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Buy coal, cap gas! Markets for fossil fuel deposits when fuel emission intensities differ

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Abstract

Climate policies can target either the demand or the supply of fossil fuels. While demand-side policies have been analyzed in the literature and applied in policy-making, supply-side policies, e.g. deposit policies, are a promising option and a recent research focus. In this paper we study deposit markets for two fuels that differ in emission intensity. We find that, with strategic action on the deposit markets, deposit policies are inefficient due to price manipulations within and between both deposit markets. Regarding the political economy of deposit policies, they generate more welfare for all countries if applied to both fuels as opposed to one or none. Further, for perfectly segmented fuel markets, importing countries do not purchase deposits of a sufficiently clean fuel. If fuels are substitutes and strongly differ in emission intensity, countries do not buy deposits of a relatively clean fuel. Finally, deposit markets can induce countries selling deposits to choose a cleaner fuel mix.

Keywords: Fossil fuel, Climate policy, Deposit market, Carbon leakage

JEL: Q31, Q38

1 Introduction

The goal of limiting the increase in global average temperature below 2°C (or even 1.5°C), as targeted in the Paris Agreement, requires significant emission reductions (Pachauri et al., 2014). Policies to reduce emissions can target either the supply or the demand of fossil fuels, in short "fuel". Moreover, those policies can be directed at both fuel supply and demand simultaneously, as analyzed e.g. by Hoel (1994), Fæhn et al. (2017), and Hagem & Storrøsten (2019). Yet, policies in place and the majority of studies focus on the demand side only. If a country unilaterally imposes a demand-side policy, international fuel prices decrease, leading to more consumption in other countries. At the same time, energy- and export-intensive industries in countries with climate policies can be disadvantaged: exports in energy-intensive sectors decrease, while imports from countries without climate policies increase. This effect is called "carbon leakage" and has been extensively studied (e.g. Hoel (1991), Felder & Rutherford (1993), Böhringer et al. (2014)).

Supply-side policies are a promising alternative, or complement, to demand-side policies, and they have recently become a research focus. Asheim (2013) provides a distributional argument in favor of supply-side policies and Asheim et al. (2019) propose a complementary supply-side treaty in conjunction with the Paris Agreement. To the best of our knowledge, Bohm (1993) was the first to suggest that countries suffering from emissions could purchase or lease deposits from other countries. Harstad (2012) further explores this idea showing that countries adversely affected by climate damage can set their demand and supply of fuels strategically and buy deposits, thereby implementing the first-best regardless of their market power on the fuel market. These countries buy deposits, that would have been exploited by the countries selling deposits, and preserve or exploit them to serve the fuel market. Eichner & Pethig (2017a) adopt the framework of Harstad (2012), and show that the first-best can also be implemented if deposits are purchased for preservation only. Finally, Eichner & Pethig (2017b) find that the outcome is inefficient, if the countries purchasing deposits act strategically on the deposit market.

Previous studies show that deposit markets with strategic action do not fully prevent carbon leakage between countries. Carbon leakage, however, can additionally occur between fuels, i.e. "interfuel" carbon leakage, if the stringency of a climate policy varies between the different fuels. Regarding deposit policies, the stringency of a policy partially depends on the potential environmental damage of the in-situ fuel. Therefore, if a deposit policy targets multiple fuels that differ in their emission intensity, interfuel carbon leakage could even amplify the deviation from an efficient outcome. More generally, we ask whether more complete supply-side policies – those that stretch over more countries and fuels – amplify the imperfections from strategic behavior. Since it is likely that those imperfections generate winning and losing countries, the implementation of such policies might not garner support from all countries. If the supply-side policy requires support from all countries, its implementation might be impossible due to political economy reasons, i.e. losing countries could impede the policy implementation.

Shedding light on these questions requires an analytical framework covering more than a single fuel. However, to the best of our knowledge, previous studies have analyzed deposit markets with models that only incorporate a single fuel[1]. Hence, they could not provide insights regarding the potential of deposit markets to prevent interfuel carbon leakage. To better understand interfuel carbon leakage effects on deposit markets, it is crucial to analyze how the substitutability between multiple fuels affects deposit trade and deposit prices of both deposits. Further, it is important to study how trade on the deposit markets is affected by the fuels' respective emission intensities. How do the substitutability between fuels and their emission intensities alter the mix of fuel production in the countries selling deposits?

There exists a strand of literature covering climate policies with multiple fuels. Among others, Golombek et al. (1995) extend the model of Hoel (1994) allowing for a mix of supply- and demand-side policies, with three different fuels. Furthermore, Michielsen (2014) analyzes how anticipated climate policies affect emissions ("green paradox") in a model with two fuels. Finally, Daubanes et al. (2019) study carbon leakage in a setting with two fuels and a unilateral climate policy. Even though these studies are concerned with multiple fuels, they do not analyze deposit policies in such a multi-fuel scenario.

In this paper, we build on the framework of Harstad (2012) and Eichner & Pethig (2017b) to analyze a situation in which two groups of countries produce and consume two fuels that are substitutes in consumption. We assume that consumers of fuels are price-takers in the fuel markets, and that fuels differ in their emission intensity. Moreover, we assume that the countries, which are adversely affected by climate damages, buy deposits for preservation only.

Our findings show that, for the case of two fuels, the first-best allocation is distorted by price manipulations on the deposit markets. More precisely, the manipulation of one

[1]With the exception of Harstad (2012), who covers a very specific case in section IV.C.

fuel's deposit price affects both, the allocation of this fuel and the outcome of the other fuel (called "interfuel" effects subsequently). Further, our model suggests that deposit markets applied to both fuels generate more welfare gains for all countries compared with a policy case where only one of the fuels is targeted by a deposit policy. In a parametric version of the model we further show that fuel importing countries abstain from buying deposits of a sufficiently clean fuel if the two fuels cannot be substituted. If the fuels are substitutes, we also find that countries do not buy deposits of a relatively clean fuel if the difference in emission intensities between the fuels is too large. Last but not least, we show that deposit markets are not only helpful in avoiding carbon leakage but that they can also induce the countries, which sell deposits, to choose a cleaner fuel mix.

The remainder of the paper is structured as follows: In section 2, we present the model, and we analyze the policy scenarios in section 3. In section 4, we turn to a detailed analysis of the interfuel effects before we conclude the paper in section 5.

2 Model

Following Harstad (2012) and Eichner & Pethig (2017b), we model an economy where some countries suffer from the emissions of fuel production, while other countries are not affected by or neglect climate damages. We assume that the adversely affected countries aim at reducing climate damages. We denote the two groups of countries i=M,N, where M might be considered as a climate coalition that implements policies to reduce emissions, and N represents all other countries. To reduce notation, we refer to the two country groups as country M and country N subsequently. In extension of the previous contributions, the countries extract and consume two different fuels f=K,G, where K might represent coal and G gas. Country i's consumption of fuel f is denoted $y^{i,f}$ and the benefit derived from this consumption is $B^i(y^{i,K},y^{i,G})$, with $\forall i : B^i_K, B^i_G > 0$, and $B^i_{K,G} \leq B^i_{K,K}, B^i_{G,G} < 0$, where subscripts denote partial derivatives with respect to the appropriate argument, so that $B^i_f = \frac{dB^i}{dy^{i,f}}$, and $B^i_{K,G} = \frac{d^2B^i}{dy^{i,K}dy^{i,G}}$, for instance. Country i's extraction of fuel f is denoted $x^{i,f}$, and imposes costs $C^{i,f}(x^{i,f})$, with $\forall i, f : C^{i,f}_f > 0$, $C^{i,f}_{f,f} > 0$, and $C^{i,f}_{K,G} = 0$. Again, subscripts denote partial derivatives with respect to the appropriate argument. Both countries' producers and consumers act as price-takers on a world market for fuels. The equilibrium price for each fuel f is denoted p^f. Country M suffers from the aggregate emissions from both countries and both fuels, which differ in their emission intensity. The harm function is written as $H(\sum_i \sum_f \eta^f x^{i,f})$, where η^f denotes a fuel's emission intensity. The marginal harm of each fuel's production is denoted $\forall f : H_f > 0$, with $H_{f,f} \geq 0$, and $H_{K,G} \geq 0$. The welfare of country i is denoted U^i, so that we have

$$\begin{aligned} U^M =& B^M(y^{M,K}, y^{M,G}) - C^{M,K}(x^{M,K}) - C^{M,G}(x^{M,G}) \\ & - p^K \cdot (y^{M,K} - x^{M,K}) - p^G \cdot (y^{M,G} - x^{M,G}) - H(\sum_i \sum_f \eta^f x^{i,f}), \end{aligned} \tag{1}$$

and

$$\begin{aligned} U^N =& B^N(y^{N,K}, y^{N,G}) - C^{N,K}(x^{N,K}) - C^{N,G}(x^{N,G}) \\ & - p^K \cdot (y^{N,K} - x^{N,K}) - p^G \cdot (y^{N,G} - x^{N,G}). \end{aligned} \tag{2}$$

In our model set-up, we assume that country M cannot act strategically on the fuel markets.

3 Policy analysis

In the following, we first introduce three benchmarks, namely the social planner case and the laissez-faire case without climate policies, as well as the case of a domestic cap on fuel production by country M. Then, we examine the deposit markets. We analyze interfuel effects for this policy scenario and compare the results with those of the benchmarks. A more detailed analysis of interfuel effects follows in section 4.

3.1 Benchmarks: Social planner, laissez-faire and domestic cap

The social planner chooses the globally first-best solution and thus maximizes aggregate welfare. She maximizes the Lagrangian by choosing the demand and supply, i.e. $\forall i, f$: $y^{i,f}$, $x^{i,f}$, keeping supply and demand of both fuels balanced:

$$\begin{aligned} \mathcal{L} =& B^M(y^{M,K}, y^{M,G}) + B^N(y^{N,K}, y^{N,G}) \\ & - C^{M,K}(x^{M,K}) - C^{M,G}(x^{M,G}) - C^{N,K}(x^{N,K}) - C^{N,G}(x^{N,G}) \\ & - H(\sum_i \sum_f \eta^f x^{i,f}) \\ & + \lambda^K \cdot (x^{M,K} + x^{N,K} - y^{M,K} - y^{N,K}) \\ & + \lambda^G \cdot (x^{M,G} + x^{N,G} - y^{M,G} - y^{N,G}) \end{aligned} \tag{3}$$

The first-order conditions yield

$$\forall f : \lambda^f = B_f^M = B_f^N = C_f^{M,f} + H_f = C_f^{N,f} + H_f. \tag{4}$$

We see that in the efficient outcome all externalities from emissions are fully internalized. In the laissez-faire benchmark, we assume that neither country M nor country N implement any climate policies, either because they are not able to effectively implement policies or because country M neglects the existing harm. In this case, the first-order conditions of both countries yield

$$\forall f : p^f = B_f^M = B_f^N = C_f^{N,f} = C_f^{M,f}. \tag{5}$$

Assuming that country M aims at reducing harm from emissions in absence of climate policies in country N, it can cap its domestic production of fuels. The equilibrium outcome is then characterized by the following conditions:

$$\forall f : p^f = B_f^M = B_f^N = C_f^{N,f} = C_f^{M,f} + H_f. \tag{6}$$

Comparing the first-order conditions of the different benchmark scenarios, we see that a unilateral production cap in country M does not lead to an efficient outcome.

