International Institute for
Applied Systems Analysis
Schlossplatz 1
A-2361 Laxenburg, Austria

Tel: +43 2236 807 342
Fax: +43 2236 71313
E-mail: publications@iiasa.ac.at
Web: www.iiasa.ac.at

Interim Report IR-01-048

Domestic Greenhouse Gas Emissions Trading Markets: Forward Pricing and Banking Impacts

Akira Maeda (akmaeda@sfc.keio.ac.jp)

Approved by

Leo Schrattenholzer
Project Leader, Environmentally Compatible Energy Strategies (ECS) Project

October 9, 2001

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Abstract

The paper describes the development of analytical models and how they assist in examining domestic greenhouse gas emissions trading markets. Issues such as forward contract pricing and the impact of the introduction of banking are highlighted. The following findings are presented in the paper: 1) Domestic emissions forward markets prices are greater than expected future spot prices if the market comprises regulated emitters only; 2) Forward prices can, however, become lower than expected future spot prices as the trade volume of non-emitter market participants exceeds that of regulated emitters; 3) When the regulatory authority allows banking, the current spot trade market and future spot markets are linked to each other. As a result, the increase of uncertainty on future spot markets may contribute to the decline of the current spot price at first due to the presence of non-emitter market participants, but will soon give rise to the increase.

Acknowledgments

The author is indebted to the staff of the Environmentally Compatible Energy Strategies Project and seminar participants at IIASA, especially, Leo Schrattenholzer, Ger Klaassen, Michael Obersteiner, Marek Makowski, Hirokazu Tatano. The author is also indebted to Andries Nentjes, The Royal Veterinary and Agricultural University, Denmark for very useful comments. The author wishes to give special thanks to Yoichi Kaya, Professor Emeritus, the University of Tokyo for his personal as well as financial support.

About the Author

Dr. Maeda is member of the Faculty of Policy Management at Keio University in Japan. The research for this study was done during the author's two-month stay at the International Institute for Applied Systems Analysis (IIASA) in 2001. Some of the basic ideas in this paper were presented in earlier studies including Maeda (2001a, b). However, extensive changes in the mathematical formulations were made in this version, which have enriched earlier results.

Domestic Greenhouse Gas Emissions Trading Markets: Forward Pricing and Banking Impacts

Akira Maeda

One of the first to rigorously study economic foundation of emissions trading was Montgomery (1972). In theory, a tradable permit system would provide an effective policy instrument for emission control in a sense that cost-efficiency and equity among regulated entities are attained. Since then, several studies have been done on tradable permits for pollution rights[1]. The theory of emissions trading and the economic benefit over traditional command-and-control approaches to environmental regulation are discussed in detail by Baumol and Oates (1988), Klaassen (1996), Tietenberg (1985), and others.

The first successful application of the theory to the real world was the U.S. sulfur dioxide (SO_2) allowance program established by a provision in Title IV of the 1990 Clean Air Act Amendments, which is also known as the Acid Rain Program.[2] Motivated by the successful implementation of the U.S. Acid Rain Program, the idea of emissions trading was taken into consideration to deal with the emissions of greenhouse gases (GHGs), in particular carbon dioxide (CO_2). In 1997, the Conference of Parties (COP) of the United Nation's Framework Convention on Climate Change (UNFCCC) adopted international GHG emissions trading into its protocol as one of the "flexibility mechanisms" that are now often cited as the "Kyoto mechanisms." Although it is uncertain as to whether the idea of international emissions trading will actually be implemented, it is certain that the Kyoto Protocol prompted the debate on the creation of domestic or regional emissions markets for GHG in or within several developed countries.[3]

As long as trading entities are well defined, there may be no difference between international and domestic GHG emissions trading in theory. Emissions markets are artificial markets where the asset traded in the market is defined by a regulated authority. Thus, the trade system would not function without a unified and consistent legal system, and an enforcing body for compliance. It is apparent that the debate on the Kyoto mechanism is presently highly political. It might be difficult to imagine that not only spot trade markets but also such sophisticated markets as derivatives markets for financial assets and commodities could be automatically created. In this sense, emissions markets for trade within a country or a well-defined region such as the European Union (EU) could be properly analyzed by economic and financial theories.

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[1] An extensive survey of the literature on market-based environmental policy instruments including tradable permits is provided by Cropper and Oates (1992).

[2] The experience and economic evaluation are reported in many studies including Cason and Plott (1996), Ellerman, Schmalensee, Joskow, Montero, and Bailey (1997), Ellerman, Joskow, and Schmalensee (1997), Joskow, Schmalensee, and Bailey (1998), Schmalensee, Joskow, Ellerman, Montero, and Bailey (1998), Stavins (1998), and others.

[3] For example, see the report of the Emissions Trading Group (1999) for the debate in the United Kingdom.

