Project-Based CO_2 Trading

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Abstract

The market mechanisms built into the Kyoto Protocol have the potential of significantly reducing the costs of meeting the aggregate emission target. But if trading proceeds on a project-by-project basis rather than on a frictionless market, the total cost saving potential of trading is unclear. This paper provides the first attempt to explain market-level implications of project-based CO_2 trading by developing a many-polluter cap-and-trade model where trades are coordinated by a time-taking search process. Trading entails frictions that alter the total number and size of private trades, and basic properties of the CO_2 market as a transfer-mechanism. Perhaps surprisingly, frictions can also increase, not only decrease, the size of private trades. A calibration using previous cost estimates of CO_2 reductions shows that frictions need not damage both sides of the market.

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1 Introduction

The Kyoto Protocol ('the Protocol'), a climate change treaty negotiated in December 1997, includes a number of flexible mechanisms intended to lower total costs of limiting greenhouse gases. Perhaps the most important such mechanism is the provision for emissions trading among the countries listed in the Protocol ('Annex B' countries) [1]. According to an overview of recent estimates produced by thirteen research teams, Annex B trading has the potential of reducing the total economic cost of the Protocol by about half in developed economies [29].

Whether or not these gains can be achieved will depend on how trading institutions develop. By and large research has considered two extreme forms of trade: CO_2 (carbon dioxide)[1] trading is seen to proceed either (i) on an anonymous and frictionless market or (ii) on a project-by-project basis. The studies estimating the cost saving potential of trading have almost exclusively focused on the first type of trade. Typically, an Annex B country is assumed to devolve its emission quota to private entities and allow free trade both domestically and across the Annex B borders. If such trading opportunities existed, full gains from the market mechanism could be achieved, as suggested by the theoretical case for the emissions-trading approach [16].

Because some or even many countries are not likely to adopt transparent trading systems ([9],[13],[25]), "achieving the potential cost saving of international trading will require some form of project-by-project credit program, as Joint Implementation"[9]. The concept of Joint Implementation (JI) allows polluters to finance other polluters' emissions reductions and in return receive 'emission reduction units', and thereby engage in cross-border exchanges even in the absence of formal domestic trading systems [9]. JI is a form of bilateralism because

[1] The Protocol covers five other greenhouse gases as well. Each type of gas can be converted into CO_2 equivalent units, with a weight reflecting the "global warming potential". Because the distinction between gases is not central to our argument, we interpret the emission limits as CO_2 limits.

project-based trades are individually negotiated rather than conducted on an anonymous market. JI is often seen to be an instance of trade between a buyer from a developed (DC) and a seller from a developing (LDC) (or East European) country[2].

Most experts agree that project-based trading entails frictions and thereby potentially large trading costs, because "it is more costly to identify trading opportunities" [13] or "trades must be individually negotiated" [1], or simply because of "the absence of a well functioning market" [9]. Despite this apparent unanimity, these costs have not been framed in any systematic and formal way. There exists no attempt to explain market-level implications of project-based CO_2 trading. The literature on JI projects emphasizes the important role of asymmetric information (e.g., [10], [30]), but it does not extend the concept of JI to a market-level and, therefore, it cannot address the total volume and cost saving potential of project-by-project trading.

These theoretical and empirical reasons call for an approach that is capable of explaining the market-level implications of project-by-project trading. We extend the concept of project-based CO_2 trading to the market level in a many-polluter cap-and-trade model where trades are coordinated by a time-taking search process. Friction in trading alters the basic properties of the cap-and-trade system[3], including the total number of trades, size of individual trades, total gains and division of gains from trade. All of these elements are

[2] Interestingly, the DC-LDC trade in general is characterized by bilateralism (see [15] for evidence), which is often explained by the low creditworthiness of LDCs: the buyer is typically involved in financing the seller's transaction [15]. Credit constraints may also be a reason for JI hosting: LDCs may be unable to finance profitable emissions reduction projects themselves and thereby support the market-based trade in CO_2 permits. The indirect evidence from DC-LDC trade is a reason to consider bilateralism as a potential institution of CO_2 trade even in the presence of formal domestic trading systems.

[3] The concept of cap-and-trade covers JI because trading takes place within the Annex B cap (see [9]). Clean Development Mechanism (CDM), also specified in the Protocol to facilitate project-by-project trading, is beyond our scope since emissions are not capped on both sides of the market (see [27]).

endogenously determined in the equilibrium of our model. We provide a characterization of the equilibrium and, in order to illustrate quantitative magnitudes, a calibration using previous cost estimates of reducing CO_2 in the European Union (EU) and East Europe (EE).

Project-based trading is characterized by frictions and bargaining over individual exchange opportunities. The relative degree of search friction faced by traders determines the division of gains from trade: polluters who face greater difficulties in finding partners will accept bargaining outcomes that allocate them a relatively low share of the trading surplus. This effect has strong allocative implications that arise because of frictions and that are entirely absent in previous attempts to allow for frictions in emissions trading [4]. The allocative implications are of particular relevance in climate change where the CO_2 market is often viewed as a transfer-mechanism helping countries to sign the climate treaty: countries that have not yet signed the climate treaty could join it without paying for the emissions reductions themselves [1]. We find that such conclusions can be premature if trading proceeds on a project-by-project basis: an increase in the number of sellers reduces the seller's share of the trading surplus. Our calibration suggests that such a change can severely damage the sellers' total gain from trading.

Frictions have allocative implications not only because of their effect on bargaining but also on traded quantities. Because frictions make it harder to find a trading partner, they reduce the total number of trades but need not reduce the size of an individual trade once the partner has been found. Perhaps surprisingly, the traded quantity in a single transaction can be larger than in the case where trading is frictionless. The effects on bargaining and traded quantities are pulling in opposite directions: a trader is successful in completing a large trade only when its bargaining position is poor. While this echoes the way prices and

[4] [26] introduces a trading cost that is formally equivalent to a tax or transportation cost. [14] considers a model where the trading cost develops endogenously as a function of the market size. Neither of these approaches explains how the trading cost is shared among traders.

quantities interact in a frictionless market, the division of gains from trade can sharply differ from that in the frictionless case, as illustrated by our calibration.