3.2 Deposit markets

To mitigate climate harm, country M can trade deposits with country N. A deposit is defined as an amount of fuel stored underground, and this deposit is characterized by its extraction costs. In a deposit market, countries trade the right to exploit deposits. For instance, country M could buy the right to exploit some of country N's deposits and leave those fuels unexploited, thereby reducing country N's fuel extraction. We restrict our analysis to cases where country M purchases country N's deposits and preserves those deposits, i.e. purchased deposits will not be extracted. In accordance with previous studies (e.g. Harstad (2012), Eichner & Pethig (2017a)), we assume that the deposit markets have already been implemented. We assume that country N's deposits are ordered by increasing extraction costs, so that extracting a marginal unit of fuel if the $x^{N,fth}$ deposit comes at the cost $C_f^{N,f}$. Country N's endowment with deposits is represented by the interval $[0, \infty[_{C_f^{N,f}}$, where the index clarifies that the deposits are ordered by increasing extraction costs. The interval of deposits that country M would purchase from country N lies within this endowment interval and is denoted $[\underline{\xi}^f, \bar{\xi}^f[_{C_f^{N,f}}$.

Following the deposit market design of Eichner & Pethig (2017b), the decisions in the deposit market scenario are sequential: First, country M chooses its deposit demand $z^{M,f}$. Second, country N chooses its deposit supply $z^{N,f}$, after which the deposit markets clear at the deposit prices $p^{z,f}$. Third, country M caps domestic fuel supply and the fuel markets clear. We assume that both countries act as price-takers on the fuel markets. The intuition is that the fuel markets are composed of many participants. Regarding the deposit markets, we assume that country M is a monopsonist and thus fully takes into account the consequences of its strategic actions.

We proceed backwards, starting with the third stage. Given the set-up, the welfare functions of the two countries read

$$\begin{aligned} U^M = {} & B^M(y^{M,K}, y^{M,G}) - C^{M,K}(x^{M,K}) - C^{M,G}(x^{M,G}) \\ & - p^K \cdot (y^{M,K} - x^{M,K}) - p^G \cdot (y^{M,G} - x^{M,G}) \\ & - H(\sum_i \sum_f \eta^f x^{i,f}) \\ & - p^{z,K} z^{M,K} - p^{z,G} z^{M,G}, \end{aligned} \tag{7}$$

and

$$\begin{aligned} U^N = {} & B^N(y^{N,K}, y^{N,G}) - K^{N,K}(x^{N,K}, \underline{\xi}^K, \bar{\xi}^K) - K^{N,G}(x^{N,G}, \underline{\xi}^G, \bar{\xi}^G) \\ & - p^K \cdot (y^{N,K} - x^{N,K}) - p^G \cdot (y^{N,G} - x^{N,G}) \\ & + p^{z,K} z^{N,K} + p^{z,G} z^{N,G}, \end{aligned} \tag{8}$$

where $K^{N,f}(x^{N,f}, \underline{\xi}^f, \bar{\xi}^f)$ is country N's cost function once the deposit trade has occurred. Country M caps domestic fuel supply, and the representative consumer in both countries chooses fuel demand. The outcome in this stage is characterized by the conditions:

$$\forall f : p^f = B^N_f = B^M_f = C^{M,f}_f + H_f. \tag{9}$$

Country N's cost functions depend on the deposit policies and are further specified below. In choosing its fuel supply, country M considers the respective fuel price and harm, so that its supply functions (where we suppress H_f for simplicity) are given by the inverse cost functions $C^{M,f-1}_f(p^f - H_f)$ according to

$$\forall f : x^{M,f} = X^{M,f}(p^f) \coloneqq C^{M,f-1}_f(p^f - H_f). \tag{10}$$

The supply function of each fuel only depends on the marginal damage and the production of this respective fuel, since we assumed $\forall i, f : C^{i,f}_{K,G} = 0$. Consequently, the supply of a fuel depends only on the market price of this specific fuel. Matters are more complicated on the demand side, since we explicitly admit $\forall i : B^i_{K,G} \neq 0$. Demand for fuels K and G in both countries requires to solve the equation system

$$\forall i, f : B^i_f(y^{i,K}, y^{i,G}) = p^f, \tag{11}$$

for $(y^{i,K}, y^{i,G})$. Then, the demand functions for both fuels in the two countries are given by the inverse benefit functions $B^{i-1}_f(p^K, p^G)$, such that

$$\forall i, f : y^{i,f} = Y^{i,f}(p^K, p^G) := B^{i-1}_f(p^K, p^G). \tag{12}$$

Regarding the representative producer in country N, she has sold deposits in the second stage in the interval $[\underline{\xi}^f, \bar{\xi}^f]$, where

$$\forall f : \bar{\xi}^f = \bar{\xi}^f(p^f) := C^{N,f-1}_f(p^f), \text{ and } \underline{\xi}^f = \underline{\xi}^f(p^{z,f}, p^f) := C^{N,f-1}_f(p^f - p^{z,f}). \tag{13}$$

Here, $C^{N,f-1}_f$ denotes country N's inverse marginal cost function. The marginal cost functions change due to the deposit trade to

$$\forall f : K^{N,f}_f(x^{N,f}, \underline{\xi}^f, \bar{\xi}^f) := \begin{cases} C^{N,f}_f(x^{N,f}) & \text{for } x^{N,f} \leq \underline{\xi}^f, \\ C^{N,f}_f(x^{N,f} + \bar{\xi}^f - \underline{\xi}^f) & \text{for } x^{N,f} \geq \underline{\xi}^f. \end{cases} \tag{14}$$

As for country M, country N's supply functions are given by the inverse cost functions. Consequently, the representative producer in country N chooses fuel supply according to

$$\forall f : X^{N,f}(p^f, \underline{\xi}^f, \bar{\xi}^f) := \begin{cases} C^{N,f-1}_f(p^f) & \text{for } p^f \leq C^{N,f}_f(\underline{\xi}^f), \\ \underline{\xi}^f & \text{for } p^f \in [C^{N,f}_f(\underline{\xi}^f), C^{N,f}_f(\bar{\xi}^f)], \\ C^{N,f-1}_f(p^f) - \bar{\xi}^f + \underline{\xi}^f & \text{for } p^f \geq C^{N,f}_f(\bar{\xi}^f). \end{cases} \tag{15}$$

Inserting these demand and supply functions, i.e. Eq. (10), (12) and (15), into the fuel market clearings conditions, we obtain

$$\forall f : X^{M,f}(p^f) + X^{N,f}(p^f, \underline{\xi}^f, \bar{\xi}^f) = Y^{M,f}(p^K, p^G) + Y^{N,f}(p^K, p^G). \tag{16}$$

This yields the equilibrium fuel prices as functions of the upper and lower bounds of deposits supplied by country N. From Eq. (13) we know that that the upper and lower bounds of deposits in turn depend on the fuel and deposit prices, so that we obtain

$$\forall f : p^f = P^f(p^{z,K}, p^{z,G}). \tag{17}$$

These functions characterize the outcome of the third stage.

In the second stage, country N maximizes its welfare by choosing the amount of deposits to sell. In absence of deposit markets, country N would extract all deposits that are profitable at the fuel market prices, so that $\forall f : x^{N,f} = \bar{\xi}^f(p^f) = C_f^{N,f-1}(p^f)$. If deposit markets are introduced, country N sells those deposits that are costly to extract, and extracts all low-cost deposits, so that

$$\forall f : x^{N,f} = \bar{\xi}^f(p^f) - z^{N,f}. \tag{18}$$

Accounting for Eq. (18), country N's first-order conditions to its welfare maximization yield

$$\forall f : C_f^{N,f}(x^{N,f}) = p^f - p^{z,f}. \tag{19}$$

Using Eq. (13), this equals the deposit supply $Z^{N,f}$ as a function of the fuel and deposit prices, so that

$$\forall f : z^{N,f} = Z^{N,f}(p^f, p^{z,f}) = \bar{\xi}^f(p^f) - \underline{\xi}^f(p^f, p^{z,f}). \tag{20}$$

Finally, the deposit markets clear according to

$$\forall f : Z^{N,f}(p^f, p^{z,f}) = z^{M,f}. \tag{21}$$

Accounting for Eq. (17), this yields the equilibrium deposit prices as functions of the deposits demanded by country M, so that

$$\forall f : p^{z,f} = P^{z,f}(p^K, p^G, z^{M,K}, z^{M,G}). \tag{22}$$

In the first stage, country M maximizes its welfare by choosing the optimal amount of deposits for purchase considering the equilibrium fuel and deposit prices determined in stages 2 and 3, i.e. Eq. (17) and Eq. (22). Following the calculations in Appendix A, country M's first-order conditions yield:

$$\begin{aligned}\forall f : \frac{dU^M}{dz^{M,f}} =& H_f - p^{z,f} - z^{M,K} \cdot P_f^{z,K} - z^{M,G} \cdot P_f^{z,G} \\ & - (y^{M,K} - x^{M,K} + H_K \bar{\xi}_K^K) \cdot (P_K^K P_f^{z,K} + P_G^K P_f^{z,G}) \\ & - (y^{M,G} - x^{M,G} + H_G \bar{\xi}_G^G) \cdot (P_K^G P_f^{z,K} + P_G^G P_f^{z,G}) \stackrel{!}{=} 0,\end{aligned} \tag{23}$$

where $P_f^{z,f} = \frac{dP^{z,f}}{dz^{M,f}}$, $\bar{\xi}_f^f = \frac{d\bar{\xi}^f}{dp^f}$, and $P_f^f = \frac{dP^f}{dp^{z,f}}$. We make several observations in Eq. (23): First, if we do not allow for strategic action in the deposit markets, such that $P_f^{z,f} \equiv 0$, we obtain by solving the first-order conditions for the optimal deposit prices $\forall f : p^{z,f} = H_f$. Inserting this into Eq. (19) yields the first-best outcome, as in Eq. (4). Consequently, without strategic action, the deposit markets combined with a domestic cap on fuel supply in country M establish efficiency. This finding extends the result of Eichner & Pethig (2017b) for the case of multiple fuels. We summarize the results as follows: Given country M caps domestic fuel production and trades deposits with country N without acting strategically, the first-best is established even in the case of two fuels that are (im)perfect substitutes in demand.

