in a step function, say $C_i : \mathbb{N} \to \mathbb{R}_+$, such that $C_i(x_i)$ is the cost of extracting the unit of fuel from the x_i^{th} deposit¹⁷ and $C_i(x_i) \leq C_i(x_i+1)$ for all $x_i \in \mathbb{N}$ (where we exclude the equality sign for analytical relief). Finally, we replace the step function $C_i(x_i)$ by its real-number approximation, denoted $C'_i :$ $\mathbb{R}_+ \to \mathbb{R}_+$. With a slight abuse of notation we refer to $C'_i(x_i)$ as the extraction cost of country *i*'s x_i^{th} deposit - which is the deposit with the x_i^{th} lowest extraction cost.¹⁸

A2: Proofs

Proof of Proposition 1:

If the coalition buys the deposits $\bigcup_{j \in N} \left[x_j^*, \xi_j^* \right]_{C'_j}$ at prices that are beneficial for both trading partners, the deposit market is in equilibrium, because the climate damage is internalized and there is no other distortion in the market economy. In order to show that the coalition is able to buy the deposits $\bigcup_{j \in N} \left[x_j^*, \xi_j^* \right]_{C'_j}$ at mutually beneficial prices, observe that the perfectly competitive deposit market is a special case of the deposit market. The competitive deposit market clears at the equilibrium price $p_z^* = \lambda_z^*$ (with λ_z^* from (6a)) and the price per deal, $p_z^* z_i^s$, all $i \in N$ is strictly beneficial for country i and the coalition. Hence, mutually beneficial deals can also be made at prices that deviate from $p_z^* z_i^s$.

Derivation of (10):

Maximizing $u_i = B_i(y_i) - K_i(x_i, p_a, \pi_z) - p(y_i - x_i) + R_i(p_a, \pi_z)$ with respect to x_i yields

$$K_i'(x_i, p_a, p_z) = p.$$

Suppose that $x_i \leq \sigma_i(p_a, \pi_z) = C_i^{\prime - 1}(p_a - \pi_z)$, then we obtain

$$C'_i(x_i) = p \quad \Longleftrightarrow \quad x_i = C'^{-1}_i(p)$$

¹⁷We need not care about an upper bound of the domain of the function C_i because deposits with extremely high extraction costs will never be exploited under realistic conditions.

¹⁸Hence the primary concept is the marginal cost function C'_i rather than the total cost function C_i . Differently put, in the deposit-trading perspective we derive C_i from C'_i rather than C'_i from C_i .

for $p \leq p_a - \pi_z$. Suppose that $x_i \geq \sigma_i(p_a, \pi_z) = C_i^{\prime - 1}(p_a - \pi_z)$, then we get

$$C'_{i}(\xi_{i}) - C'_{i}(\sigma_{i}) + C'_{i}(x_{i}) = p \iff x_{i} = C'^{-1}_{i}[p - C'_{i}(\xi_{i}) + C'_{i}(\sigma_{i})]$$

for $p \ge p_a$ (due to $C'_i(\sigma_i) - C'_i(\xi_i) = -\pi_z$).

Proof of Lemma 1:

Solve the Lagrangean

$$\mathcal{L}(z_{1}^{s}, \dots, z_{N}^{s}, z_{M}^{d}, \lambda_{z}) = \sum_{N} \left[B_{j}(y_{j}) - C_{j}(\xi_{i}(p_{a}) - z_{j}^{s}) - p_{a}(y_{j} - \xi_{j}(p_{a}) + z_{j}^{s}) \right] + B_{M}(y_{M}) - C_{M}(X_{M}(p_{a}, \pi_{z})) - p_{a}(y_{M} - X_{M}(p_{a}, \pi_{z})) - H \left[X_{M}(p_{a}, \pi_{z}) + \sum_{N} \xi_{j}(p_{a}) - z_{M}^{d} \right] - \pi_{z} \left(z_{M}^{d} - \sum_{N} z_{j}^{s} \right)$$
(A1)

with respect to $z_1^s, \ldots, z_N^s, z_M^d$ and λ_z for predetermined p_a, π_z, y_M and $y_i \forall i \in \Omega$. The first-order conditions yield

$$C'_{i}(x_{i}) = p_{a} - \lambda_{z} \quad \text{and hence} \quad x_{i} = \sigma_{i}(p_{a}, \lambda_{z}) := C'^{-1}_{i}(p_{a} - \lambda_{z}) \quad \forall i \in N \quad (A2)$$

and
$$\lambda_z = H' \left[X_M(p_a, \pi_z) + \sum_N \sigma_j(p_a, \lambda_z) \right].$$
 (A3)