A matching model (or a search model) is a natural framework for the analysis of project-based CO_2 trading, because the key issue in this approach is the economic activity in a decentralized market where trading is bilateral (see [7], [2])[5]. Trading involves frictions because (i) time is needed to find a partner and (ii) each trading opportunity is indivisible. The latter assumption ensures tractability and is also reasonable in connection with JI projects that may be hard to divide among many traders[6]. It should be emphasized that there are no indivisibilities at the level of the economy: the size of a single JI project is insignificant relative to the total number of projects undertaken by an Annex B country.

Search friction and indivisibility involved in project-by-project trading have disconnected effects on the losses in market-level trading volumes and welfare. We can quantify these losses and identify circumstances in which both types of frictions vanish, implying that the losses in volumes and welfare vanish as well. While this is in sharp contrast with the usual conclusion that project-by-project trading necessarily entails significant trading costs, the general case is however characterized by losses in volumes and welfare.

Another important element of the matching approach is the duration of a bilateral contract. In one class of models, agents trade their objects (if they have agreed on the terms of the trade), and then they immediately separate [7]. In another, agents enter a long-lived relationship in order to produce (if they have agreed on the division of output). We follow the latter approach, which is the one used in labor market matching models ([8], [22]). A

[5] Other topics are, e.g., price and wage dispersion ([6], [3]) and money [12].

[6] The assumption restricts trading opportunities by preventing, e.g., the seller from splitting a JI project into several saleable pieces. Because aggregators (brokers, clearinghouses) may to some extent overcome indivisibility, our approach should be seen as the first approximation. Indivisibilities are common in most search models, including the recent contributions to the theory of money [12]. Full divisibility typically jeopardizes the tractability of matching models (see [28], p. 134).

special feature of our model, compared to most matching models, is the regulatory aspect of the trading institution. To our knowledge, the matching framework has not been previously applied in connection with the regulation of pollution.

The next section sets up the model and solves for the transfer in a private trade as well as the total number of trades. We then isolate the effect of frictions on polluters' relative bargaining positions (section 3) and on total trading volumes and welfare (section 4). Having identified the forces at work, we calibrate the model in section 5.

2 The Model

We postulate a two-region model where a global CO_2 cap is implemented by issuing in each period a given fixed number of CO_2 rights (permits) that are usable only in the period of issuance. The total regional and per polluter pre-trade shares of the permits remain constant over time. The firms within each region are identical, but there are two asymmetries across the regions: polluters' valuations of additional units of CO_2 are higher in region b (=buyer) than in region s (=seller); and the numbers of buyers and sellers may differ.

Exchange Opportunity. We deviate from the perfect market framework by making the meetings of traders incomplete and assuming that each exchange of permits is a bilateral project between two polluters of opposite types. We use the words 'project' and 'match' interchangeably. Thus, whenever two polluters of opposite types meet and agree on the terms of trade, they enter a match[7]. For tractability, we assume that each polluter can enter a match only with a single partner. Given this assumption, both traders prefer to trade quantities that maximize their joint surplus from the (indivisible) trading opportunity.

[7] If trades are subject to regulatory approval, the approval process is completed at the time traders are matched. Potential delays from this source can be thought of as being incorporated into the matching process defined below.

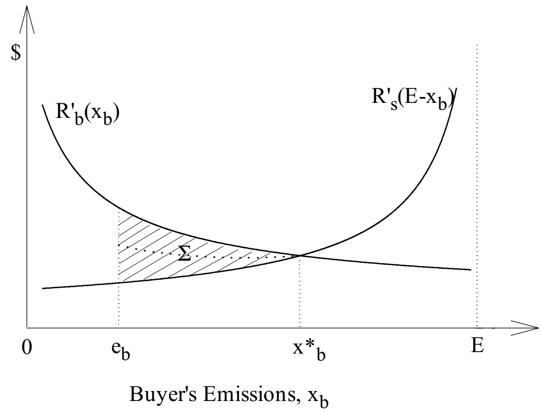

Figure 1: Exchange Opportunity

How polluters agree on the division of the trading surplus, meet each other, and anticipate the length of the project are determined later in this section. We show first how polluters exchange CO_2 permits during the match. Let e_b and e_s denote the flow endowments of CO_2 permits for the buyer and seller, respectively. The total per period number of permits to be allocated in a match is denoted by

$$E \equiv e_b + e_s. \tag{1}$$

The revenue function for a polluter of type i $(= b, s)$ is $R_i(x_i)$ which is increasing and strictly concave in emission level x_i. The revenue function can be thought of as arising from a relationship between the polluter's output and a vector of CO_2-intensive inputs. It is assumed that the pre-trade marginal valuation of emissions is higher for the buyer, $R_b'(e_b) > R_s'(e_s)$. Moreover, we assume that $R_i'(x_i) \longrightarrow \infty$ as $x_i \longrightarrow 0$, for $i = b, s$. By this and the strict concavity of $R_i(x_i)$, there exists an interior allocation $(x_b^*, x_s^*) = (x_b^*, E - x_b^*)$ of E such that the productivity gap between the two matched polluters is eliminated.

Traders' valuations of additional units of CO_2 for any given allocation $(x_b, x_s) = (x_b, E - x_b)$ are graphed in fig. 1, where for a given buyer's allocation x_b, the seller' allocation is given by the residual $E - x_b$. The gains from the trading opportunity are exhausted when permits are exchanged until allocation (x_b^*, x_s^*) is reached[8]. The surplus flow created is denoted by Σ from now on (see fig. 1).