Second, if we allow for strategic action, the first-best allocation is distorted resulting in inefficiency. The reason for this inefficiency is that country M strategically manipulates the deposit prices through terms $P_f^{z,f}$ and $P_f^{z,f} P_f^f$. Looking at the inefficiencies more closely, we observe that both fuels, K and G, are relevant for this distortion, independent of which deposit country M chooses. For instance, in Eq. (23), if country M chooses the optimal coal deposit for purchase, its demand for gas deposits affects this choice through the term $z^{M,G} \cdot P_f^{z,G}$. Moreover, the trade balance of gas, $(y^{M,G} - x^{M,G})$, and the marginal harm of gas multiplied with the price elasticity of gas deposits, $H_G \bar{\xi}_G^G$, affect the coal deposit choice. Consequently, in addition to the inefficiencies that Eichner & Pethig (2017b) detect in their analysis, we find *interfuel* effects to distort the first-best. As described above for the example of country M's coal deposit choice, those interfuel effects are composed of three parts, the we will describe in the following. For later reference, we coin them the *interfuel deposit effect*, the *interfuel trade effect* and the *interfuel harm effect*. To gain further insights into how these interfuel effects affect the optimal deposit choice, we can solve Eq. (23) implicitly for country M's optimal coal deposit demand, $z^{M,K}$. Then, we obtain

$$\begin{aligned}\forall f : z^{M,K} =& \frac{1}{P_f^{z,K}} \cdot (H_f - p^{z,f} - z^{M,G} \cdot P_f^{z,G} \\ & - (y^{M,K} - x^{M,K} + H_K \bar{\xi}_K^K) \cdot (P_K^K P_f^{z,K} + P_G^K P_f^{z,G}) \\ & - (y^{M,G} - x^{M,G} + H_G \bar{\xi}_G^G) \cdot (P_K^G P_f^{z,K} + P_G^G P_f^{z,G}),\end{aligned} \tag{24}$$

Looking at the signs of the interfuel effects, we first note that $\forall f : P_f^f, P_f^{z,f} > 0$, further $P_G^K, P_K^G > 0$, and $P_G^{z,K}, P_K^{z,G} \lesseqgtr 0$, which we prove in Appendix A. Assuming that $\forall f : C_{f,f,f}^{N,f}$ is either positive or negative, we can differentiate between two cases for the signs of $P_G^{z,K}$ and $P_K^{z,G}$, namely that both are positive or negative. If both, $P_G^{z,K}$ and $P_K^{z,G}$ are positive, the interfuel deposit effect decreases country M's optimal deposit choice. Regarding the interfuel harm effect, we first note that $\bar{\xi}_f^f > 0$ (see Appendix A for derivation). Then, the interfuel harm effect decreases the optimal deposit demand. Moreover, the interfuel trade effect increases (decreases) the optimal deposit demand of one fuel if country M is a net exporter (importer) of the other fuel. If, however, both of the terms $P_G^{z,K}$ and $P_K^{z,G}$ are negative, the interfuel deposit effect increases the optimal demand for deposits. Further, the interfuel harm effect of fuel G increases the deposit choice of fuel K if we have additionally that $\forall f : P_K^G + P_G^G \frac{P_f^{z,K}}{P_f^{z,G}} < 0$. The direction of the impact of the interfuel trade effect of fuel G on the choice of deposits K depends on both, whether country M imports or exports fuel G and on the sign of term $\forall f : P_K^G + P_G^G \frac{P_f^{z,K}}{P_f^{z,G}} < 0$. We summarize these results as follows:

Proposition 1. *Given country M caps domestic fuel production, trades deposits with country N, and acts strategically on the deposit markets, the first-best choice of deposits is distorted through country M's manipulation of the deposit prices. In the case of two fuels that are (im)perfect substitutes in demand an interfuel deposit effect, an interfuel trade effect, and an interfuel harm effect additionally distort the first-best allocation. The impact of the interfuel effects of fuel G on the deposit choice of fuel K are summarized in Table 1:*

Table 1: Impact of the three interfuel effects of fuel G on the deposit choice of fuel K for given signs of $P_G^{z,K}$ and $P_K^{z,G}$ (equivalently for the choice of deposits of fuel G).

Interfuel effect w.r.t.	**Impact of the respective interfuel effect of fuel G on the deposit choice of fuel K for... ...$P_G^{z,K} > 0$, $P_K^{z,G} > 0$**	**...$P_G^{z,K} < 0$, $P_K^{z,G} < 0$**
...deposit	< 0	> 0
...harm	< 0	> 0, if $\forall f : P_K^G + P_G^G \frac{P_f^{z,K}}{P_f^{z,G}} < 0$, < 0, else
...trade	> 0 if country M is a net fuel G exporter, < 0, else	< 0 if country M is a net fuel G exporter and $\forall f : P_K^G + P_G^G \frac{P_f^{z,K}}{P_f^{z,G}} < 0$, > 0, else

4 Interfuel effects analysis

We now turn to a more detailed illustration of the interfuel effects. To derive further insights, we resort to a parametric functional form of the model in this section. We follow

Dixit (1979)[2] for the benefit function with two goods:

$$\forall i: B^i(y^{i,K}, y^{i,G}) = \alpha \cdot (y^{i,K} + y^{i,G}) - \frac{\beta}{2} \cdot ((y^{i,K})^2 + (y^{i,G})^2) - \gamma y^{i,K} y^{i,G}, \tag{25}$$

with parameters $\alpha > 0$, $\beta > 0$, and $\beta \geq \gamma \geq 0$. Furthermore, in extension of Dixit (1979), who assumes linear cost functions, we assume

$$\forall i, f: C^{i,f}(x^{i,f}) = \frac{\kappa^{i,f}}{2}(x^{i,f})^2, \tag{26}$$

with cost parameters $\forall i, f : \kappa^{i,f} > 0$. Except for the last part in section 4.1, we will assume $\forall i, f : \kappa^{i,f} \equiv \kappa$, so that both countries are symmetric with respect to their endowment of deposits. Finally,

$$H(\sum_i \sum_f \eta^f x^{i,f}) = \delta \cdot (\eta^K \cdot (x^{M,K} + x^{N,K}) + \eta^G \cdot (x^{M,G} + x^{N,G})), \tag{27}$$

where the marginal harm is $\delta > 0$, and the fuels' emission intensities are $\forall f : \eta^f > 0$. Similar to Chakravorty et al. (2008), we assume that $\eta^K > \eta^G$, since the emissions from coal combustion have more severe environmental effects compared to those created from gas.

Applying these parametric functions to the analytical framework yields the optimal quantities of fuels and deposits for both countries, as well as the optimal respective prices. To highlight the interfuel effects detected in the preceding section, we now turn to studying two boundary cases. First, we assume that the markets are perfectly segmented, which implies that $\gamma \equiv 0$ in Eq. (25), so that no interfuel effects are present. Second, we study the case when both fuels are perfect substitutes, i.e when $\gamma \equiv \beta$ in Eq. (25). Here, interfuel effects become most prevalent.

4.1 Perfectly segmented markets

If we assume that fuel markets are perfectly segmented, all interfuel effects disappear. In this section, we will therefore omit the superscript f for fuels whenever possible. For the cases of the social planner, laissez-faire, and the cap policy, we obtain the quantities and prices in Table 5 in Appendix B. Regarding the deposit policies, we obtain similar results to Eichner & Pethig (2017b) for the case of two fuels with perfectly segmented markets. Prices and quantities for deposit markets with and without strategic action, as well as deviations from efficiency can be found in Table 6 and Table 7 in Appendix B.

[2]Thanks to Mark Schopf for pointing out the original source of this specification.

Although the two fuel markets are perfectly segmented, the choice of climate policies impacts the fuel mix in country N, i.e. there are interfuel effects. To differentiate between the various scenarios, we use in country N's fuel production the subscripts SP for social planner, LF for laissez-faire, C for cap policy, and finally, D for deposit market with strategic action. Comparing country N's production of coal and gas, we find for the fuel mix in the different scenarios:

Proposition 2. *The fuel mix in country N depends on the climate policies chosen by country M according to*

$$\frac{x_C^{N,K}}{x_C^{N,G}} > 1 = \frac{x_{LF}^{N,K}}{x_{LF}^{N,G}} > \frac{x_D^{N,K}}{x_D^{N,G}} > \frac{x_{SP}^{N,K}}{x_{SP}^{N,G}}. \tag{28}$$

Implementing a cap policy thus not only leads to carbon leakage, as mentioned above, but it also makes the fuel mix in country N dirtier. Deposit policies, in contrast, lead to a cleaner fuel mix in country N. We obtain the cleanest fuel mix in case deposit policies are not strategic. With strategic action country M deviates from the optimal deposit purchase according to $z^M - z_*^M = -\frac{2\delta\eta(3\beta+2\kappa)}{\kappa(7\beta+8\kappa)}$, as shown in Table 7. This deviation increases in absolute terms in the term $\delta\eta$. Consequently, country M's deviation from the optimum is stronger in its coal deposit purchases compared with those of gas, and, accordingly, the fuel mix in country N becomes dirtier than in the efficiency case.