(A3) implicitly characterizes λ_z as a function of p_a and π_z , and this function possesses a fixed point, denoted $\lambda_z = \pi_z = \pi_z(p_a)$, for all p_a in the relevant sub-domain. Under consideration of $\lambda_z = \pi_z = \pi_z(p_a)$, we determine the solution of (A1) as

$$z_i^s = Z_i^s(p_a) := \xi_i(p_a) - \hat{\sigma}_i(p_a) \quad \forall i \in N,$$
(A4)

where $\hat{\sigma}_i(p_a) := \sigma_i(p_a, \pi_z(p_a)).$

Proof of Proposition 2:

The partial derivatives of (13) with respect to y_M and x_M evaluated at the equilibrium values referred to in Proposition 2(ii) read

$$\frac{\partial U_M}{\partial y_M}\Big|_{y_M^*} = \underbrace{B_M^{'*} - p^*}_{=0} - \left(y_M^* - x_M^* + H^{'*} \sum_N S_j^{'*}\right) \cdot \frac{\partial P}{\partial y_M}\Big|_{y_M^*},\tag{A5}$$

where $\frac{\partial P}{\partial y_M} > 0$ and for all $i \in N$

$$S_{i}^{\prime *} = \frac{\partial S_{i}}{\partial p}\Big|_{p^{*}=p_{a}^{*}} = \begin{cases} S_{i+}^{\prime *} > 0, & \text{if } dp = \frac{\partial P}{\partial y_{M}} \underbrace{dy_{M}}_{(+)} > 0, \\ S_{i-}^{\prime *} = 0, & \text{if } dp = \frac{\partial P}{\partial y_{M}} \underbrace{dy_{M}}_{(-)} < 0, \end{cases}$$
(A6)

and

$$\frac{\partial U_M}{\partial x_M}\Big|_{x_M^*} = \underbrace{-C_M^{\prime *} + p^* - H^{\prime *}}_{=0} - \left(y_M^* - x_M^* + H^{\prime *} \sum_N S_j^{\prime *}\right) \cdot \frac{\partial P}{\partial x_M}\Big|_{x_M^*},\tag{A7}$$

where $\frac{\partial P}{\partial x_M} < 0$ and for all $i \in N$

$$S_{i}^{'*} = \frac{\partial S_{i}}{\partial p}\Big|_{p^{*}=p_{a}^{*}} = \begin{cases} S_{i+}^{'*} > 0, & \text{if } dp = \frac{\partial P}{\partial x_{M}} \underbrace{\mathrm{d}x_{M}}_{(-)} > 0, \\ S_{i-}^{'*} = 0, & \text{if } dp = \frac{\partial P}{\partial x_{M}} \underbrace{\mathrm{d}x_{M}}_{(+)} < 0. \end{cases}$$
(A8)

Consider first the marginal welfare (A5) and distinguish the following four cases.

- (a) Suppose that $y_M^* x_M^* > 0$. If $dy_M > 0$, (A6) yields $S_i^{\prime *} = S_{i+}^{\prime *} > 0$ and $\frac{\partial U_M}{\partial y_M}\Big|_{y_M^*} < 0$ follows from (A5). Hence $dU_M = \frac{\partial U_M}{\partial y_M}\Big|_{y_M^*} \cdot dy_M < 0$. If $dy_M < 0$, (A6) yields $S_i^{\prime *} = S_{i-}^{\prime *} = 0$ and $\frac{\partial U_M}{\partial y_M}\Big|_{y_M^*} < 0$ follows from (A5). Hence $dU_M = \frac{\partial U_M}{\partial y_M}\Big|_{y_M^*} \cdot dy_M > 0$.
- (b) Suppose that $y_M^* x_M^* < 0$ and $y_M^* x_M^* + H'^* \sum_N S_{j+}'^* < 0$. If $dy_M > 0$, (A6) yields $S_i'^* = S_{i+}'^*$ and $\frac{\partial U_M}{\partial y_M}\Big|_{y_M^*} > 0$ follows from (A5). Hence $dU_M = \frac{\partial U_M}{\partial y_M}\Big|_{y_M^*} \cdot dy_M > 0$. If $dy_M < 0$, (A6) yields $S_i'^* = S_{i-}'^* = 0$ and $\frac{\partial U_M}{\partial y_M}\Big|_{y_M^*} > 0$ follows from (A5). Hence $dU_M = \frac{\partial U_M}{\partial y_M}\Big|_{y_M^*} \cdot dy_M < 0$.
- (c) Suppose that $y_M^* x_M^* < 0$ and $y_M^* x_M^* + H'^* \sum_N S_{j+}'^* \ge 0$. If $dy_M > 0$, (A6) yields $S_i'^* = S_{i+}'^* > 0$ and $\frac{\partial U_M}{\partial y_M}\Big|_{y_M^*} \le 0$ follows from (A5). Hence $dU_M = \frac{\partial U_M}{\partial y_M}\Big|_{y_M^*} \cdot dy_M \le 0$. If $dy_M < 0$, (A6) yields $S_i'^* = S_{i-}'^* = 0$ and $\frac{\partial U_M}{\partial y_M}\Big|_{y_M^*} > 0$ follows from (A5). Hence $dU_M = \frac{\partial U_M}{\partial y_M}\Big|_{y_M^*} \cdot dy_M < 0$.
- (d) Suppose $y_M^* x_M^* = 0$. If $dy_M > 0$, (A6) yields $S_i^{\prime *} = S_{i+}^{\prime *}$ and $\frac{\partial U_M}{\partial y_M}\Big|_{y_M^*} < 0$ follows from (A5). Hence $dU_M = \frac{\partial U_M}{\partial y_M}\Big|_{y_M^*} \cdot dy_M < 0$. If $dy_M < 0$, (A6) yields $S_i^{\prime *} = S_{i-}^{\prime *}$ and $\frac{\partial U_M}{\partial y_M}\Big|_{y_M^*} = 0$ follows from (A5). Hence $dU_M = \frac{\partial U_M}{\partial y_M}\Big|_{y_M^*} \cdot dy_M = 0$.