Capital Values of Polluters. Any given seller or buyer is either matched or unmatched depending on whether it has already found a trading partner or not. We shall specify a Poisson process that determines endogenously the probability for each polluter to enter a match during a given time interval, but for the time being, we merely take these probabilities as given. The individual matching rate is denoted by q_i, which is the probability per unit of time that an individual polluter of type $i = b, s$ enters a match. We assume that time is continuous and confine attention to the steady state where the matching probabilities as well as the capital values of the matched and unmatched traders remain stationary. The capital values of the unmatched and matched traders are denoted by V_i and W_i, respectively $(i = b, s)$. In equilibrium, these values satisfy the following dynamic programming equations[9]:

$$rV_b = R_b + q_b(W_b - V_b), \tag{2}$$

$$rW_b = R_b^* - T - \theta(W_b - V_b), \tag{3}$$

$$rV_s = R_s + q_s(W_s - V_s), \tag{4}$$

$$rW_s = R_s^* + T - \theta(W_s - V_s), \tag{5}$$

where $R_i \equiv R_i(e_i)$, $R_i^* \equiv R_i(x_i^*)$, r is the constant discount rate, and θ is the constant separation rate that gives the probability per unit of time that a match breaks down due to an exogenous event. The rate of return rV_i for unmatched firm i is given by the pre-trade revenue R_i, plus the expected capital gain from entering a match, which is characterized

[8] If the buyer were to meet many sellers, either simultaneously or sequentially, it could reduce each seller's marginal valuation of CO_2 by buying less from each seller. The allocation in fig. 1 is the equilibrium in this more general trading environment if there is a one-time fixed cost involved in each trade such that the buyer is needed to finance that cost (see the concluding section) and that the gain from the next trade falls short of the fixed cost.

[9] See e.g. [4], [7], [8], or [19] for the derivation of dynamic programming equations in a matching model.

by $q_i(W_i - V_i)$ (eqs. (2) and (4)). The rate of return rW_b for a matched buyer is the gross after-trade revenue R_b^*, minus the transfer T made in pollution trading and the expected loss of the capital gain per unit of time from the event that the match breaks down, $\theta(W_b - V_b)$ (eq. 3). The rate of return for a matched seller is similarly defined except that the transfer increases the seller's revenues (eq. (5)).

Bargaining. The total capital gain of a trading opportunity is given by the sum of the capital gains that the traders obtain by entering a match:

$$(W_b - V_b) + (W_s - V_s). \tag{6}$$

The division of the capital gain (6), when two traders of opposite type meet, is a bilateral bargaining problem. As is common in the literature, we consider the symmetric Nash bargaining solution, which implies that the capital gain is shared equally among traders. Given this bargaining solution, we next determine the size of the equilibrium transfer T[10].

Proposition 1 *The transfer that supports the equal division of the value of the trading opportunity is*

$$T = C + \frac{1}{1+\delta}\Sigma,$$

where $C \equiv R_s - R_s^*$, *and* $\delta \equiv \frac{r+\theta+q_b}{r+\theta+q_s}$.

Proof. The equal division of the capital gain implies that $W_b - V_b = W_s - V_s$. Use (2)-(5) to obtain

$$W_b - V_b = \frac{R_b^* - T - R_b}{r+\theta+q_b}, \tag{7}$$

$$W_s - V_s = \frac{R_s^* + T - R_s}{r+\theta+q_s}. \tag{8}$$

[10]The symmetric Nash bargaining solution is the most straightforward benchmark case; see [8] and [17]. The solution to a general Nash bargaining problem in the context of the present model is $T = \arg\max\{(W_b - V_b)^\beta (W_s - V_s)^{1-\beta}\}$, where β is the buyer's bargaining power. Solving it gives $T = C + \Sigma H$, where $H = (1 + \frac{\beta}{1-\beta}\delta)^{-1}$. That is, the larger is β, the lower is T. Setting $\beta = \frac{1}{2}$ gives the symmetric Nash bargaining solution.

Equating (7) and (8) yields

$$T = \frac{(r+\theta+q_s)(R_b^* - R_b) + (r+\theta+q_b)(R_s - R_s^*)}{2(r+\theta)+q_b+q_s}. \tag{9}$$

Using $R_s - R_s^* \equiv C$, $\frac{r+\theta+q_b}{r+\theta+q_s} \equiv \delta$, and $R_b^* - R_b = C + \Sigma$ in (9), the result follows. Q.E.D.

The seller will reduce its emissions when entering a match. This results in a loss in the seller's revenues by the amount $R_s - R_s^*$. The transfer flow T compensates the seller for this loss and, in addition, allocates to it the fraction $\frac{1}{1+\delta}$ of the total surplus flow Σ created by the trade. The seller's share of the surplus flow depends on the parameter δ that denotes the ratio of the traders' *effective discount rates.* The factor $r+\theta+q_i$ is the effective discount rate for a trader of type i, because the equilibrium capital gain is determined by using this discount rate, e.g. $W_b - V_b = \int_0^\infty \{R_b^* - T - R_b\} e^{-(r+\theta+q_b)t} dt$ (by (7)).

Matching. The equilibrium number of successful projects is in part determined by the matching rates q_b and q_s. These rates depend on the characteristics of a time-taking matching process which can be specified in a number of ways[11]. For purposes of calibration, we assume that the process is purely mechanistic, without decisions on search intensities. The event that an unmatched trader of type i makes a successful contact is governed by a Poisson process with arrival rate q_i, which is a sum of two arrival rates: (1) the rate with which unmatched trader i successfully contacts an unmatched trader of the opposite type, and (2) the rate with which i is successfully contacted by an unmatched trader of the opposite type.

[11] Assuming continuous time (our model; [7], [17], [18], [11]) is the most common approach, while some models are in discrete time [24]. An agent may decide on his search intensity ([17], [18], [21], [11]), or alternatively, he cannot affect the rate with which he meets potential partners (our model; [8], [19]). A searching agent may either contact both matched and unmatched agents (our model; [8], [18]), or he can direct his search to unmatched agents only ([18], [11]). Projects are either identical (our model; [8]); or they may vary in value, in case an agent decides on a reservation value ([22]). The number of agents in both sides is either fixed (our model; [8], [17], [18]), or the size of one population is fixed while the size of the other population depends on the profitability of searching ([21], [23], [19]).

Accordingly, we define the arrival rates

$$q_b \equiv S/\overline{S} + S/\overline{B}, \tag{10}$$

$$q_s \equiv B/\overline{B} + B/\overline{S}, \tag{11}$$

where S is the number of unmatched sellers, B is the number of unmatched buyers,$\overline{S}$ is the total number of sellers, and $\overline{B}$ is the total number of buyers.[12] The factors $S/\overline{S}$ and $B/\overline{B}$ denote the rates of type 1, and the factors $S/\overline{B}$ and $B/\overline{S}$ denote the rates of type 2. Because independent Poisson processes are "additive", the probability per unit of time for a successful contact is just the sum of the arrival rates of type 1 and 2.