We can further compare the welfare of both countries and the harm for the various cases (see Appendix B for results). For this purpose, we also include the policy option of trading deposits of only either of the two fuels. We denote the welfare resulting from a coal deposit policy only $U_{D,K}^i$, and the welfare in the gas deposit only case $U_{D,G}^i$. Equivalently, the harm resulting from either of the policies is denoted $H_{D,f}$. Comparing these values, we find

Proposition 3. *When fuel markets are perfectly segmented, the welfare of both countries as well as the resulting harm in the different policy scenarios is ranked in the following order:*

$$\begin{aligned} &U_{SP}^M > U_D^M > U_{D,K}^M > U_{D,G}^M > U_C^M > U_*^M > U_{LF}^M, \\ &U_*^N > U_D^N > U_{D,K}^N > U_{D,G}^N > U_C^N > U_{LF}^N > U_{SP}^N, \\ &H_{LF} > H_C > H_{D,G} > H_{D,K} > H_D > H_{SP} = H_*. \end{aligned} \tag{29}$$

Country M prefers the social planner scenario over the deposit policy since it does not need to compensate country N for keeping deposits unextracted. Regarding the deposit policy, country M is better off trading deposits of both fuels, and if trade is only possible for either of the fuels, it prefers trading the dirtier fuel. The deposit policy is strictly preferred to the cap policy since it reduces leakage effects. If country M cannot act strategically on the deposit market, however, it prefers the cap policy. Finally, the laissez-faire case is the worst outcome from country M's perspective. For country N, the deposit policy without strategic action is the preferred option. Here, country N receives a higher compensation compared with a deposit policy where country M acts strategically. This compensation decreases further, if only one fuel is traded on the deposit market, and it vanishes in the cap policy scenario. In the laissez-faire case, country N does not profit from the leakage effect that is present in the cap policy and, therefore, it prefers the cap policy. Finally, country N is better off in the laissez-faire case compared with the social planner scenario since it does not profit from reduced emissions. Regarding harm, it is most prevalent in the laissez-faire case, and decreases if country M caps domestic supply. The harm is even smaller once deposits are traded, and the smallest harm is achieved in the social planner case which is identical to the efficiency scenario.

We can further analyze how trade effects affect country M's deposit choice. Since we assume perfectly segmented markets in this section, the resulting trade effect is not identical to the *interfuel* trade effect stated in Proposition 1. However, this analysis still sheds light on the potential extent of an interfuel trade effect. For this purpose we let the cost parameter κ^i vary, so that $\kappa^M \neq \kappa^N$. In this case country M's deposit demand and the respective deposit prices amount to

$$\begin{aligned} z^M =& \frac{\beta\kappa^M(\alpha(\kappa^N-\kappa^M)+\delta\eta(3\kappa^N+2\kappa^M))+\beta^2\delta\eta\kappa^N+4\delta\eta\kappa^N(\kappa^M)^2}{\beta^2\left(2(\kappa^N)^2+3\kappa^N\kappa^M+2(\kappa^M)^2\right)+\beta\kappa^N\kappa^M(8\kappa^N+7\kappa^M)+8(\kappa^N)^2(\kappa^M)^2}, \\ p^z =& \frac{\kappa(\beta\kappa^M(\alpha(\kappa^N-\kappa^M)+\delta\eta(3\kappa^N+2\kappa^M))+\beta^2\delta\eta\kappa^N+4\delta\eta\kappa^N(\kappa^M)^2)}{\beta^2\left(2(\kappa^N)^2+3\kappa^N\kappa^M+2(\kappa^M)^2\right)+\beta\kappa^N\kappa^M(8\kappa^N+7\kappa^M)+8(\kappa^N)^2(\kappa^M)^2}. \end{aligned} \tag{30}$$

We observe that if $\kappa^M < \kappa^N$, both, deposit prices and deposit demand are positive. In other words, country M always purchases deposits, if it is a net exporter of a fuel, because it benefits in two ways: Since country N extracts less, country M is less affected by climate damage. Furthermore, cutting fuel supply of country N results in a fuel price increase, which increases gains for producers in country M. For the opposite case, we find

Proposition 4. *If $\kappa^M > \kappa^N$, so that country M is a net importer of fuels, both, deposit prices and deposit demand are only positive if country M is sufficiently adversely affected* *by climate damages according to*

$$\delta\eta > \frac{\alpha\beta(\kappa^M)^2 - \alpha\beta\kappa^N\kappa^M}{\beta^2\kappa^N + 3\beta\kappa^N\kappa^M + 2\beta(\kappa^M)^2 + 4\kappa^N(\kappa^M)^2}. \tag{31}$$

If country M is a net importer of the fuels, its consumers lose from fuel price increases induced by the supply cut via deposit purchases. Consequently, for country M to purchase deposits regardless, the damages from fuel extraction must be sufficiently severe, i.e. it must surpass the above mentioned minimum level. For this case to be an interior solution, the parameter set additionally requires to fulfill that $\frac{\beta\kappa^M}{2\beta+4\kappa^M} < \kappa^N$, so that the production costs of country M are small enough to ensure that fuel production is feasible. If country M implements a cap policy without the deposit markets, we obtain an interior solution if the damage is between the minimum damage level and $\delta\eta < \frac{\alpha\kappa^N+\alpha\kappa^M}{\kappa^N}$, and for $\frac{\beta\kappa^M}{2\beta+4\kappa^M} < \kappa^N$.

4.2 Perfect substitutability between fuels

We now turn to the boundary case, where both fuels are perfect substitutes, so that interfuel effects become most prevalent. We will use the superscript $f = r, s$, with $r \neq s$, to refer to either of the two fuels. For the cases of the social planner, laissez-faire, and the cap policy, we obtain the quantities and prices in Table 2. In the social planner case,

Table 2: Quantities and prices for the cases of social planner, laissez-faire, and cap policy, when fuels are perfect substitutes.

	Social planner	**Laissez-faire**	**Cap policy**
$\forall i, f : y^{i,r}$	$\frac{\beta\delta(\eta^s-\eta^r)+(\alpha-\delta\eta^r)\kappa}{\kappa(2\beta+\kappa)}$	$\frac{\alpha}{2\beta+\kappa}$	$\frac{2\alpha\kappa+\beta\delta\eta^s-\delta\eta^r(\beta+\kappa)}{4\beta\kappa+2\kappa^2}$
$\forall f : x^{M,r}$	$\frac{\beta\delta(\eta^s-\eta^r)+(\alpha-\delta\eta^r)\kappa}{\kappa(2\beta+\kappa)}$	$\frac{\alpha}{2\beta+\kappa}$	$\frac{\beta\delta(-3\eta^r+\eta^s)+2(\alpha-\delta\eta^r)\kappa}{4\beta\kappa+2\kappa^2}$
$\forall f : x^{N,r}$	$\frac{\beta\delta(\eta^s-\eta^r)+(\alpha-\delta\eta^r)\kappa}{\kappa(2\beta+\kappa)}$	$\frac{\alpha}{2\beta+\kappa}$	$\frac{2\alpha\kappa+\beta\delta(\eta^r+\eta^s)}{4\beta\kappa+2\kappa^2}$
$\forall f : p^r$	-	$\frac{\alpha\kappa}{2\beta+\kappa}$	$\frac{2\alpha\kappa+\beta\delta(\eta^r+\eta^s)}{2(2\beta+\kappa)}$

demand and supply of one fuel are decreasing in the same fuel's emission intensity and increasing in the other fuel's emission intensity for both countries as expected. For these quantities to be positive, the parameter set now requires to fulfill $\delta\eta^K \leq \frac{\alpha\kappa}{\kappa+\beta}$, in addition to the parameter restrictions mentioned above. Further, we see that in the laissez-faire case, both countries' production and consumption are higher than optimal for both fuels.

In the cap policy case, for the fuel supply of country M to be positive, the parameter set is now required to fulfill $\delta\eta^K < \frac{2\alpha\kappa}{3\beta+2\kappa}$. With a cap policy only, we see that the production in country N increases compared to the laissez-faire (carbon leakage).

If both countries trade deposits and country M caps domestic fuel supply, we obtain the quantities and prices in Table 3 for the cases with and without strategic action. We first

Table 3: Quantities and prices in the deposit market with and without strategic action, when fuels are perfect substitutes.

	Deposit markets..	
	...without strategic action	**...with strategic action**
$\forall i,f : y^{i,r}$	$\frac{\beta\delta(\eta^s-\eta^r)+(\alpha-\delta\eta^r)\kappa}{\kappa(2\beta+\kappa)}$	$\frac{-42\beta^2\delta(\eta^r-\eta^s)+\beta(56\alpha-61\delta\eta^r+29\delta\eta^s)\kappa}{8\kappa(2\beta+\kappa)(7\beta+4\kappa)} + \frac{8(4\alpha-3\delta\eta^r)\kappa^2}{8\kappa(2\beta+\kappa)(7\beta+4\kappa)}$
$\forall f : x^{M,r}$	$\frac{\beta\delta(\eta^s-\eta^r)+(\alpha-\delta\eta^r)\kappa}{\kappa(2\beta+\kappa)}$	$\frac{\beta^2\delta(-10\eta^r+4\eta^s)+\beta(7\alpha+3\delta(-4\eta^r+\eta^s))\kappa}{\kappa(2\beta+\kappa)(7\beta+4\kappa)} + \frac{4(\alpha-\delta\eta^r)\kappa^2}{\kappa(2\beta+\kappa)(7\beta+4\kappa)}$
$\forall f : x^{M,r} - y^{M,r}$	0	$-\frac{\delta(19\beta\eta^r+5\beta\eta^s+8\eta^r\kappa)}{8\kappa(7\beta+4\kappa)} < 0$
$\forall f : x^{N,r}$	$\frac{\beta\delta(\eta^s-\eta^r)+(\alpha-\delta\eta^r)\kappa}{\kappa(2\beta+\kappa)}$	$\frac{\beta^2\delta(-2\eta^r+13\eta^s)+\beta(28\alpha+\delta(-13\eta^r+17\eta^s))\kappa}{4\kappa(2\beta+\kappa)(7\beta+4\kappa)} + \frac{8(2\alpha-\delta\eta^r)\kappa^2}{4\kappa(2\beta+\kappa)(7\beta+4\kappa)}$
$\forall i,f : z^{i,r}$	$\frac{\delta\eta^r}{\kappa}$	$\frac{9\beta\delta\eta^r-5\beta\delta\eta^s+8\delta\eta^r\kappa}{4\kappa(7\beta+4\kappa)}$
$\forall f : p^r$	$\frac{\beta\delta(\eta^r+\eta^s)+\alpha\kappa}{2\beta+\kappa}$	$\frac{4\beta^2\delta(\eta^r+\eta^s)+\beta(7\alpha+3\delta(\eta^r+\eta^s))\kappa+2\alpha\kappa^2}{(2\beta+\kappa)(7\beta+4\kappa)}$
$\forall f : p^{z,r}$	$\delta\eta^r$	$\frac{\delta(9\beta\eta^r-5\beta\eta^s+8\eta^r\kappa)}{4(7\beta+4\kappa)}$

note that, again, the fuel supply and demand in the case of deposit markets without strategic action coincide with the quantities of the social planner in Table 2, since this policy scenario restores efficiency. For the case of deposit markets with strategic action, we observe that the fuel prices are increasing in the sum of both emission intensities, since the fuels are perfect substitutes. Both countries' demand for a fuel r decrease in the emission intensity of fuel r, and increase in the emission intensity of fuel s. Due to the cap policy, country M's supply of fuel r decreases with this same fuel's emission intensity, while the supply increases with the emission intensity of fuel s. Comparing fuel supply and demand, we obtain that country M is a net importer of fuels. Regarding deposits, both, deposit demand and deposit price of one fuel, are increasing in this same fuel's emission intensity, and vice versa for the other fuel's emission intensity. For these quantities to be positive, the parameter set requires to fulfill $\delta\eta^K < \frac{\alpha\kappa(7\beta+4\kappa)}{10\beta^2+12\beta\kappa+4\kappa^2}$. More interestingly, however, we find