Next we investigate whether variations of x_M enhance welfare under the conditions specified in the cases (c) and (d).

- (e) Suppose $y_M^* x_M^* < 0$ and $y_M^* x_M^* + H'^* \sum_N S'_{j+} \ge 0$ (as in (c)). If $dx_M > 0$, (A8) yields $S'_i = S'_{i-} = 0$ and $\frac{\partial U_M}{\partial x_M}\Big|_{x_M^*} < 0$ follows from (A7). Hence $dU_M = \frac{\partial U_M}{\partial x_M}\Big|_{x_M^*} \cdot dx_M < 0$. If $dx_M < 0$, (A8) yields $S'_i = S'_{i+} > 0$ and $\frac{\partial U_M}{\partial x_M}\Big|_{x_M^*} \ge 0$ follows from (A7). Hence $dU_M = \frac{\partial U_M}{\partial x_M}\Big|_{x_M^*} \cdot dx_M \le 0$.
- (f) Suppose $y_M^* x_M^* = 0$ (as in (d)). If $dx_M > 0$, (A8) yields $S_i^{'*} = S_{i-}^{'*}$ and $\frac{\partial U_M}{\partial x_M}\Big|_{x_M^*} = 0$ follows from (A7). Hence $dU_M = \frac{\partial U_M}{\partial x_M}\Big|_{x_M^*} \cdot dx_M = 0$. If $dx_M < 0$, (A8) yields $S_i^{'*} = S_{i+}^{'*}$ and $\frac{\partial U_M}{\partial x_M}\Big|_{x_M^*} > 0$ follows from (A7). Hence $dU_M = \frac{\partial U_M}{\partial x_M}\Big|_{x_M^*} \cdot dx_M < 0$.

In view of (a) - (f), the equilibrium of the three-stage game with strategic action on the fuel market is inefficient, if and only if the equilibrium of the market economy in Proposition 2 satisfies (23).

A3: An analysis of (24)

(i)
$$dx_M > 0 \Longrightarrow dp = P_{x_M}^* dx_M < 0 \Longrightarrow S_j^{\prime *} = 0$$

 $\Longrightarrow dU_M = \frac{\partial U_M^*}{\partial x_M} dx_M = \begin{cases} -(y_M^* - x_M^*) P_{x_M}^* dx_M \ge 0, & \text{if } y_M^* \ge x_M^* \\ -(y_M^* - x_M^*) P_{x_M}^* dx_M < 0, & \text{if } y_M^* < x_M^* \end{cases}$