Since it takes two traders of opposite type to carry out a project, the numbers of matched buyers and sellers are equal. Hence,

$$\overline{B} - B \equiv \overline{S} - S. \tag{12}$$

In the steady state, the pools of unmatched and matched traders remain stationary, which implies that on both sides of the market the total number of new matches per unit of time just equals the total number of matches that break down per unit of time:

$$Sq_s = \theta(\overline{S} - S), \tag{13}$$

$$Bq_b = \theta(\overline{B} - B). \tag{14}$$

Clearly, the steady state number of matches given by (13) coincides with that given by (14). Using (11) and (12), equation (13) can be rewritten as

$$S(\overline{B} - \overline{S} + S)(\frac{1}{\overline{B}} + \frac{1}{\overline{S}}) = \theta(\overline{S} - S), \tag{15}$$

[12] To obtain this specification of the matching process, set $U \equiv S, L \equiv \overline{S}, V \equiv B, K \equiv \overline{B}$, $a_u(V/K) \equiv B/\bar{B}$, and $a_v(U/L) \equiv S/\bar{S}$ in [8], or in [18], set $\alpha_1 = \alpha_2 = 1$ and assume that the number of agents may differ. Note that our aggregate matching function is $Bq_b = SB/\bar{B} + SB/\bar{S}$. It has the usual property that the individual rates q_b and q_s are independent on scaling the total number of firms (matched and unmatched).

which is a quadratic equation in S. For given $\overline{B}$, $\overline{S}$, and θ, equation (15) has a unique positive root $S = S^*$ that is the steady state number of the unmatched sellers. By equation (12), the steady state number of the unmatched buyers is given by $B^* = \overline{B} - \overline{S} + S^*$. Throughout the rest of the paper, we shall consider only equilibrium numbers of traders in the above sense and drop the superscript '*', i.e. from now on (B, S) denotes (B^*, S^*). Note that by (12), $S = B$ if $\overline{S} = \overline{B}$, $S < B$ if $\overline{S} < \overline{B}$, and $S > B$ if $\overline{S} > \overline{B}$. Using these relations and $Sq_s = Bq_b$, yields

Remark 1 *Matching rates satisfy: (i) $q_s = q_b$ if $\overline{S} = \overline{B}$; (ii) $q_s > q_b$ if $\overline{S} < \overline{B}$; and (iii) $q_s < q_b$ if $\overline{S} > \overline{B}$.*

The remark shows that the trader type that is more numerous faces greater difficulties in finding a trading partner than the type that is fewer in number; if the two types are equally numerous, all traders have identical matching probabilities.

Remark 2 *For a given $\overline{B}$, (i) $q_s \longrightarrow \infty$ as $\overline{S} \longrightarrow 0$; and (ii) $q_s \longrightarrow 0$ as $\overline{S} \longrightarrow \infty$.*

Proof. Item (i). By $\overline{S} > S$, $S \longrightarrow 0$ as $\overline{S} \longrightarrow 0$. By this and (12), $B \longrightarrow \overline{B}$ as $\overline{S} \longrightarrow 0$. Thus, $q_s \longrightarrow \infty$ as $\overline{S} \longrightarrow 0$. Item (ii). In a steady state, $q_s = \frac{\theta(\overline{B}-B)}{S}$. Because $\overline{B} - B$ is bounded, $S \longrightarrow \infty$ as $\overline{S} \longrightarrow \infty$, by (12). Thus, $q_s \longrightarrow 0$ *as* $\overline{S} \longrightarrow \infty$. Q.E.D.

When there are extremely few sellers, a seller will find a trading partner almost immediately, because the buyers' search can be well directed. On the other hand, when the sellers become increasingly numerous, the rate of successful contacts vanishes. The reason is that the pool of unmatched buyers shrinks, which makes its unlikely that a seller contacts or is contacted by an unmatched buyer.

3 The Division of Surplus Flow

The division of the surplus flow Σ depends on the traders' relative degree of search friction. A low q_i indicates difficulties in finding a trading partner, which reduces the effective discount rate for a trader of type i, thereby increasing trader i's capital gain from the match. Similarly, if q_i is high, trader i will heavily discount the future gains from making a pollution-trading deal, which reduces i's capital gain. Whenever traders' discount rates are asymmetric in the above sense, they will not share the surplus Σ equally, given the symmetric Nash bargaining solution.

Proposition 2 *The seller's share of the surplus flow is: (i)* $\frac{1}{1+\delta} = \frac{1}{2}$ *if* $\overline{S} = \overline{B}$*; (ii)* $\frac{1}{1+\delta} > \frac{1}{2}$ *if* $\overline{S} < \overline{B}$*; and (iii)* $\frac{1}{1+\delta} < \frac{1}{2}$ *if* $\overline{S} > \overline{B}$*. Also, for a given* $\overline{B}$*,* $\frac{1}{1+\delta} \longrightarrow 1$ *as* $\overline{S} \longrightarrow 0$ *and* $\frac{1}{1+\delta} \longrightarrow 0$ *as* $\overline{S} \longrightarrow \infty$*.*

Proof. Items (i)-(iii) follow directly from remark 1 and proposition 1. For the rest, let $\overline{S} \longrightarrow 0$ first. In a steady state, $q_b = \frac{\theta(\overline{S}-S)}{B}$. By $\overline{S} > S$ and (12), $S \longrightarrow 0$ and $B \longrightarrow \overline{B} < \infty$ as $\overline{S} \longrightarrow 0$, implying $q_b \longrightarrow 0$. By this and $q_s \longrightarrow \infty$ as $\overline{S} \longrightarrow 0$ (remark 2), $\delta \longrightarrow 0$ and $\frac{1}{1+\delta} \longrightarrow 1$. Then, let $\overline{S} \longrightarrow \infty$. Because $\overline{B} - B$ is bounded, $S \longrightarrow \infty$ as $\overline{S} \longrightarrow \infty$, by (12). Thus, $q_b \longrightarrow \infty$ as $\overline{S} \longrightarrow \infty$. Since $q_s \longrightarrow 0$ (remark 2), $\delta \longrightarrow \infty$ and $\frac{1}{1+\delta} \longrightarrow 0$. Q.E.D.