Proposition 5. *For country M to purchase deposits of fuel G strategically, the relation* *between the emission intensities requires to fulfill*

$$\eta^K < \eta^G(\frac{9}{5} + \frac{8\kappa}{5\beta}). \tag{32}$$

Every additional gas deposit that country M buys results in a gas supply cut. Since the fuels are perfect substitutes, consumers will substitute this gas supply cut with an increase in coal consumption. This leads to an additional harm and, if $\eta^K > \eta^G(\frac{9}{5} + \frac{8\kappa}{5\beta})$, this additional harm is stronger than the welfare gain of reduced emissions from a decrease in gas consumption. This restriction does not apply to the efficiency case, where deposit purchases of both fuels are feasible for $\eta^K > \eta^G$. In strategic consideration, however, country M purchases less deposits than optimal, especially regarding coal deposits, and consequently country N produces more fuels than optimal, especially regarding coal (see Proposition 6 and its discussion below). As a result, the harm level in the deposit policy case is higher than in the efficiency case to start with, and the restriction on the maximum value of η^K comes into effect. The restriction on the maximum value of η^K tightens with the benefit parameter β, and it relaxes with the cost parameter κ. The intuition is that the welfare is decreasing in β. Consequently, as β increases the welfare gain decreases relative to the harm from fuel extraction. Thus, the maximum value of η^K that allows for gas deposit purchases decreases. Regarding the cost parameter κ, production levels are decreasing in κ and consequently, the harm from emissions decreases in κ as well. With an initially lower harm level, gas deposits are feasible for larger values of η^K.

We can further compare quantities and prices for the deposit markets with and without strategic action. The differences show in which direction the respective amounts deviate from efficiency, as shown in Table 4. We see that also in the case of perfect substitutes, with strategic deposit choice, country M buys less deposits than optimal. This leads to lower deposit and fuel prices, and higher fuel consumption in both countries than optimal. By this, country M can improve its welfare, whereas country N is worse off than in the efficient deposit markets without strategic action.

Again, comparing the above results, we can show how the fuel mix of country N is affected by the different policies. To differentiate between the various scenarios, we use in country N's fuel production the subscripts introduced in Eq. (28). Comparing country N's production of coal and gas, we find

Table 4: Strategic deposit policy: deviations from efficiency (marked with asterisk (*)), when fuels are perfect substitutes, for absolute values of welfare see Appendix B.

	Deviations from efficiency
$\forall i, f : y^{i,r} - y_*^{i,r}$	$\frac{\delta(14\beta^2(\eta^r - \eta^s) + 3\beta(9\eta^r - \eta^s)\kappa + 8\eta^r\kappa^2)}{8\kappa(2\beta+\kappa)(7\beta+4\kappa)} > 0$
$\forall f : x^{M,r} - x_*^{M,r}$	$-\frac{\beta\delta(\eta^r+\eta^s)(3\beta 2\kappa)}{\kappa(2\beta+\kappa)(7\beta+4\kappa)} < 0$
$\forall f : x^{N,r} - x_*^{N,r}$	$\frac{\delta(\beta^2(26\eta^r - 2\eta^s) + \beta(31\eta^r + \eta^s)\kappa + 8\eta^r\kappa^2)}{4\kappa(2\beta+\kappa)(7\beta+4\kappa)} > 0$
$\forall i, f : z^{i,r} - z_*^{i,r}$	$-\frac{\delta(19\beta\eta^r + 5\beta\eta^s + 8\eta^r\kappa)}{4\kappa(7\beta+4\kappa)} < 0$
$\forall f : p^r - p_*^r$	$-\frac{\beta\delta(\eta^r+\eta^s)(3\beta+\kappa)}{(2\beta+\kappa)(7\beta+4\kappa)} < 0$
$\forall f : p^{z,r} - p_*^{z,r}$	$-\frac{\delta(19\beta\eta^r + 5\beta\eta^s + 8\eta^r\kappa)}{4(7\beta+4\kappa)} < 0$
$U^M - U_*^M$	$(\frac{\delta^2(\beta^2(50(\eta^K)^2 + 44\eta^K\eta^G + 50(\eta^G)^2) + 3\beta((\eta^K)^2 + 6\eta^K\eta^G + 13(\eta^G)^2)\kappa}{8\kappa(2\beta+\kappa)(7\beta+4\kappa)}$ $+\frac{8((\eta^K)^2 + (\eta^G)^2)\kappa^2)}{8\kappa(2\beta+\kappa)(7\beta+4\kappa}) > 0$
$U^N - U_*^N$	$-(\frac{3\delta^2(\beta^3(314(\eta^K)^2 + 236\eta^K\eta^G + 314(\eta^G)^2)}{16\kappa(2\beta+\kappa)(7\beta+4\kappa)^2}$ $+\frac{\beta^2(449(\eta^K)^2 + 254\eta^K\eta^G + 449(\eta^G)^2)\kappa}{16\kappa(2\beta+\kappa)(7\beta+4\kappa)^2}$ $+\frac{16\beta(13((\eta^K)^2 + 4\eta^K\eta^G + 13(\eta^G)^2)\kappa^2 + 32((\eta^K)^2 + (\eta^G)^2)\kappa^3)}{16\kappa(2\beta+\kappa)(7\beta+4\kappa)^2}) < 0$

Proposition 6. *If both fuels are perfect substitutes, the fuel mix in country N depends on the climate policies chosen by country M according to*

$$1 = \frac{x_C^{N,K}}{x_C^{N,G}} = \frac{x_{LF}^{N,K}}{x_{LF}^{N,G}} > \frac{x_D^{N,K}}{x_D^{N,G}} > \frac{x_{SP}^{N,K}}{x_{SP}^{N,G}}. \tag{33}$$

As in the case of perfectly segmented markets, we see that compared with the laissez-faire case and the cap policy scenario, the deposit markets with strategic action result in a cleaner fuel mix in country N, i.e. less coal is produced compared with gas. However, the fuel mix is still dirtier than optimal. As can be observed from Table 4, in strategic consideration country M deviates from the optimal deposit purchase according to $\forall f$: $z^{M,r} - z_*^{M,r} = -\frac{\delta(19\beta\eta^r + 5\beta\eta^s + 8\eta^r\kappa)}{4\kappa(7\beta+4\kappa)}$. The deviation of a deposit purchase $z^{M,r}$ increases in absolute terms in both emission intensities $\delta\eta^f$, but more so in the emission intensity of fuel r than fuel s. Consequently, country M's deviation from the optimum is stronger in its coal deposit purchases compared with those of gas, and, accordingly, the fuel mix in country N becomes dirtier than in the efficiency case. With perfect substitutes, the fuel mix in the cap policy scenario is identical to the fuel mix of the laissez-faire case. Thus, even if the fuels are perfect substitutes, deposit markets not only reduce emissions in country N, but they also make its fuel mix cleaner.

Finally, we can compared both countries welfare and harm for each policy case and surprisingly find

Proposition 7. *In the case of perfect substitutability between fuels, the welfare of both countries as well as the resulting harm in the different policy scenarios follows exactly the same ranking as in Eq. (29), where fuel markets are perfectly segmented.*

5 Conclusion

Mitigating adverse effects of climate change requires the implementation of demand- or supply-side climate policies. Deposit markets have recently become a research focus in the analysis of supply-side policies. While previous studies focus on the effect of deposit markets on carbon leakage between countries (e.g. Harstad (2012), and Eichner & Pethig (2017b)), we analyze how deposit policies affect interfuel carbon leakage. In our model, country M and country N produce and consume two different fuels that are substitutes in consumption and differ in their emission intensity. We assume that consumers are price-takers in the fuel markets and that country M buys deposits for preservation only.

Our findings show that, for the case of two fuels, the first-best allocation is distorted by price manipulations on the deposit markets, which include an interfuel deposit effect, an interfuel trade effect and an interfuel harm effect. Further, our model suggests that deposit markets applied to both fuels generate more welfare gains for all countries compared with a policy case where only on of the fuels is targeted by a deposit policy. Furthermore, in a parametric version of the model we find insights on the feasibility of deposit markets with respect to the fuels' emission intensities. First, if the fuel markets are perfectly segmented, a fuel importing country M refrains from purchasing deposits of a sufficiently clean fuel. Second, if the fuels are substitutes, country M does not buy deposits of a fuel if its emission intensity is too low compared with the other fuel. Finally, we show, for the case of two fuels, that deposit markets do not only help avoid carbon leakage, as in the single fuel case, but instead, they also induce country N to produce a cleaner fuel mix.

The analysis of the deposit markets in this paper relies on some simplifying assumptions. First, we assume that there are only two country groups, although one of these groups can be interpreted as a coalition of countries. In our paper, we abstain from considering the stability of this coalition, which is in line with previous literature (e.g. Harstad (2012) and

Eichner & Pethig (2017b))[3]. Second, as in previous studies, we assume that the countries buying deposits act as a single agent and that these countries only are affected by climate damages. Finally, our static partial equilibrium model neglects potential time-consistency and commitment issues. Country N could, for instance, sell deposits to country M today but break the contract in the future and extract the deposits. Although beyond the scope of this paper, these issues are relevant for policy-making and and should become subject of future research.

References

Asheim, G. B. (2013). A distributional argument for supply-side climate policies. *Environmental and Resource Economics*, *56*, 239–254.

Asheim, G. B., Fæhn, T., Nyborg, K., Greaker, M., Hagem, C., Harstad, B., Hoel, M. O., Lund, D., & Rosendahl, K. E. (2019). The case for a supply-side climate treaty. *Science*, *365*, 325–327. arXiv:https://science.sciencemag.org/content/365/6451/325.full.pdf.