Theoretical issues that Montgomery did not discuss have been addressed by many studies. For example, the studies by Bohi and Burtraw (1992) and Coggins and Swinton (1996) address the influence of uncertainty regarding the regulation policy of public utility commissions on regulated entities' behavior. Uncertainty on abatement cost function is studied by Stavins (1996). Operational and practical aspects of emissions markets are also emphasized. Hahn (1983) and Misolek and Elder (1989) discuss such issues of market imperfection as concentration in permit markets. Doucet and Strauss (1994), Montero (1998), Stavins (1995), and others develop their models to include transaction costs in the theoretical frame. Cason (1993, 1995) analyzes auction designs and rules.

As one traces the development of the theory of emissions trading, we realize that the theory of derivative markets including forward contracts, futures, options, swaps, and others is significantly lacking. In the world of financial assets and commodities, truly sophisticated financial theories for derivative assets have been developed. Derivatives are needed to hedge future risks and are widely used in these asset markets. As GHG emissions permit markets would grow, derivative contracts on the asset would also become popular in the future. In fact, under the U.S. SO_2 allowance program, there exist forward contracts and options markets. These trades are growing among practitioners. However, they have remained out of sight among economic and financial theorists. Few studies are available for this subject while such tutorial documents as Edward and Varilek (2000) and Emissions Trading Education Initiative (1999) are offered for practitioners.

Emissions rights are different from any other financial assets and commodities in that it is artificially created as an instrument for environmental regulation. Thus, the economic nature and financial property might be completely different. For example, holding a security would yield dividend flow. Consuming a commodity such as sugar would bring the consumer some utility or benefit. The primal purpose of holding emissions allowances is for compliance to a regulated standard set by the authority. This difference implies that conventional financial theories on traditional assets would not apply to emissions rights. This is the reason as to why we need to develop a financial theory on emissions derivatives, and to which the paper addresses.

On the same line of emissions derivatives, another important issue, which is much more policy-oriented, is the banking and borrowing of emissions rights. The scheme of banking or borrowing can be structured by the use of swap trades. Thus, at least for individuals, whether the regulated authority allows banking or not would not change anything provided that derivatives markets are easily accessible. However, for the whole market, the authority's decision of allowing banking creates a significant effect. Although some studies including Cronshaw and Kruse (1996), Klaassen and Nentjes (1997), Kling and Rubin (1997), Rubin (1996) and Schennach (1998) are available on banking, their focus is on dynamic strategies of the use of banking. None of them addresses banking and borrowing in the context of forward contracts and swaps, which is a significant shortcoming.

This paper develops an analytical frame that yields a forward pricing model. Based on the pricing model, the specific nature of domestic GHG forward markets are examined. It is also shown that the pricing model helps analyze the impact of the introduction of banking on spot trade markets. These analyses give important policy implications for the design of domestic GHG trading markets.

The paper is organized as follows: Section I summarizes a possible domestic GHG market design and provides definitions of terms and forms of various trades. Section

II discusses uncertain factors that drive spot trade markets. These two sections are intended to serve as preparations for the subsequent sections. Section III develops an analytical model that describes GHG forward market equilibrium. The model yields a forward pricing formula that provides us some important implications on the nature of the forward markets, in particular, the relation between forward prices and expected future spot trade prices. The meaning of the pricing model is also examined in contrast to the traditional capital asset pricing model (CAPM). Section IV makes use of the forward pricing model to examine the impacts of the introduction of banking to GHG markets on current spot market prices. The emphases are put upon how changes in such factors as future uncertainty, technological progress, types of market participants, would affect current market prices under a banking regime. The final section summarizes and integrates these results.

I. Emissions Market Profile

No domestic GHG emissions market has seen implemented in any country in the world so far. This means there is no consensus for a design of domestic GHG emissions market by either policy makers or academia. We have, however, existing markets for SO_2 and NO_x emission permits in the U.S. since the early 90s, which have served as base for the debates on creating GHG markets. This section summarizes a market design that is commonly used in current GHG market debates, and gives definitions of terms and forms of trades, which are referred to later in the paper.

I-A. Tradable permits

A popular regulatory framework in which emissions rights are traded is a cap-and-trade system.[4] In a cap-and-trade system, the regulatory authority would impose targets for each regulated source, which define “the rights to emit.” In order for regulated sources to trade their rights to emit in a transparent manner, the rights to emit are represented by “tradable permits” or “allowances.”[5]

Tradable permits or allowances[6] can represent the rights to emit in any time horizon. A permit could describe the right to emit certain amount of gases within a week, month, year, decade, etc. It would be a realistic regulation policy to define the emission rights as the rights to emit gases within a year, which is also in use in the U.S. program. We will follow this practice in the remainder of this study. In such a yearly-defined permit system, each permit is issued on its year of origination, which is called “vintage.” Vintage is the year where the permit considered could be used or become effective. If a given year-permit is allowed to be used in the year considered only, then we define the system to not allow for “banking.” On the other hand, if the permit can be used in the vintage year but also thereafter then the system does allow for banking.