If the numbers of the two types of traders are equal, they will split the surplus Σ in half, i.e., $\frac{1}{1+\delta} = \frac{1}{2}$. Otherwise, the trader type that is more numerous receives a smaller share of the surplus. These traders face greater difficulties in finding a partner, which makes them willing to accept a pollution-trading deal that allocates them less than half of the surplus Σ. In particular, given the number of the buyers, if the number of the sellers is vanishingly small, the seller will capture the entire surplus that is created in trading. Similarly, if the sellers are extremely numerous, their share of the surplus will vanish.

4 Trading Volumes

The effect of indivisibility. Frictionless trading is characterized by full divisibility. Typically, an aggregator (clearinghouse, auctioneer) arrays individual bids and asks as market-level supply and demand schedules which determine equilibrium prices and quantities. Given the equilibrium price, an individual buyer, for example, purchases any preferred quantity with full flexibility. The size of the individual purchase need not be equalized with the quantity sold by a particular seller, but may be compiled from different sources, or alternatively, be only a fraction of the quantity sold by a typical seller.

Our concept of project-based trading introduces a deviation from the frictionless ideal by incorporating an element of indivisibility into trading: because each polluter can exchange permits only by entering a match with a single partner, the exchange opportunity is indivisible. As opposed to the frictionless case, the quantity purchased by a matched buyer must exactly coincide with the quantity sold by a particular seller. Although the matched pairs of traders will choose quantities that maximize their joint surplus from trading (as explained in section 2), traded quantities will generally differ from those achieved under frictionless trading. To identify this discrepancy, let $(\tilde{x}_b, \tilde{x}_s)$ denote each polluter's after-trade allocation when trading is frictionless and $\overline{E}$ denotes the global aggregate number of permits in each period. The emission cap $\overline{E}$ is given by the climate agreement and assumed to remain constant over time. For a given cap $\overline{E}$, any frictionless allocation satisfies the aggregate accounting relationship

$$\overline{E} = \overline{B}x_b + \overline{S}x_s, \text{ or } \overline{B}(x_b - e_b) = \overline{S}(e_s - x_s). \tag{16}$$

The efficient frictionless allocation $(\tilde{x}_b, \tilde{x}_s) = (\tilde{x}_b, \frac{\overline{E} - \overline{B}\tilde{x}_b}{\overline{S}})$ is determined by the condition

$$R_b'(\tilde{x}_b) = R_s'(\tilde{x}_s). \tag{17}$$

Similarly, for each matched pair of traders the accounting relationship

$$E = e_b + e_s = x_b + x_s, \tag{18}$$

and the condition defining $(x_b^*, x_s^*) = (x_b^*, E - x_b^*)$,

$$R_b'(x_b^*) = R_s'(x_s^*), \tag{19}$$

must hold. In view of (17) and (19), frictionless trading eliminates the productivity gap between all polluters whereas project-by-project trading eliminates this gap only between the matched pairs of polluters. This leads to the following result.

Proposition 3 *When buyers are more (less, resp.) numerous than sellers:*
(i) the quantity purchased in a match exceeds (falls short of, resp.) the quantity purchased by an individual buyer in frictionless trading;
(ii) the quantity sold in a match falls short of (exceeds, resp.) the quantity sold by an individual seller in frictionless trading. When the numbers of buyers and sellers are equal:
(iii) indivisibility does not alter the size of individual trades.

Proof. Consider first the case $\overline{B} > \overline{S}$. The pairs $(\tilde{x}_b, \tilde{x}_s)$ and (x_b^*, x_s^*) satisfy

$$\tilde{x}_b + \tilde{x}_s < e_b + e_s = x_b^* + x_s^*, \tag{20}$$

where the inequality follows from (16) and the equality from (18). By (20), $(\tilde{x}_b, \tilde{x}_s) \neq (x_b^*, x_s^*)$. If $\tilde{x}_b > x_b^*$, then $R_b'(\tilde{x}_b) < R_b'(x_b^*)$, and by (17) and (19), $R_s'(\tilde{x}_s) < R_s'(x_s^*) \iff \tilde{x}_s > x_s^*$ - a contradiction to (20). If $\tilde{x}_b = x_b^*$, then $R_b'(\tilde{x}_b) = R_b'(x_b^*)$ and $R_s'(\tilde{x}_s) = R_s'(x_s^*) \iff \tilde{x}_s = x_s^*$, contradicting again (20). Thus, we are left with the case $\tilde{x}_b < x_b^*$, which implies $R_b'(\tilde{x}_b) > R_b'(x_b^*)$ and $R_s'(\tilde{x}_s) > R_s'(x_s^*) \iff \tilde{x}_s < x_s^*$. This gives $\tilde{x}_b - e_b < x_b^* - e_b$ (item (i)) and $e_s - \tilde{x}_s > e_s - x_s^*$ (item (ii)). In the case $\overline{B} < \overline{S}$, all of the above inequalities are reversed

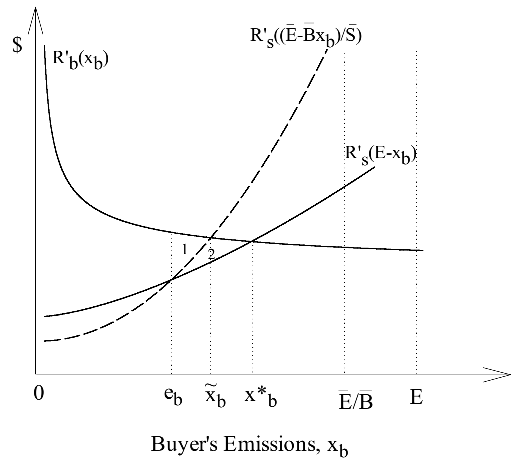

Figure 2: Buyer's Equilibrium Allocation, $\bar{B} > \bar{S}$

which completes the proof of items (i)-(ii). For item (iii), the inequality in (20) is seen to hold as an equality, giving $\tilde{x}_b - e_b = x_b^* - e_b$ and $e_s - \tilde{x}_s = e_s - x_s^*$, by the strict concavity of $R_i(x_i)$. Q.E.D.