(ii)
$$dx_M < 0 \Longrightarrow dp = P_{x_M}^* dx_M > 0 \Longrightarrow S'_j > 0$$
$$\Longrightarrow dU_M = \frac{\partial U_M^*}{\partial x_M} dx_M = \left\{ \underbrace{\underbrace{-(y_M^* - x_M^*) P_{x_M}^* dx_M}_{(-,0)}}_{(-,0)} \underbrace{-(y_M^* - x_M^*) P_{x_M}^* dx_M}_{(+)} \underbrace{-\underbrace{(H'\sum_N S'_j) P_{x_M}^* dx_M}_{(-)}}_{(-)} \underbrace{-\underbrace{(Y_M^* - x_M^*) P_{x_M}^* dx_M}_{(-)}}_{(-)} \underbrace{-\underbrace{(H'\sum_N S'_j) P_{x_M}^* dx_M}_{(-)}}_{(-)} \underbrace{-\underbrace{(Y_M^* - x_M^*) P_{x_M}^* dx_M}_{(+)}}_{(-)} \underbrace{-\underbrace{(H'\sum_N S'_j) P_{x_M}^* dx_M}_{(-)}}_{(-)} \underbrace{-\underbrace{(Y_M^* - x_M^*) P_{x_M}^* dx_M}_{(-)}}_{(-)} \underbrace{-\underbrace{(Y_M^* - x_M^*) P_{x_M}^* dx_M}_{(+)}}_{(-)} \underbrace{-\underbrace{(Y_M^* - x_M^*) P_{x_M}^* dx_M}_{(-)}}_{(-)} \underbrace{-\underbrace{(Y_M^* - x_M^*$$

(iii)
$$dy_M > 0 \Longrightarrow dp = P_{y_M}^* dy_M > 0 \Longrightarrow S'_j > 0$$

 $\Longrightarrow dU_M = \frac{\partial U_M^*}{\partial y_M} dy_M =$

$$\begin{pmatrix} \underbrace{-(y_M^* - x_M^*) P_{y_M}^* dy_M}_{(-)} \underbrace{-(H'\sum_N S'_j) P_{y_M}^* dy_M}_{(-)} < 0, & \text{if } y_M^* > x_M^* \\ \underbrace{-(H'\sum_N S'_j) P_{y_M}^* dy_M}_{(+)} \underbrace{-(H'\sum_N S'_j) P_{y_M}^* dy_M}_{(-)} < 0, & \text{if } y_M^* = x_M^* \\ \underbrace{-(y_M^* - x_M^*) P_{y_M}^* dy_M}_{(+)} \underbrace{-(H'\sum_N S'_j) P_{y_M}^* dy_M}_{(-)} \gtrless 0, & \text{if } y_M^* < x_M^* \\ \underbrace{-(y_M^* - x_M^*) P_{y_M}^* dy_M}_{(+)} \underbrace{-(H'\sum_N S'_j) P_{y_M}^* dy_M}_{(-)} \gtrless 0, & \text{if } y_M^* < x_M^* \\ \underbrace{-(y_M^* - x_M^*) P_{y_M}^* dy_M}_{(+)} \underbrace{-(H'\sum_N S'_j) P_{y_M}^* dy_M}_{(-)} \end{Bmatrix}$$

	$y_M^* > x_M^*$	$y_M^* = x_M^*$	$y_M^* < y_M^*$
$\mathrm{d}x_M > 0$	$\mathrm{d}w_F > 0, \mathrm{d}w_H = 0$	$\mathrm{d}w_F = \mathrm{d}w_H = 0$	$\mathrm{d}w_F < 0, \mathrm{d}w_H = 0$
$\mathrm{d}x_M < 0$	$\mathrm{d}w_F < 0, \mathrm{d}w_H < 0$	$\mathrm{d}w_F = 0, \mathrm{d}w_H < 0$	$\mathrm{d}w_F > 0, \mathrm{d}w_H < 0$
$\mathrm{d}y_M > 0$	$\mathrm{d}w_F < 0, \mathrm{d}w_H < 0$	$\mathrm{d}w_F = 0, \mathrm{d}w_H < 0$	$\mathrm{d}w_F > 0, \mathrm{d}w_H < 0$
$\mathrm{d}y_M < 0$	$\mathrm{d}w_F > 0, \mathrm{d}w_H = 0$	$\mathrm{d}w_F = \mathrm{d}w_H = 0$	$\mathrm{d}w_F < 0, \mathrm{d}w_H = 0$
$\mathrm{d}U_M$	$\mathrm{d}U_M > 0$	$\mathrm{d}U_M = 0$	$\mathrm{d}U_M \gtrless 0$

Table 1: Comparative statics of the fuel caps

(iv)
$$dy_M < 0 \Longrightarrow dp = P_{y_M}^* dy_M < 0 \Longrightarrow S'_j = 0$$

 $\Longrightarrow dU_M = \frac{\partial U_M^*}{\partial y_M} dy_M = \begin{cases} -(y_M^* - x_M^*) P_{y_M}^* dy_M \ge 0, & \text{if } y_M^* \ge x_M^* \\ -(y_M^* - x_M^*) P_{y_M}^* dy_M < 0, & \text{if } y_M^* < x_M^* \end{cases}$

We summarize the results (i)-(iv) in Table 1.