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[4] Another system that is sometimes mentioned is a baseline-and-credit system. In the U.S. Clean Air Program, a cap-and-trade system is in use. In the remainder of the paper, only the cap-and-trade system is considered.

[5] The initial allocation of permits or allowances is an issue of public policy and a matter of equity, not economic efficiency. We do focus on trading aspects of the system, thus do not discuss how permits should be initially allocated.

[6] These two terms are used interchangeably although the latter is commonly used in the U.S. Clean Air Program.

Whether banking should be allowed or not is an issue left open for the regulatory authority. In the context of GHG abatement, in particular in the debates of the Kyoto protocol, setting a target on yearly emissions would have been an initial goal of environmental regulation and/or agreements among parties concerned. This means that allowing banking might be a defective form of emission regulation. However, some advocates insist that allowing banking would minimize price fluctuations and thus benefit market participants. In the practice of the U.S. Clean Air Act Program, banking is actually allowed. In the present paper, we first consider the system that does not allow banking, and then move on to the analysis of the impacts of a banking possibility.

As a compliance procedure, a regulated entity would have to report the total amount of emissions it would have emitted through the year at the end of every year to the regulatory authority. At the same time, it would have to submit permits of the year-vintage. The total amount of the permits must be equal to the yearly emissions reported.[7]

I-B. Trades

Any trade, in general, can be made in a way that settlement is made either immediately or later. Physical availability of a tradable permit or an allowance of a certain vintage depends on when the authority would plan to issue these permits. Keeping this in mind, let us give definitions of market trades as follows.

“Spot market trades” are defined as immediate settlement trades of current-year vintage permits. “Advance trades” are defined as immediate settlement trades of future-year vintage permits. Advance trades are available only when the regulatory authority issues these future-year vintages, as is in the U.S. Clean Air Program. Even though future-year vintages are not physically available, market participants are able to make a trade on future-year vintages. “Forward contracts” are contracts between parties in which settlements happen some time in the future. With a forward contract, a party promises to deliver permits to another on an agreed date or during an agreed period and the counter party makes a payment for it at an agreed price at the time of delivery. In the context of emissions markets, a forward contract would be made on a specific future-vintage permit that will become effective in the future year.

Note that the party who receives a permit will be able to sell it at the spot market immediately and make a profit provided spot markets are always accessible. Also, the counter party can offer to buy it back at the spot market price, which is called “cash settlement.” Although physical settlement is originally intended in a standard forward contract, a contract with cash settlement is also possible and even if your counter party would not want to do so, you can make a similar arrangement using spot market trades at the same time. In the rest of the paper, we do not worry about whether a forward contract would be followed by either physical settlement or cash settlement because the two methods of settlement are financially the same as long as spot trade markets are accessible.

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[7] In the U.S. Clean Air Act Program, a compliance period begins January 1 and ends December 31, but the program allows a “true-up" period that is until the end of the following February. Regulated sources are also allowed to trade during this true-up period in order to adjust differences between the yearly amount of emissions already fixed and total numbers of permits held.

"Futures contracts" are similar to forward contracts in that they are contracts on future-year vintages. As customs of financial and commodity trades, there are two differences between futures and forward contracts. First, cash settlement is much more prevailing for futures. Second, futures are traded at exchanges that offer parties transparent and secure marketplace while forward contracts are over-the-counter (OTC) trades. The second feature provides market participants with a specific procedure of settlements, which is called "mark-to-market." All futures positions held by the current market participants are marked-to-market every day so that they are cash-settled at the end of each transaction day. The specific feature of futures trades minimizes "default risks" between parties: the risks that a party might turn out not to be able to make an obliged payment. It is well known that without the possibility of default and without changing interest rates, futures and forwards contracts are financially equivalent. In this paper, we will consider the two contract forms as the same and use the terms interchangeably.[8]

"Swaps" are transactions between two parties in which one party exchanges permits of one vintage year for permits of another vintage year from another party. Since, in a strict sense, immediate physical exchanges of permits are intended in swaps, this form of transactions are possible only when the regulated authority issues permits of future-year vintages, that is; when advance trades are available. In reality, there can be some variations of swaps. For example, parties make a contract to deliver different vintage permits to each other in the near future, but actual timing of delivery is slightly different. In such cases, they can adjust the time difference by paying cash, which is a combination of immediate settled swaps and loans. For this reason, we only consider immediate settled swaps in the remainder of the paper.