The intuition of the result is the following. A buyer, drawn from a relatively large pool of potential buyers ($\overline{B} > \overline{S}$), faces a favorable trading opportunity when entering a match, because the seller has a large endowment of permits to sell (the regional endowment of permits is shared among few sellers). The seller faces only the limited demand of a single buyer, whereas if frictionless trading opportunities existed it would sell more in total but to many buyers and less to each. Because the outside trading opportunities are excluded, the buyer purchases excessive quantities but still leaves the seller with an after-trade allocation that is ineffectively large. When the pool of buyers is relatively small ($\bar{B} < \overline{S}$), the exclusion of outside trading opportunities acts as an effective constraint to the buyers: in frictionless trading they would buy more in total but from many sellers and less from each.

The result can be illustrated using fig. 2 which depicts traders' marginal valuation graphs under the two trading regimes for the case $\bar{B} > \overline{S}$. The figure shows on its horizontal axis the allocation x_b which is the buyer's allocation in a bilateral match and, alternatively, the representative buyer's allocation in frictionless trading. In the former regime, the seller's allocation is the residual $E - x_b$. In the latter, the representative seller's allocation is given by $(\overline{E} - \overline{B}x_b)/\overline{S}$. There are two intersections of buyer's and seller's marginal valuation graphs, one for each trading regime: the intersection of the solid graphs at $(x_b^*, E - x_b^*)$ corresponds to the bilateral allocation, and the intersection of the dotted graph and $R_b'(x_b)$ at $(\tilde{x}_b, \frac{\overline{E} - \overline{B}\tilde{x}_b}{\overline{S}})$ corresponds to the frictionless allocation.

By the low number of sellers, an individual seller is a 'large' bilateral trading partner for the buyer. This is indicated by the gap $E - \overline{E}/\overline{B}$ in fig. 2: the buyer's largest conceivable allocation in a match, E, is greater than the representative buyer's largest conceivable frictionless allocation, $\overline{E}/\overline{B}$. Thus, for any given quantity $x_b - e_b$ purchased by the buyer, the quantity left for the seller is larger in a match than in frictionless trading. Because of this, the seller's marginal valuation is relatively insensitive to increases in the buyer's bilateral purchase, which leads to a large purchase. As $\overline{S}$ is increased towards $\overline{B}$, still keeping the total cap $\overline{E}$ constant, the seller's two valuation graphs rotate counterclockwise around the point $(e_b, R_s'(e_s))$ and move closer to each other, which reduces the gap $x_b^* - \tilde{x}_b$ in fig. 2. For $\overline{S} = \overline{B}$, these graphs coincide, and for $\overline{S} > \overline{B}$, their identities are changed. In this way, the results stated in proposition 3 can be recast in terms of fig. 2.

A corollary of proposition 3 is that the 'cake' created in a match looks larger or smaller than the 'cake' created in frictionless trading depending on whether the trader is a buyer or seller. Suppose again that the buyers are more numerous than sellers ($\bar{B} > \overline{S}$). For the buyer, the total surplus flow created in a bilateral trade is seen to be the sum of areas 1 and 2 in fig. 2, whereas the total surplus created in frictionless trading is only area 1. For the seller, the ranking of surplus flows under the two regimes is reversed because bilateralism effectively limits the seller's trading opportunities.

The effect of search friction. The market-level trading volume is determined by (i) the size of each individual trade and (ii) the number of matches. The former determinant is affected by the indivisibility of the exchange opportunity discussed above, and the latter by the degree of search friction at the market level. We isolate next these two determinants and address their joint impact on the market-level trading volume and welfare.

Because bilateral contracts do not last forever and time is needed to find a new partner, there exists an equilibrium pool of unmatched polluters who are not active traders. Taking this pool of unmatched traders into account, the market-level trading volume is seen to be $(\bar{B}-B)(x_b^*-e_b)=(\bar{S}-S)(e_s-x_s^*)$, whereas the corresponding volume in the frictionless market is $\overline{B}(\tilde{x}_b-e_b)=\overline{S}(e_s-\tilde{x}_s)$. Subtracting the former equation from the latter gives two alternative expressions for the loss in total volumes:

$$\begin{aligned} \overline{S}(x_s^*-\tilde{x}_s)+S(e_s-x_s^*) &= \qquad (21) \\ & \overline{B}(\tilde{x}_b-x_b^*)+B(x_b^*-e_b). \qquad (22) \end{aligned}$$

Remark 3 *At the market-level, trading volume falls short of the frictionless one.*

Expressions (21)-(22) can be used to see this result and isolate the impact of indivisibility and search friction on the loss in volumes. First, in the evenly matched case ($\overline{B}=\overline{S}$), quantities x_i^* and $\tilde{x}_i$ $(i=b,s)$ coincide, implying that the loss exists solely due to search friction, the latter term in (21) and (22). The reduction in volumes is thus the number of unmatched pairs of traders times the size of each unrealized trade. In particular, if the pool of unmatched traders shrinks, the loss in volumes becomes vanishingly small [13].

Second, in unevenly matched cases, volumes are distorted not only by search friction but also by indivisibility. In case $\overline{B}>\overline{S}$, the seller's after-trade allocation is larger than the frictionless one, i.e. $x_s^*>\tilde{x}_s$. This deviation implies a loss in volumes solely due to

[13] Using (15) in the case $\overline{B}=\overline{S}$, we have $S,B\to 0$ when $\theta\to 0$. That is, if bilateral contracts become almost everlasting, the pool of unmatched agents shrinks. In the case $\overline{B}\neq\overline{S}$, this conclusion applies to those unmatched agents that are fewer in number.

indivisibility, the first term in (21). Again, if we let $S \to 0$, the loss in volumes due to search friction shrinks, but the loss due to indivisibility remains. In case $\overline{B} < \overline{S}$, the buyer's after-trade allocation is lower than the frictionless one, i.e. $\tilde{x}_b > x_b^*$. Thus, the first and second terms in (22) are positive, implying again that both indivisibility and search friction contribute to the loss in volumes.