Benchekroun, H., & Long, N. v. (2012). Collaborative environmental management: A review of the literature. *International Game Theory Review*, *14*, 1240002.

Bohm, P. (1993). Incomplete international cooperation to reduce CO_2 emissions: Alternative policies. *Journal of Environmental Economics and Management*, *24*, 258–271.

Böhringer, C., Lange, A., & Rutherford, T. F. (2014). Optimal emission pricing in the presence of international spillovers: Decomposing leakage and terms-of-trade motives. *Journal of Public Economics*, *110*, 101–111.

Chakravorty, U., Moreaux, M., & Tidball, M. (2008). Ordering the extraction of polluting nonrenewable resources. *American Economic Review*, *98*, 1128–44.

Daubanes, J. X., Henriet, F., & Schubert, K. (2019). *More Gas, Less Coal, and Less CO_2? Unilateral CO_2 Reduction Policy with More than One Carbon Energy Source*. CESifo Working Paper Series 6697 CESifo Group Munich. URL: https://ideas.repec.org/p/ces/ceswps/_6697.html.

[3]The stability of climate coalitions is examined by a seperate strand of literature (see e.g. Benchekroun & Long, 2012; Hagen et al., 2020, for surveys).

Dixit, A. (1979). A model of duopoly suggesting a theory of entry barriers. *The Bell Journal of Economics*, *10*, 20–32.

Eichner, T., & Pethig, R. (2017a). Buy coal and act strategically on the fuel market. *European Economic Review*, *99*, 77–92.

Eichner, T., & Pethig, R. (2017b). Trade in fossil fuel deposits for preservation and strategic action. *Journal of Public Economics*, *147*, 50–61.

Eichner, T., & Pethig, R. (2019). Bottom-up world climate policies: Preserving fossil fuel deposits vs. capping fuel consumption. *Canadian Journal of Economics/Revue canadienne d'économique*, *52*, 993–1035. `arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/caje.12398`.

Fæhn, T., Hagem, C., Lindholt, L., Mæland, S., & Rosendahl, K. E. (2017). Climate policies in a fossil fuel producing country: Demand versus supply side policies. *Energy Journal*, *38*.

Felder, S., & Rutherford, T. F. (1993). Unilateral CO_2 reductions and carbon leakage: The consequences of international trade in oil and basic materials. *Journal of Environmental Economics and Management*, *25*, 162–176.

Golombek, R., Hagem, C., & Hoel, M. (1995). Efficient incomplete international climate agreements. *Resource and Energy Economics*, *17*, 25–46.

Hagem, C., & Storrøsten, H. B. (2019). Supply- versus demand-side policies in the presence of carbon leakage and the green paradox. *The Scandinavian Journal of Economics*, *121*, 379–406. `arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/sjoe.12277`.

Hagen, A., von Mouche, P., & Weikard, H.-P. (2020). The two-stage game approach to coalition formation: Where we stand and ways to go. *Games*, *11(1)*, 3.

Harstad, B. (2012). Buy coal! A case for supply-side environmental policy. *Journal of Political Economy*, *120*, 77–115.

Hoel, M. (1991). Global environmental problems: The effects of unilateral actions taken by one country. *Journal of Environmental Economics and Management*, *20*, 55–70.

Hoel, M. (1994). Efficient climate policy in the presence of free riders. *Journal of Environmental Economics and Management*, *27*, 259–274.

Michielsen, T. O. (2014). Brown backstops versus the green paradox. *Journal of Environmental Economics and Management*, *68*, 87 – 110.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., Church, J. A., Clarke, L., Dahe, Q., Dasgupta, P. et al. (2014). *Climate Change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. IPCC.

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Appendix A Analytical results

Derivation of Eq. (23):

Regarding country M's welfare optimization we obtain by using Eq. (9), (17), and (22) the first-order conditions

$$\begin{aligned}
\forall f: \frac{dU^M}{dz^{M,f}} =& H_f - p^{z,f} - z^{M,K} \cdot P_f^{z,K} - z^{M,G} \cdot P_f^{z,G} \\
&- (y^{M,K} - x^{M,K} + H_K \bar{\xi}_K^K) \cdot (P_K^K P_f^{z,K} + P_G^K P_f^{z,G}) \\
&- (y^{M,G} - x^{M,G} + H_G \bar{\xi}_G^G) \cdot (P_K^G P_f^{z,K} + P_G^G P_f^{z,G}) \\
&+ (-C_K^{M,K} + p^K - H_K) \cdot X_f^{M,K} P_f^{z,f} \\
&+ (-C_G^{M,G} + p^G - H_G) \cdot X_f^{M,G} P_f^{z,f} \\
&+ (B_K^M - p^K) \cdot Y_f^{M,K} P_f^{z,f} + (B_G^M - p^G) \cdot Y_f^{M,G} P_f^{z,f} \\
=& H_f - p^{z,f} - z^{M,K} \cdot P_f^{z,K} - z^{M,G} \cdot P_f^{z,G} \\
&- (y^{M,K} - x^{M,K} + H_K \bar{\xi}_K^K) \cdot (P_K^K P_f^{z,K} + P_G^K P_f^{z,G}) \\
&- (y^{M,G} - x^{M,G} + H_G \bar{\xi}_G^G) \cdot (P_K^G P_f^{z,K} + P_G^G P_f^{z,G}) \stackrel{!}{=} 0,
\end{aligned} \tag{34}$$

where $P_f^{z,f} = \frac{dP^{z,f}}{dz^{M,f}}$, $\bar{\xi}_f^f = \frac{d\bar{\xi}^f}{dp^f}$, $P_f^f = \frac{dP^f}{dp^{z,f}}$, $X_f^{M,f} = \frac{dX^{M,f}}{dp^{z,f}}$, and $Y_f^{M,f} = \frac{dY^{M,f}}{dp^{z,f}}$.

Derivation of $\frac{d\bar{\xi}^f}{dp^f} > 0$:

Since $\bar{\xi}^f = C_f^{N,f-1}(p^f) =: \bar{\xi}^f(p^f)$ and $C_{f,f}^{i,f} > 0$, we get $\bar{\xi}_f^f = \frac{d\bar{\xi}^f}{dp^f} = C_{f,f}^{N,f-1}(p^f) > 0$.

Derivation of $P_K^G = \frac{dp^G}{dp^{z,K}} > 0$ and $P_K^K = \frac{dp^K}{dp^{z,K}} > 0$ (equivalently for gas deposit price):

Similar to Eichner & Pethig (2019), we totally differentiate

$$\begin{aligned}
&\forall f: C_f^{N,f}(x^{N,f}) = p^f - p^{z,f}, \\
&\forall f: C_f^{M,f}(x^{M,f}) = p^f - H_f, \\
&\forall i, f: B_f^i(y^{i,K}, y^{i,G}) = p^f, \\
&\forall f: x^{M,f} + x^{N,f} = y^{M,f} + y^{N,f},
\end{aligned} \tag{35}$$

and obtain

$$\forall f : C^{N,f}_{f,f}(x^{N,f})dx^{N,f} = dp^f - dp^{z,f}, \tag{36}$$

$$\forall f : C^{M,f}_{f,f}(x^{M,f})dx^{M,f} = dp^f - H_{f,f}dx^{M,f}, \tag{37}$$

$$\forall i, f : B^i_{f,K}(y^{i,K}, y^{i,G})dy^{i,K} + B^i_{f,G}(y^{i,K}, y^{i,G})dy^{i,G} = dp^f, \tag{38}$$

$$\forall f : dx^{M,f} + dx^{N,f} = dy^{M,f} + dy^{N,f}, \tag{39}$$

Assuming symmetric benefit functions for both countries, so that $B := B^M \equiv B^N$, we can solve this equation system for P^K_K and P^G_K, respectively, so that

$$P^K_K = \frac{dp^K}{dp^{z,K}} = \frac{a}{b} \in]0, 1[, \tag{40}$$

$$P^G_K = \frac{dp^G}{dp^{z,K}} = \frac{c}{b} \in]0, 1[, \tag{41}$$

where

$$\begin{aligned} a :=&(C^{M,K}_{K,K} + H_{K,K})(-B_{G,G}B_{K,K}(C^{M,G}_{G,G} + H_{G,G} + C^{N,G}_{G,G}) \\ &+ B^2_{K,G}(C^{M,G}_{G,G} + H_{G,G} + C^{N,G}_{G,G}) + 2B_{K,K}C^{N,G}_{G,G}(C^{M,G}_{G,G} + H_{G,G})), \\ b :=&B^2_{K,G}(C^{M,G}_{G,G} + H_{G,G} + C^{N,G}_{G,G})(C^{M,K}_{K,K} + H_{K,K} + C^{N,K}_{K,K}) \\ &- (B_{G,G}(C^{M,G}_{G,G} + H_{G,G} + C^{N,G}_{G,G}) \\ &- 2(C^{M,G}_{G,G} + H_{G,G})C^{N,G}_{G,G})(B_{K,K}(C^{M,K}_{K,K} + H_{K,K} + C^{N,K}_{K,K}) \\ &- 2(C^{M,K}_{K,K} + H_{K,K})C^{N,K}_{K,K}), \\ c :=&2(C^{M,G}_{G,G} + H_{G,G})B_{K,G}(C^{M}_{K,K} + H_{K,K})C^{N,G}_{G,G}, \end{aligned} \tag{42}$$

with $b < a < 0$ and $b < c < 0$.