I-C. Distinctions on spot trades

Spot trades are different from advance trades in that the former trades are made on current vintages while the latter on future vintages. Since the future is an uncertain world, advance trades are always made in an uncertain environment. (We will treat "uncertainty" with a more specific meaning later.) On the other hand, if you make a spot trade near to the end of the current compliance period including a "true-up period," you are almost sure about how much GHG has been emitted and how much will be emitted in the rest of the compliance period. If, however, you make a spot trade at the very beginning of the current compliance year, the trade would be very close to a one-year vintage advance trade that could have been made just before the beginning of the period. In such cases, you would never be sure about how much you would emit all through the year ahead. In this sense, whether or not you are sure about how much you have already emitted and will emit in the rest of the year at the time of your spot trade would depend upon your timing of your trade within the compliance period. With this idea in mind, we make a fundamental assumption in the present paper: *Spot trades are assumed to be made when all market participants have already been sure about their total possible emissions in the compliance period considered.*

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[8] Although the latter assumption of constant interest rate might be debatable in general in the context of financial markets, emissions trade markets have longer time horizons and thus interest rates concerned can be assumed more stable. Even in existent financial markets, forwards and futures are sometimes treated to be a good proxy to one another.

Let us give a clear definition of uncertainty in the context of emissions. When we look at the past, the amount of actual emissions as a statistical record is the amount of emissions that would have been realized if there would have been no abating actions, less the amount of emissions abated. The former is called “counterfactual.” When we look at the future, we have a “business-as-usual” projection and an estimated abatement based on the projection. In the next section, we will use the term, “potential emissions” in order to specify the amount of emissions that would have been realized in the past or could be realized in the future without any emission abatement actions. When we look at the future, a potential emission is assumed “uncertain” and “stochastic” because it can only be estimated now. In addition, it is assumed to turn out to be certain before spot trades are made. This assumption is crucial because assuming this, at the time of spot trades, a regulated source would be sure about how much emissions it would need to abate from the potential emissions in the rest of the compliance period including the true-up period.

I-D. Redundancy of trading choices

An advance trade can be replicated by the combination of a forward contract and loan provided no delivery default occurs. Suppose you are buying a future-year vintage permit, which is an advance trade. You are supposed to pay for it now to obtain the permit. Since the permit would not be effective until the future year, you would not have to physically hold it in your hand until the assigned year. Assuming no delivery default risks, you would be indifferent about when the asset is supposed to be delivered as long as it is no later than the year in question. Assuming loan opportunities or bond markets are available, you would be able to borrow money that is equivalent to the payment for the asset, which would impose on you an obligation of payment in the future year. The financial and asset-delivery scheme constructed above is the same with a forward contract. In other words, if there are forward contract markets available, advance trades are redundant. From the regulatory viewpoint, it would never affect regulated entities' behavior whether the regulatory authority would issue future-year vintage permits now or later.

Swap contracts are also redundant provided forward markets are well equipped. As defined above, a swap trade is a physical exchange of different-year vintages. Selling an advance and buying another advance can replicate it. Again, advances are redundant, as well as swap contracts.

Banking and borrowing are redundant, too. This statement is, however, slightly confusing. It is “to bank a permit” when a regulated entity would reserve a current-year vintage permit to intend to use it in a future year. It is possible for an entity to construct the same scheme by swapping the current-year vintage permit with another-year vintage. Borrowing would be the opposite. Thus, whether or not the regulatory authority would allow regulated sources to bank or borrow permits would never affect regulated sources' market behavior at least at an individual level. However, when we look at the markets as a whole, there is a significant difference between markets with and without banking or borrowing opportunities.

Suppose that neither banking nor borrowing is allowed. When a market participant is buying a permit, either current-year or future-year vintage, there must be a counter party who is selling the permit. This means that total amount of permits of any vintage year within the market remains the same. On the other hand, when banking or borrowing is allowed, any party can convert a vintage into another one, which could change the total amount of one-year-vintage permits. From the economic point of view, banking possibility has significant impacts on market equilibrium and prices. We will analyze these impacts in Section IV.

II. Spot Trade Markets

This section reviews a spot trade market equilibrium model. It is well known that an equilibrium price turns out to be equal to marginal abatement cost in a perfect market. The focus here is spot trades in future years, which are estimated at the present. It is easy to surmise that uncertainty in future spot trade market prices reflects all uncertain factors in the future. This section discusses these uncertainty factors, which prepares us for the analysis of forward contracts in the next section.

II-A. Notations and setting

Let us define the notations as follows:

$i = 1 \cdots N$: Regulated emission sources.

N : Total number of regulated emission sources.