Given that indivisibility and search friction distort the traded quantities, they obviously imply market-level welfare losses. To identify these losses, note that the polluters' first-best total capital value is given by $\tilde{Q} \equiv (\overline{B}\tilde{R}_b + \overline{S}\tilde{R}_s)/r$, where $\tilde{R}_b \equiv R_b(\tilde{x}_b)$ is each buyer's after-trade frictionless revenue flow, and $\tilde{R}_s \equiv R_s(\tilde{x}_s)$ is the corresponding flow for each seller. The polluters' total capital value in project-based trading is given by $Q^* \equiv (\overline{B} - B)W_b + BV_b + (\overline{S} - S)W_s + SV_s$, where each term is the market-level value for the corresponding polluter type. Using the definitions of W_i and V_i and the conditions for the equilibrium in the matching process, gives the following expression for the loss in the total rate of return:

$$r(\tilde{Q} - Q^*) = \overline{B}(\tilde{R}_b - R_b) + \overline{S}(\tilde{R}_s - R_s) - (\overline{S} - S)\Sigma. \tag{23}$$

The first two terms on the right comprise the first-best (frictionless) surplus flow, whereas the last term is the surplus flow generated by realized matches. By the first fundamental welfare theorem, the sum of these terms is nonnegative. The source of the welfare loss can be isolated in limiting cases. As indicated by the analysis of trading volumes, in the evenly matched case the welfare loss exists only due to search friction. In fact, for $\overline{B} = \overline{S}$, equation (23) simplifies to $r(\tilde{Q} - Q^*) = S\Sigma = B\Sigma$, which is just the number of unrealized potential matches times the pairwise trading surplus. As the search friction vanishes ($\theta \to 0$), the welfare approaches the first-best welfare. Any departure from the evenly matched case implies further losses due to indivisibility. To isolate a pure effect of indivisibility, let the seller side be fewer in number and let the search friction vanish ($S \to 0$, and $B \to (\overline{B} - \overline{S})$). In this case, $r(\tilde{Q} - Q^*)$ approaches $\overline{S}(\tilde{R}_b - R_b^* + \tilde{R}_s - R_s^*) + (\overline{B} - \overline{S})(\tilde{R}_b - R_b)$. Consider first the last term where $(\overline{B}-\overline{S})$ is the number of matches never to be realized due to the uneven number of traders, and $(\tilde{R}_b - R_b)$ is the departure of the revenue flow from the first-best level. The last term is thus the loss due to the fact that bilateralism necessarily leaves these traders without a partner, even when all potential matches are realized. The first term, being negative (by $x_b^* > \tilde{x}_b$ and $x_s^* > \tilde{x}_s$), tends to alleviate the loss implied by the latter term: going from project-based to frictionless trading reduces the raw revenue from production for those traders that were matched because each buyer reduces its purchase and each seller increases the quantity sold.

5 Application

To illustrate quantitative magnitudes, we next calibrate the model using previous cost estimates of CO_2 reductions for the European Union (EU) and East Europe (EE). There are numerous estimates for various regions of the world (see [29] for an overview of recent cost estimates produced by thirteen research teams). We focus on the above two regions because the variation of estimates is not large within each trader pool. We also believe that bilateral trading arrangements are likely in these regions because of the EU enlargement plans. We adopt estimates from the Global Trade and Environment Model (GTEM) rather than using a combination of estimates for three reasons. First, estimates are to a large extent driven by scenarios about changes, for example, in energy efficiency and output which vary between studies. To keep the scenarios and the estimates consistent, we use the results of a single study. Second, all data needed for the calibration is reported in [5]. Third, according to a review of different simulation approaches [29], the GTEM estimates are not outliers among the recent estimates.

The steps of the calibration are the following[14]. First, we fit the Nordhaus' [20] marginal

[14] The calibration involves entirely straightforward calculations which are not reported here.

cost function to the pre- and after-trade marginal costs given by the GTEM results. We obtain the cost schedules for the representative EU buyer and EE seller. These can be used to approximate the gains from frictionless trading for the representative traders. Second, we fix the sizes of the buyer and seller pools and calculate the equilibrium where trades are projects, using the calibrated cost schedules. We then calculate the traded quantities and gains under project-based and frictionless trading for the EU and EE traders, both individually and as groups. Third, as we do not have reliable estimates of the sizes of trader pools, we repeat the above comparison for various sizes of these pools (e.g., for various numbers of JI projects in the EE region).

The breakdown of an equilibrium project is provided in table 1 where each row corresponds to a different size of the seller pool. Consider first the case of 1500 traders on both sides of the market ($EU1500/EE1500$). The quantity purchased by a EU trader is 16.1 percent of its business-as-usual emission flow, which is just equal to the quantity purchased under frictionless trading (indicated by the number in parenthesis)[15]. Decreasing the number of sellers down to 500 leads to a relatively large purchase. Increasing this number up to 3000 reduces the purchase below the frictionless one. Traded quantities depend on the relative numbers of traders as explained by proposition 3[16].

Consider then the second column of table 1 which shows the division of the surplus flow. In the EE500 case, the division is extremely unfavorable to a EU buyer: its share of the surplus flow is only 4.6 percent. Enlarging the seller group raises the buyer's share because the latter's bargaining position improves, as shown by Proposition 2. Note that if the trader pools are of equal size, traders share the surplus flow equally.

[15] The pre-trade reduction of emissions is about 25 percent of the business-as-usual flow. Thus, the after-trade reduction is about 9 percent of the business-as-usual flow.

[16] The numbers appearing in parenthesis (column 1) are identical in each row, because the calibration was undertaken such that each row is consistent with the GTEM estimates.

Columns 3-4 report the surplus flow as a percentage of the frictionless surplus flow for the buyer and the seller, respectively. Going from one row to another changes this number not only because of changes in surplus sharing but also in traded quantities, although the former determinant is more important in this calibration. Note that enlarging the group of sellers from 500 first benefits and then damages the representative EE seller. The reason is that each seller becomes 'smaller' which increases the size of the bilaterally sold quantity (relative to seller's business-as-usual emissions) but reduces each seller's bargaining power. The former effect explains the increase from 167 to 226.7, and the latter the decrease from 226.7 to 63.6, in column 4.