Derivation of $P^{z,K}_K = \frac{dp^{z,K}}{dz^{M,K}} > 0$ (equivalently for gas deposit price):

Following Eichner & Pethig (2019), we totally differentiate

$$\begin{aligned} z^{N,K} &= \bar{\xi}^K(p^K) - x^{N,K}, \\ z^{N,K} &= z^{M,K}, \end{aligned} \tag{43}$$

and obtain

$$dz^{N,K} = \bar{\xi}^K_K dp^K - dx^{N,K}, \tag{44}$$

$$dz^{N,K} = dz^{M,K}. \tag{45}$$

With Eq. (36) and $\bar{\xi}^f_f = C^{N,f-1}_{f,f}(p^f)$, we insert Eq. (44) into Eq. (45) and obtain

$$\frac{dp^K}{C^{N,K}_{K,K}(\bar{\xi}^K)} - \frac{dp^K - dp^{z,K}}{C^{N,K}_{K,K}(x^{N,K})} = dz^{M,K}, \tag{46}$$

which is equivalent to

$$\underbrace{\Big(\frac{P^K_K}{C^{N,K}_{K,K}(\bar{\xi}^K)} - \frac{P^K_K - 1}{C^{N,K}_{K,K}(x^{N,K})}\Big)}_{\text{I}} dp^{z,K} = dz^{M,K}, \tag{47}$$

where $I > 0$, since $P^K_K \in]0,1[$. Finally, we obtain

$$P^{z,K}_K = \frac{dp^{z,K}}{dz^{M,K}} = \frac{1}{\frac{P^K_K}{C^{N,K}_{K,K}(\bar{\xi}^K)} - \frac{P^K_K - 1}{C^{N,K}_{K,K}(x^{N,K})}} > 0. \tag{48}$$

Derivation of $P^{z,K}_G = \frac{dp^{z,K}}{dz^{M,G}} \lesseqgtr 0$ (equivalently for gas deposit price):

Analogous to Eq. (46), we have for gas deposits that

$$\frac{dp^G}{C^{N,G}_{G,G}(\bar{\xi}^G)} - \frac{dp^G - dp^{z,G}}{C^{N,G}_{G,G}(x^{N,G})} = dz^{M,G}. \tag{49}$$

Dividing Eq. (49) by $dp^{z,K}$, we obtain

$$\frac{dp^G}{dp^{z,K}} \underbrace{\Big(\frac{1}{C^{N,G}_{G,G}(\bar{\xi}^G)} - \frac{1}{C^{N,G}_{G,G}(x^{N,G})}\Big)}_{=:\text{u}} = \frac{dz^{M,G}}{dp^{z,K}}, \tag{50}$$

We know from Eq. (41) that $\frac{dp^G}{dp^{z,K}} = \frac{c}{b} > 0$. The sign of u depends of the functional form of the cost function, so that $u \lesseqgtr 0$. Therefore, we have that $P^{z,K}_G = \frac{dp^{z,K}}{dz^{M,G}} \lesseqgtr 0$.

Appendix B Parametric results

For the parametric results, we assume that $\alpha > \delta\eta$, so that negative consumption or production is ruled out. In the cap policy case with perfectly segmented markets, the parameter set is additionally required to fulfill $\delta\eta < \frac{2\alpha\kappa}{\beta+2\kappa}$. Regarding the case of deposit markets with strategic action, for the quantities to be positive, the parameter set requires to fulfill $\delta\eta^K < \frac{\alpha\kappa(7\beta+8\kappa)}{3\beta^2+9\beta\kappa+8\kappa^2}$.

Table 5: Quantities and prices for the cases of social planner, laissez-faire, and cap policy, when markets are perfectly segmented.

	Social planner	Laissez-faire	Cap policy
$\forall i: y^i$	$\frac{\alpha-\delta\eta}{\beta+\kappa}$	$\frac{\alpha}{\beta+\kappa}$	$\frac{2\alpha-\delta\eta}{2(\beta+\kappa)}$
x^M	$\frac{\alpha-\delta\eta}{\beta+\kappa}$	$\frac{\alpha}{\beta+\kappa}$	$\frac{2\alpha\kappa-\delta\eta(\beta+2\kappa)}{2\beta\kappa+2\kappa^2}$
x^N	$\frac{\alpha-\delta\eta}{\beta+\kappa}$	$\frac{\alpha}{\beta+\kappa}$	$\frac{2\alpha\kappa+\delta\eta\beta}{2\beta\kappa+2\kappa^2}$
p	-	$\frac{\alpha\kappa}{\beta+\kappa}$	$\frac{2\alpha\kappa+\delta\eta\beta}{2(\beta+\kappa)}$

Table 6: Quantities and prices in the deposit markets with and without strategic action, when markets are perfectly segmented.

	Deposit markets..	
	...without strategic action	...with strategic action
$\forall i: y^i$	$\frac{\alpha-\delta\eta}{\beta+\kappa}$	$\frac{7\alpha\beta-4\beta\delta\eta+8\alpha\kappa-6\delta\eta\kappa}{(\beta+\kappa)(7\beta+8\kappa)}$
x^M	$\frac{\alpha-\delta\eta}{\beta+\kappa}$	$\frac{-3\beta^2\delta\eta+\beta(7\alpha-9\delta\eta)\kappa+8(\alpha-\delta\eta)\kappa^2}{\kappa(\beta+\kappa)(7\beta+8\kappa)}$
x^M-y^M	0	$-\frac{\delta\eta(3\beta+2\kappa)}{\kappa(7\beta+8\kappa)} < 0$
x^N	$\frac{\alpha-\delta\eta}{\beta+\kappa}$	$\frac{3\beta^2\delta\eta+\beta(7\alpha+\delta\eta)\kappa+4(2\alpha-\delta\eta)\kappa^2}{\kappa(\beta+\kappa)(7\beta+8\kappa)}$
$\forall i: z^i$	$\frac{\delta\eta}{\kappa}$	$\frac{\delta\eta(\beta+4\kappa)}{\kappa(7\beta+8\kappa)}$
p	$\frac{\beta\delta\eta+\alpha\kappa}{\beta+\kappa}$	$\frac{4\beta^2\delta\eta+\beta(7\alpha+6\delta\eta)\kappa+8\alpha\kappa^2}{(\beta+\kappa)(7\beta+8\kappa)}$
p^z	$\delta\eta$	$\frac{\delta\eta(\beta+4\kappa)}{7\beta+8\kappa}$

Table 7: Strategic deposit policy: deviations from efficiency (marked with asterisk (*)), when markets are perfectly segmented.

	Deviations from efficiency
$\forall i: y^i-y^i_*$	$\frac{\delta\eta(3\beta+2\kappa)}{(\beta+\kappa)(7\beta+8\kappa)} > 0$
$x^M-x^M_*$	$-\frac{\beta\delta\eta(3\beta+2\kappa)}{\kappa(\beta+\kappa)(7\beta+8\kappa)} < 0$
$x^N-x^N_*$	$\frac{\delta\eta(3\beta^2+8\beta\kappa+4\kappa^2)}{\kappa(\beta+\kappa)(7\beta+8\kappa)} > 0$
$\forall i: z^i-z^i_*$	$-\frac{2\delta\eta(3\beta+2\kappa)}{\kappa(7\beta+8\kappa)} < 0$
$p-p_*$	$-\frac{\beta\delta\eta(3\beta+2\kappa)}{(\beta+\kappa)(7\beta+8\kappa)} < 0$
$p^z-p^z_*$	$-\frac{2\delta\eta(3\beta+2\kappa)}{7\beta+8\kappa} < 0$
$U^M-U^M_*$	$\frac{\delta^2((\eta^K)^2+(\eta^G)^2)(3\beta+2\kappa)^2}{2\kappa(\beta+\kappa)(7\beta+8\kappa)} > 0$
$U^N-U^N_*$	$-\frac{3\delta^2((\eta^K)^2+(\eta^G)^2)(3\beta+2\kappa)^2(3\beta+4\kappa)}{2\kappa(\beta+\kappa)(7\beta+8\kappa)^2} < 0$

Table 8: Welfare of country M in different scenarios, when markets are perfectly segmented.

Scenario	U^M
Social planner	$\frac{2\alpha^2-4\alpha\delta(\eta^K+\eta^G)+3\delta^2\left((\eta^K)^2+(\eta^G)^2\right)}{2(\beta+\kappa)}$
Laissez-faire	$\frac{\alpha(\alpha-2\delta(\eta^K+\eta^G))}{\beta+\kappa}$
Cap	$\frac{4\kappa\left(2\alpha^2-4\alpha\delta(\eta^K+\eta^G)+\delta^2\left((\eta^K)^2+(\eta^G)^2\right)\right)-3\beta\delta^2\left((\eta^K)^2+(\eta^G)^2\right)}{8\kappa(\beta+\kappa)}$
Deposit	$\frac{\beta\kappa\left(14\alpha^2-28\alpha\delta(\eta^K+\eta^G)+3\delta^2\left((\eta^K)^2+(\eta^G)^2\right)\right)}{2\kappa(\beta+\kappa)(7\beta+8\kappa)}+\frac{4\kappa^2\left(4\alpha^2-8\alpha\delta(\eta^K+\eta^G)+3\delta^2\left((\eta^K)^2+(\eta^G)^2\right)\right)-5\beta^2\delta^2\left((\eta^K)^2+(\eta^G)^2\right)}{2\kappa(\beta+\kappa)(7\beta+8\kappa)}$
Efficiency	$\frac{\kappa\left(2\alpha^2-4\alpha\delta(\eta^K+\eta^G)+\delta^2\left((\eta^K)^2+(\eta^G)^2\right)\right)-2\beta\delta^2\left((\eta^K)^2+(\eta^G)^2\right)}{2\kappa(\beta+\kappa)}$
Deposit on fuel r	$\frac{4\beta\kappa\left(14\alpha^2-28\alpha\delta(\eta^r+\eta^s)+\delta^2\left(3(\eta^r)^2+(\eta^s)^2\right)\right)}{8\kappa(\beta+\kappa)(7\beta+8\kappa)}+\frac{16\kappa^2\left(4\alpha^2-8\alpha\delta(\eta^r+\eta^s)+\delta^2\left(3(\eta^r)^2+2(\eta^s)^2\right)\right)-\beta^2\delta^2\left(20(\eta^r)^2+21(\eta^s)^2\right)}{8\kappa(\beta+\kappa)(7\beta+8\kappa)}$

Table 9: Welfare of country N in different scenarios, when markets are perfectly segmented.