$T_i(t)$: Targets imposed on source *i* in a compliance year *t*, that is; initial endowments of year-*t*-vintage tradable emission permits allocated to source *i*. [Ton-CO2]

$G_i(t)$: Potential emission by source *i* in a compliance year *t*. [Ton-CO2]

$X_i(t)$: Emission abatement by source *i* in a compliance year *t*. [Ton-CO2]

$C_i(X_i(t),t)$: Annual emission abatement cost function for source *i* in a compliance year *t*. [$]

$S(t)$: Spot trade market price in a compliance year *t*. [$/Ton-CO2]

$R_i(t)$: Payoff for source *i* in a compliance year *t* which accrues from abatement and spot trades. [$/year]

Notice, as discussed in the previous section, that potential emission for a compliance year *t* is assumed to be generally uncertain and stochastic until the year and to turn out to be certain at the time of spot trading. In the terminology of probability theory, it is called “information-adapted.” On the other hand, we assume that there is no uncertainty on an annual abatement cost function although it can change as time goes by. Some analysts might criticize this setting with uncertainty on emissions and certainty on abatement cost functions. They might insist that abatement cost functions should be considered uncertain. “Abatement cost” here is by definition the cost for some activities that should be taken to reduce emissions from the plausible business-as-usual level. Since, as discussed in the previous section, we are imposing all possible uncertain factors upon future business-as-usual emissions, which we call “potential” emissions, the uncertainty originated from abatement activities can be naturally included in the uncertainty on potential emissions.

Another possible criticism on the above setting might be that the cost function defined would not include path-dependent nature of abatement activities, for instance, induced technological changes. This is true. In fact, the present setting treats only autonomous technological change. Although we admit that the setting could be extended to a much more complicated one, it would be done only at the sacrifice of mathematical tractability and clear economic insights.

II-B. Spot market equilibrium

With the setting described above, an actual emission of an individual emission source and its market trade volume turn out to be $G_i(t) - X_i(t)$ and $T_i(t) - (G_i(t) - X_i(t))$, respectively, in year *t*. We omit parentheses which represent years as long as no confusion occurs in the following context.

The following optimization problem is solved for the optimal level of emission abatement for source *i* in the year considered.

$$\max_{X_i \geq 0} R_i \qquad \text{where } R_i = S \cdot \{T_i - (G_i - X_i)\} - C_i(X_i).$$

Assuming that abatement cost functions are twice-differentiable, and that the first and second-order derivatives are positive, the optimal level of emission abatement is the following:

$$X_i^* = MC_i^{-1}(S)$$

where *MC* represents the marginal abatement cost function and “-1” represents the inverse function.

Spot trade market clearing condition is described as follows, which gives a spot trade market equilibrium price.

$$(1) \qquad \sum_{i=1}^{N} MC_i^{-1}(S) = \sum_{i=1}^{N} (G_i - T_i)$$

It is easy for us to observe from the above market clearing condition that the volatile and changing nature of spot trade market prices is due to that of potential emissions. Spot trade prices can change from year to year depending upon potential emissions.

II-C. Spot trade market price uncertainty

GHG emissions, especially carbon emissions, are closely related to energy use. Energy use is then closely related to economic activities such as production and consumption. Thus, the level of potential GHG emissions of each source might be subject to the economic environment that surrounds the source. For example, an electric utility would give off GHG more when the domestic economy is booming while it would give off less GHG when it is in a recession. Although it is conjectured that any industry would generally increase emissions when the domestic economy is in a boom, a counter example can be pointed out. When the economy is in a good condition, an automobile manufacturer that has moved its main factories to overseas or other countries would increase its imports from its subsidiaries while its manufacturing activity at home would be almost unchanged or even declined. In addition, the industrial organization of a country would in general be changing from an energy-intensive structure toward a less intensive one if it would be observed in a long term, which indicates some industries would decline their emissions as a whole at least within the country.

On the same line of the above conjecture, we assume there is a single factor to which all emissions from various sources are correlated. The factor can be GDP of the county, some regional or national industrial production index, consumer index, interest rate, etc. Any thing will do as long as it represents some indicator that is closely related to GHG emission sources. Multi-factors could also be considered. However, introducing them may bring little advantage. If we introduce a bundle of these factors, then we can reduce them to a single factor.

Let Y be the single factor that represent a macro-economic indicator that is closely related to domestic emissions. We assume the following relation.

$$(2) \qquad \tilde{G}_i - \overline{G}_i = \beta_i \cdot \left(\tilde{Y} - \overline{Y}\right) + \tilde{\varepsilon}_i$$

where $Cov\left(\tilde{Y}, \tilde{\varepsilon}_i\right) = 0$ and $E[\tilde{\varepsilon}_i] = 0$ for all *i*, $E\left[\tilde{\varepsilon}_i \tilde{\varepsilon}_j\right] = 0$ for all *i*, *j*.