TABLE 1. BREAKDOWN OF AN EQUILIBRIUM PROJECT

	Project-based Trading			
	(1) purchased,%	(2) buyer's share,%	(3) buyer's surplus flow,%	(4) seller's surplus flow,%
*EU*1500 *EE*500	19.1 (16.1)	4.6	6.8	167
*EU*1500 *EE*1500	16.1 (16.1)	50	64.1	226.7
*EU*1500 *EE*3000	12.4 (16.1)	91.3	94.5	63.6

In parenthesis: corresponding number in frictionless trading. Col. 1: % of business-as-usual flow. Col. 2: % of trading surplus flow. Col 3-4: % of the trader's surplus flow in frictionless trading. Assumptions: r=.06, θ=.05, GTEM estimates.

To gain some market-level insight into project-based trading, table 2 provides a breakdown of the total trading activity for the case of 3000 sellers (corresponding to the last row in table 1). Each row in table 2 is labeled by the separation rate θ, which characterizes the expected length of a match; the larger is the value of θ, the shorter is the expected duration of a project, which, at the market level, makes the pool of matched traders smaller. This is shown in the first column, where in each period a large number of trades (= 1500) is completed for a low value of θ (= .001), and a low number of trades (= 317) is completed for a high value of θ (= 10).[17]

Because a reduction in the total number of trades does not alter the size of a single

[17] We rounded to whole numbers, which is why the reduction in the total number of trades is not perceptible when $b = .001$.

trade, the top-down reduction in the total trading volume in column 2 is entirely due to the reduction in the total number of trades. In view of this column, an increase in search friction can dramatically reduce the market-level trading volumes.

Columns 3-4 report the percentage reduction from the frictionless surplus flow for the EU and EE regions, respectively. This number also indicates the loss in discounted surplus flows because there is no uncertainty at the market level, as opposed to a single bilateral trade. The top-down increase in the EU loss is due to two factors pulling in the same direction. First, a smaller number of matches reduces the total trading volume. Second, a larger θ means reduced bargaining power for each individual EU buyer. The reason is that the ratio of the polluters' effective discount rates, δ, which determines the division of the surplus flow, approaches unity from above as θ becomes large (when the length of the match becomes extremely short, polluters share the surplus almost equally because ongoing trading becomes equally difficult for all trader types). For the EE region the above two factors are pulling in opposite directions: a larger θ means lower total trading volumes but an improved bargaining position for an individual EE trader. Because of the latter, going from $\theta = .001$ to $\theta = 1$ reduces the loss in this region. Note that the global loss is always greater, the shorter are the pollution-trading deals (column 5, table 2).

Finally, we show that frictions need not damage both sides of the market. To this end, consider table 1 and the last column where the number 226.7 indicates that for a matched seller the surplus flow is more than two times the frictionless surplus flow. Multiplying 226.7 by $(\bar{S}-S)/\bar{S}$ gives the corresponding ratio at the market level: the number $226.7\times(\bar{S}-S)/\bar{S}$ is the EE surplus as a percentage of the EE frictionless surplus. Thus, whenever at least 45 percent of the sellers are matched, the project-based trading favors the EE region. The conclusion holds for a wide range of values for θ. In particular, letting $\theta \longrightarrow 0$ implies that the number of unmatched firms, S, vanishes and, thereby, that $226.7 \times (\bar{S} - S)/\bar{S} \longrightarrow 226.7$ (θ does not alter bargaining positions when $\overline{B} = \overline{S}$).

TABLE 2: MARKET LEVEL BREAKDOWN OF TRADING: $EU1500/EE3000$

Project-based Trading					
	(1) #of matches	(2) EU purchase,%	(3) EU loss,%	(4) EE loss,%	(5) Total loss,%
$\theta = .001$	1500	12.4	.5	86.1	19.3
$\theta = 1$	1000	8.3	54.3	17.6	46.2
$\theta = 10$	317	2.6	88.4	63.8	83

Col. 2: % of EU business-as-usual flow. Cols. 3-4: % drop from region's frictionless surplus flow. Col. 5:% drop from frictionless surplus flow. Assumptions: r=.06, GTEM estimates.

6 Conclusions

This paper provided the first attempt to explain market-level implications of project-based CO_2 trading. The topic is of particular relevance because the economic stakes in this market are vastly greater than in any earlier emissions-trading experiment. There is a need to address the cost saving potential of feasible, as opposed to idealized, trading institutions [9]. We accomplished a deviation from the perfect market setting using a search (matching) theoretic approach. We undertook a systematic examination of trading frictions that were shown to alter the basic economic properties of the cap-and-trade system. In particular, we showed that the relative number of buyers and sellers dictates to a large degree the division of gains in individual trades and is thus an important determinant of winners and losers in project-based trading. A climate treaty that uses the CO_2 market as a transfer-mechanism should acknowledge this endogeneity.

In the interest of introducing one idea at a time and easy calibration, we developed a matching model that is among the simplest one can think of. A number of extensions are conceivable. First, polluters could decide on their search intensities, rather than following mechanistic matching. This change is analytically straightforward and leads to the presence of trading externalities because more intensive search by agents of one type increases the probability that agents of the opposite type make successful contacts during a given time interval (see e.g. [17]). But we do not believe that endogenous search intensities are central to our results, as long as traders meet sequentially and trade bilaterally.

Second, the assumption that trading opportunities are indivisible was made for tractability. Alternatively, polluters can trade sequentially with numerous partners. While this is a nontrivial search-theoretic problem, it could be more insightful to explain the sources of indivisibilities and bilateralism in CO_2 trading. For instance, traders can fail to achieve their total combined level of emissions reductions due to moral hazard. In such an event each party to the climate treaty is responsible for its own level of emissions set out in the Protocol. Bilateral contracts may solve this problem which could otherwise prevent the realization of gains from trade (as in [15]). On the other hand, profitable emissions reduction projects are often in LDC/EE countries which have low creditworthiness. Sellers may be unable to finance these projects and support the development of an anonymous market. Bilateral contracts may restore the creditworthiness or facilitate a creditor-debtor relationship besides the buyer-seller relationship. In view of these possibilities, we see prominent reasons that may explain bilateralism as an institution of trade in the context of climate change.

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