Scenario	U^N
Social planner	$\frac{2\alpha^2-\delta^2\left((\eta^K)^2+(\eta^G)^2\right)}{2(\beta+\kappa)}$
Laissez-faire	$\frac{\alpha^2}{\beta+\kappa}$
Cap	$\frac{8\alpha^2\kappa+\beta\delta^2\left((\eta^K)^2+(\eta^G)^2\right)}{8\kappa(\beta+\kappa)}$
Deposit	$\frac{\beta^2\kappa\left(98\alpha^2+57\delta^2\left((\eta^K)^2+(\eta^G)^2\right)\right)+4\beta\kappa^2\left(56\alpha^2+15\delta^2\left((\eta^K)^2+(\eta^G)^2\right)\right)}{2\kappa(\beta+\kappa)(7\beta+8\kappa)^2}+\frac{16\kappa^3\left(8\alpha^2+\delta^2\left((\eta^K)^2+(\eta^G)^2\right)\right)+17\beta^3\delta^2\left((\eta^K)^2+(\eta^G)^2\right)}{2\kappa(\beta+\kappa)(7\beta+8\kappa)^2}$
Efficiency	$\frac{2\alpha^2\kappa+2\beta\delta^2\left((\eta^K)^2+(\eta^G)^2\right)+\delta^2\kappa\left((\eta^K)^2+(\eta^G)^2\right)}{2\kappa(\beta+\kappa)}$
Deposit on fuel r	$\frac{4\beta^2\kappa\left(98\alpha^2+\delta^2\left(57(\eta^r)^2+28(\eta^s)^2\right)\right)+16\beta\kappa^2\left(56\alpha^2+\delta^2\left(15(\eta^r)^2+4(\eta^s)^2\right)\right)}{8\kappa(\beta+\kappa)(7\beta+8\kappa)^2}+\frac{64\kappa^3\left(8\alpha^2+\delta^2(\eta^r)^2\right)+\beta^3\delta^2\left(68(\eta^r)^2+49(\eta^s)^2\right)}{8\kappa(\beta+\kappa)(7\beta+8\kappa)^2}$

Table 10: Harm in different scenarios, when markets are perfectly segmented.

Scenario	H
Social planner	$-\frac{2\delta\left(\delta\left((\eta^K)^2+(\eta^G)^2\right)-\alpha(\eta^K+\eta^G)\right)}{\beta+\kappa}$
Laissez-faire	$\frac{2\alpha\delta(\eta^K+\eta^G)}{\beta+\kappa}$
Cap	$-\frac{\delta\left(\delta\left((\eta^K)^2+(\eta^G)^2\right)-2\alpha(\eta^K+\eta^G)\right)}{\beta+\kappa}$
Deposit	$\frac{2\delta\left(\alpha(7\beta+8\kappa)(\eta^K+\eta^G)-2\delta(2\beta+3\kappa)\left((\eta^K)^2+(\eta^G)^2\right)\right)}{(\beta+\kappa)(7\beta+8\kappa)}$
Efficiency	$-\frac{2\delta\left(\delta\left((\eta^K)^2+(\eta^G)^2\right)-\alpha(\eta^K+\eta^G)\right)}{\beta+\kappa}$
Deposit on fuel r	$\frac{\delta}{\beta+\kappa}\left(2\alpha(\eta^r+\eta^s)-\frac{\delta\left(8\beta(\eta^r)^2+7\beta(\eta^s)^2+12(\eta^r)^2\kappa+8(\eta^s)^2\kappa\right)}{7\beta+8\kappa}\right)$

Table 11: Welfare of country M in different scenarios, when fuels are perfect substitutes.

Scenario	U^M
Social planner	$\frac{\kappa\left(2\alpha^2-4\alpha\delta(\eta^K+\eta^G)+3\delta^2\left((\eta^K)^2+(\eta^G)^2\right)\right)+3\beta\delta^2(\eta^K-\eta^G)^2}{2\kappa(2\beta+\kappa)}$
Laissez-faire	$\frac{\alpha(\alpha-2\delta(\eta^K+\eta^G))}{2\beta+\kappa}$
Cap	$\frac{4\kappa\left(2\alpha^2-4\alpha\delta(\eta^K+\eta^K)+\delta^2\left((\eta^K)^2+(\eta^G)^2\right)\right)+\beta\delta^2\left((\eta^K)^2-14\eta^K\eta^G+(\eta^G)^2\right)}{8\kappa(2\beta+\kappa)}$
Deposit	$\frac{\beta\kappa\left(56\alpha^2-112\alpha\delta(\eta^K+\eta^G)+3\delta^2\left(17(\eta^K)^2-26\eta^K\eta^G+17(\eta^G)^2\right)\right)}{8\kappa(2\beta+\kappa)(7\beta+4\kappa)}+\frac{8\kappa^2\left(4\alpha^2-8\alpha\delta(\eta^K+\eta^G)+3\delta^2\left((\eta^K)^2+(\eta^G)^2\right)\right)+}{8\kappa(2\beta+\kappa)(7\beta+4\kappa)}+\frac{2\beta^2\delta^2\left(11(\eta^K)^2-62\eta^K\eta^G+11(\eta^G)^2\right)}{8\kappa(2\beta+\kappa)(7\beta+4\kappa)}$
Efficiency	$\frac{\kappa\left(2\alpha^2-4\alpha\delta(\eta^K+\eta^G)+\delta^2\left((\eta^K)^2+(\eta^G)^2\right)\right)-\beta\delta^2\left((\eta^K)^2+6\eta^K\eta^G+(\eta^G)^2\right)}{2\kappa(2\beta+\kappa)}$
Deposit on fuel r	$\frac{\beta\kappa\left(30\alpha^2-60\alpha\delta(\eta^r+\eta^s)+\delta^2\left(27(\eta^r)^2-34\eta^r\eta^s+17(\eta^s)^2\right)\right)}{2\kappa(2\beta+\kappa)(15\beta+8\kappa)}+\frac{4\kappa^2\left(4\alpha^2-8\alpha\delta(\eta^r+\eta^s)+\delta^2\left(3(\eta^r)^2+2(\eta^s)^2\right)\right)}{2\kappa(2\beta+\kappa)(15\beta+8\kappa)}+\frac{5\beta^2\delta^2\left(2(\eta^r)^2-12\eta^r\eta^s+(\eta^s)^{2\,2}\right)}{2\kappa(2\beta+\kappa)(15\beta+8\kappa)}$

Table 12: Welfare of country N in different scenarios, when fuels are perfect substitutes.

Scenario	U^N
Social planner	$-\frac{-2\alpha^2\kappa+\beta\delta^2(\eta^K-\eta^G)^2+\delta^2\kappa\left((\eta^K)^2+(\eta^G)^2\right)}{2\kappa(2\beta+\kappa)}$
Laissez-faire	$\frac{\alpha^2}{2\beta+\kappa}$
Cap	$\frac{8\alpha^2\kappa+\beta\delta^2(\eta^K+\eta^G)^2}{8\kappa(2\beta+\kappa)}$
Deposit	$\frac{\beta^2\kappa\left(784\alpha^2+\delta^2\left(389(\eta^K)^2+134\eta^K\eta^G+389(\eta^G)^2\right)\right)}{16\kappa(2\beta+\kappa)(7\beta+4\kappa)^2}$ $+\frac{16\beta\kappa^2\left(56\alpha^2+\delta^2\left(13(\eta^K)^2+4\eta^K\eta^G+13(\eta^G)^2\right)\right)}{16\kappa(2\beta+\kappa)(7\beta+4\kappa)^2}$ $+\frac{32\kappa^3\left(8\alpha^2+\delta^2\left((\eta^K)^2+(\eta^G)^2\right)\right)+2\beta^3\delta^2\left(117(\eta^K)^2+38\eta^K\eta^G+117(\eta^G)^2\right)}{16\kappa(2\beta+\kappa)(7\beta+4\kappa)^2}$
Efficiency	$\frac{2\alpha^2\kappa+\beta\delta^2\left(3(\eta^K)^2+2\eta^K\eta^G+3(\eta^G)^2\right)+\delta^2\kappa\left((\eta^K)^2+(\eta^G)^2\right)}{2\kappa(2\beta+\kappa)}$
Deposit on fuel r	$\frac{3\beta^2\kappa\left(150\alpha^2+\delta^2\left(75(\eta^r)^2+46\eta^r\eta^s+19(\eta^s)^2\right)\right)}{2\kappa(2\beta+\kappa)(15\beta+8\kappa)^2}$ $+\frac{4\beta\kappa^2\left(120\alpha^2+\delta^2\left(27(\eta^r)^2+10\eta^r\eta^s+4(\eta^s)^2\right)\right)+16\kappa^3\left(8\alpha^2+\delta^2(\eta^r)^2\right)}{2\kappa(2\beta+\kappa)(15\beta+8\kappa)^2}$ $+\frac{3\beta^3\delta^2\left(50(\eta^r)^2+40\eta^r\eta^s+17(\eta^s)^2\right)}{2\kappa(2\beta+\kappa)(15\beta+8\kappa)^2}$

Table 13: Harm in different scenarios, when fuels are perfect substitutes.

Scenario	H
Social planner	$-\frac{2\delta\left(-\alpha\kappa(\eta^K+\eta^G)+\beta\delta(\eta^K-\eta^G)^2+\delta\kappa\left((\eta^K)^2+(\eta^G)^2\right)\right)}{\kappa(2\beta+\kappa)}$
Laissez-faire	$\frac{2\alpha\delta(\eta^K+\eta^G)}{2\beta+\kappa}$
Cap	$-\frac{\delta\left(-2\alpha\kappa(\eta^K+\eta^G)+\beta\delta(\eta^K-\eta^G)^2+\delta\kappa\left((\eta^K)^2+(\eta^G)^2\right)\right)}{\kappa(2\beta+\kappa)}$
Deposit	$-\frac{\delta\left(\beta\kappa\left(\delta\left(61(\eta^K)^2-58\eta^K\eta^G+61(\eta^G)^2\right)-56\alpha(\eta^K+\eta^G)\right)\right)}{4\kappa(2\beta+\kappa)(7\beta+4\kappa)}$ $-\frac{\delta\left(-8\kappa^2\left(4\alpha(\eta^K+\eta^G)-3\delta\left((\eta^K)^2+(\eta^G)^2\right)\right)+42\beta^2\delta(\eta^K-\eta^G)^2\right)}{4\kappa(2\beta+\kappa)(7\beta+4\kappa)}$
Efficiency	$-\frac{2\delta\left(-\alpha\kappa(\eta^K+\eta^G)+\beta\delta(\eta^K-\eta^G)^2+\delta\kappa\left((\eta^K)^2+(\eta^G)^2\right)\right)}{\kappa(2\beta+\kappa)}$
Deposit on fuel r	$-\frac{\delta(\beta\kappa(\delta(32(\eta^r)^2-21\eta^r\eta^s+23(\eta^s)^2)-30\alpha(\eta^r+\eta^s))}{\kappa(2\beta+\kappa)(15\beta+8\kappa)}$ $+\frac{4\kappa^2(\delta\left(3(\eta^r)^2+2(\eta^s)^2)-4\alpha(\eta^r+\eta^s)\right)+4\beta^2\delta(5(\eta^r)^2-9\eta^r\eta^s+4(\eta^s)^2))}{\kappa(2\beta+\kappa)(15\beta+8\kappa)}$