As is the custom in probability theory, bars and tildes represent expected values and random variables, respectively, which we will use throughout the paper. It is known that the "beta" is the correlation coefficient multiplied by the standard deviations of G divided by the standard deviations of Y, that is: $\beta_i \equiv corr(G_i, Y) \times sdev(G_i) / sdev(Y)$

Let us approximate the abatement cost functions by using the Taylor expansion around expected emission abatement levels, neglecting third and higher order terms, as follows.

$$(3) \qquad C(X) \cong C\left(\overline{X}\right) + MC\left(\overline{X}\right) \cdot \left(X - \overline{X}\right) + \frac{1}{2} C''\left(\overline{X}\right) \cdot \left(X - \overline{X}\right)^2$$

The equilibrium condition (1) implies:

$$\frac{1}{N}\left(\sum_{i=1}^{N} \frac{1}{C_i''\left(\overline{X}_i\right)}\right) \cdot \left(\tilde{S} - \overline{S}\right) = \frac{1}{N}\left(\sum_{i=1}^{N} \beta_i\right) \cdot \left(\tilde{Y} - \overline{Y}\right) + \frac{1}{N}\sum_{i=1}^{N} \tilde{\varepsilon}_i \; .$$

Notice that the variance of the last term disappears when N goes to infinity, that is:

$$Var\left(\frac{1}{N}\sum_{i=1}^{N} \tilde{\varepsilon}_i\right) = \frac{1}{N^2}\sum_{i=1}^{N} Var\left(\tilde{\varepsilon}_i\right) \to 0 \qquad as\, N \to \infty \, .$$

This indicates that for large numbers of emission sources, the probabilistic nature of the spot trade market price would depend upon only that of the single factor to which emissions have correlation. More specifically, a spot trade market price for year *t* can be expressed as follows.

$$(4) \qquad \tilde{S}(t) \cong \overline{S}(t) + Z \cdot \left(\tilde{Y}(t) - \overline{Y}(t)\right)$$

where

$$Z \equiv \frac{1}{N}\left(\sum_{i=1}^{N} \beta_i\right) \cdot C''_{ave}$$

$$C''_{ave} \equiv \left(\frac{1}{N}\left(\sum_{i=1}^{N} \frac{1}{C_i''\left(\overline{X}_i\right)}\right)\right)^{-1}$$

The above expression brings us interesting insights about the stochastic nature of spot prices. First, uncertainty of a future spot price is entirely subject to the single factor and its multiplier, *Z*. Other uncertainties that are specific to each emitter and that have no correlation to each other are diversified and disappear when there are large numbers of emitters in the market. We can recognize our single factor as a "systematic risk" that drives spot markets.

Another interesting insight is the multiplier, *Z*. It contains the sum of betas that represent correlation between some macroeconomic indicator and potential emissions. Let us consider an example. Suppose we have only two emitters. One of which emits much while the other emits less when the economic indicator is high. In this case, the sum of their betas can be zero, which means there can be no uncertain changes in spot trade prices. In general, when there are negative betas, spot market prices can happen to be deterministic even though emissions from various sources are much volatile. In this sense, stochastic and volatile nature of spot trade markets is not self-explanatory. It might be too superficial if we would consider the uncertainty on the side of emitters as an apparent source of price volatility. It is a necessary condition, but not sufficient.

III. Forward Markets

When we look at future spot trade markets, they are uncertain in a sense that these spot prices are random variables, as discussed earlier. Since economic agents would not prefer facing risks, they would want to hedge the future. That is the need for forward contracts. In this section, we develop a mathematical model to analyze emissions forward markets. The focus here is on how emissions forwards are different from other financial and commodity markets. We derive theoretical forward price formulae to examine the similarities and differences.

III-A. Single-period forward market model

Let us consider a single-period model. There exist present time and only one future time, which are t=0 and t=1, respectively. At time 0, economic agents would make their decisions for holding forward market positions for time 1.[9] As mentioned in the previous section, the spot trade market price for time 1 is uncertain at time 0. It will turn into being certainly observable at time 1. In addition, the risk is systematic. Thus, all economic agents would benefit from holding forward positions for time 1 at time 0 because it helps reduce risks that come from spot price uncertainty. Following the custom of microeconomic theory, it is assumed that economic agents would maximize their expected utilities. We assume expected utility has the form of the following:

$$E\left[U\left(\tilde{R}\right)\right] \equiv E\left[\tilde{R}\right] - \frac{\gamma}{2} Var\left(\tilde{R}\right)$$

where γ represents an individual's risk-averse coefficient.

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[9] This single-period setting can be easily extended to a multi-period setting although such an extension will not lead to any additional insight.

This assumption means that an agent's expected utility is high when its expected return is high and when the variance of the return is low.[10]

In addition to notations and model settings described above, let us introduce a distinction about types of market participants. Suppose that we have market participants who are regulated emission sources, namely emitters, and those who are not regulated sources. In the discussion on spot markets in the previous section, we had implicitly considered only emitters as typical market participants. An explicit treatment of non-emitter market participants would not change anything. However, in forward markets, not only “real” demand but also speculative demand for holding the assets is an important driving force of the market. We illustrate this point here in this section. Let us use the following notations.

F: Forward trade price at time 0.

N: The number of regulated emission sources.

K: The number of non-emitter forward market participants.

$m \equiv K/(N+K)$: The proportion of non-emitter forward market participants over the total number of market participants.

h_i: Contract position for a market participant.

The hedging problem for a regulated emission source:

Let $\tilde{R}_i^F$ be the random payoff for time 1 estimated at time 0 for regulated emission source *i*. This is the sum of the profit (or loss) from a spot trade at time 1 and the profit (or loss) from forward contract that is fixed at time 0, less the GHG abatement cost for the compliance. That is:

$$(5) \qquad \tilde{R}_i^F = \tilde{S}(1) \cdot \left\{ T_i(1) - \left(\tilde{G}_i(1) - \tilde{X}_i^*(1) \right) \right\} - C_i\left(\tilde{X}_i^*(1) \right) + h_i \cdot \left(\tilde{S}(1) - F \right)$$

Notice that a potential gas emission is a function of the single factor that we introduced in the previous section. In addition, the optimal level of abatement would be determined on the realized spot trade price and gas emission. Since there is one-to-one mapping relation between spot trade price and the single factor, the randomness of the above payoff entirely depends on the spot price risk. Arranging the equation (5), we obtain an expected utility for regulated source *i* at time 0 as follows. For a detailed derivation, see Appendix A.

$$\begin{aligned}
E\left[U_i\left(\tilde{R}_i^F \right) \right] &= Var\left(\tilde{S} \right) \cdot \left(\frac{1}{2C_i''\left(\bar{X}_i^* \right)} - \frac{\beta_i}{Z} \right) + \bar{S} \cdot \left(T_i - \bar{G}_i + \bar{X}_i^* \right) - C_i\left(\bar{X}_i^* \right) + h_i \cdot \left(\bar{S} - F \right) \\
(6) \qquad & - \frac{\gamma_i}{2} \cdot \left\{ Var\left(\tilde{S} \right) \cdot \left(h_i + T_i - \bar{G}_i + \bar{X}_i^* - \frac{\bar{S}\beta_i}{Z} \right)^2 + 2 \cdot \left(Var\left(\tilde{S} \right) \right)^2 \cdot \left(\frac{1}{2C_i''\left(\bar{X}_i^* \right)} - \frac{\beta_i}{Z} \right)^2 \right\} \\
& - \frac{\gamma_i}{2} \cdot \left(Var\left(\tilde{S} \right) + \bar{S}^2 \right) \cdot Var\left(\tilde{\varepsilon}_i \right)
\end{aligned}$$

Taking the derivative of the above with respect to contract position, *h*, we obtain the following first order necessary condition for the optimality, which is also sufficient due to its concavity.

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[10] It is known that this form of expected utility is justified either when an agent would have an exponential utility function and random variables would be approximated by normal distributions, or when an agent would be assumed to care about only expectations and variances of random variables.

(7) $$\frac{\bar{S}-F}{\gamma_i Var\left(\tilde{S}\right)}+\frac{\bar{S}\beta_i}{Z}=h_i^*+T_i-\bar{G}_i+\bar{X}_i^*$$

The hedging problem for a non-source market participant:

Let $\tilde{R}_j^F$ be the random payoff for time 1 estimated at time 0 for non-source market participant *j*. Without participating in the emissions forward market, its payoff would have nothing to do with the uncertainty of the emissions market. Let $\tilde{W}_j$ be initial "wealth" of the agent *j*. This would be a payoff without the emissions forward market. Participating in the market would give the agent the following payoff at time 1.

(8) $$\tilde{R}_j^F=\tilde{W}_j+h_j\cdot\left(\tilde{S}-F\right)$$

Following the calculation similar to the case of regulated sources, we obtain the optimal solution for the hedging problem as follows.

(9) $$\frac{\bar{S}-F}{\gamma_j Var\left(\tilde{S}\right)}-\frac{Cov\left(\tilde{W}_j,\tilde{S}\right)}{Var\left(\tilde{S}\right)}=h_j^*$$

Market equilibrium:

Market clearing conditions for a forward market at time 0 and a spot market at time 1 are the following:

$$\sum_{i=1}^{N}h_i^*+\sum_{j=1}^{K}h_j^*=0$$

$$\sum_{i=1}^{N}\left(T_i-\tilde{G}_i+\tilde{X}_i^*\right)=0$$

These conditions yield forward market equilibrium price as follows.

(10) $$F=E\left[\tilde{S}\right]-m\cdot\gamma Cov\left(\tilde{w},\tilde{S}\right)+\left(1-m\right)\cdot E\left[\tilde{S}\right]\cdot\gamma Var\left(\tilde{S}\right)/C''_{ave}\quad,$$

where

$$\gamma\equiv\left(N+K\right)\cdot\left(\sum_{i=1}^{N}\gamma_i^{-1}+\sum_{j=1}^{K}\gamma_j^{-1}\right)^{-1}$$

$$w\equiv\frac{1}{K}\sum_{j=1}^{K}W_j$$

We call γ the representative risk-averse coefficient. w represents the total wealth in the economy although it is in the form of per capita.

III-B. Properties of emissions forward markets

The equation (10) tells us some important findings. The most important one is about the relation between a forward price *F* and the expected value of the future spot price *E[S(1)]*. To just briefly address this issue, let us consider two extreme cases. One is the case where there are no non-emitter market participants. That is: *m* is equal to zero. The other case, on the contrary, is the case where the number of non-emitter market participants overwhelms that of regulated emission sources. Setting *m* equal to one can approximate it. The first case of all source-participants reduces the equation (10) to the following.

$$(11) \qquad F = \left\{1 + \gamma Var\left(\tilde{S}\right) / C''_{ave}\right\} \bar{S} \qquad \text{(when } m=0\text{)}$$

The second case of a large number of non-emitters reduces the equation (10) to the following.

$$(12) \qquad F \cong \bar{S} - \gamma Cov\left(\tilde{w}, \tilde{S}\right) \qquad \text{(when } m \cong 1\text{)}$$

Since marginal abatement cost function is increasing, the equation (11) indicates that the forward price is greater than the expected value of a future spot market price. In fact, the market is a "contango," in a sense that $F>E[S(t)]$. On the other hand, the equation (12) would most likely show the opposite. As discussed earlier, spot market prices can be positively correlated to macroeconomic indicators including production, consumption, and so on. Thus, these prices can also positively be correlated to the wealth *w* in the above setting. The equation (12) implies that the forward price is less than the expected future spot market price: $F<E[S(t)]$, which is sometimes called a "normal backwardation."[11]

What the equations (11) and (12) indicate is very interesting in that the ambiguity between contango and normal backwardation in the emissions markets is entirely due to the ratio of emitter and non-emitter market participants. Without non-emitters, the market would generally show a contango. We can relate this result to the properties of an emissions permit as an asset as follows.

Any financial or commodity assets traded in exchanges would be supposed to produce dividends, yields, benefits from the consumption, or any other payoffs in the future. Such expected payoffs or benefits motivate market participants to hold these assets. Emissions permits, however, by nature would produce nothing in the future. Emitters' motivation for holding the asset is simply for the purpose of compliance. The meaning of emissions permits for emitters is thus different from that of typical financial assets. The emitters are obliged to hold the asset that is exposed to a systematic risk. The use of forward contracts thus gives them a way to hedge such systematic risk. Due to the real option value of hedging, they are willing to pay higher prices than the expected future spot prices. This results in the market being a contango.

It is natural to find that the properties specific to emissions permits would be weakened and gradually disappear, as the size of trades by non-emitter market participants gets larger. We see that the right hand side of the equation (10) is linear and strictly decreasing with respect to *m*. The increase of non-emitters' trade volume would change the nature of the market from a contango to a normal backwardation.

In commodity and financial markets in general, it is simply up to the nature of the asset in question and the properties as a financial and economic instrument whether it shows a contango or a normal backwardation.[12] Since a forward price implies a "certainty

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[11] The usage of the term "backwardation" is sometimes confusing because some futures market practitioners use a different definition. The term "contango" can also be confusing because of the same reason. In the present paper, we define having forward price less than expected spot price as a "normal backwardation," and the opposite for a "contango." We believe the definitions are most popular nowadays although John Maynard Keynes' usage was different.

[12] For a comprehensive survey on the longstanding discussion on this issue, see Duffie (1989).

equivalent" in a sense that it reflects the economic value of uncertain payoff in the future, a forward price plus "risk premium" would be equal to the expected asset price. Thus, in typical financial asset markets, it is natural for us to observe normal backwardation. In this sense, we see that the emissions market changes its appearances to those of a typical financial market, as non-emitters become the majority.

III-C. Extended CAPM for emissions forward markets

The equilibrium price equation (10) unfortunately contains a generally unobservable parameter, which is the representative risk-averse coefficient. It also contains total wealth per capita, which is not easy to define. For practical purposes, it would be useful to substitute some observable economic indicators for the parameter and the variable. It is quite common in financial markets to consider a market index such as the S&P 500 contract as a proxy for total wealth. Such a market index is called the "market contract."

If we assume that there is an appropriate market contract available, we can rewrite the equation (10). Let p be the spot price of the market contract and f_p is the futures price. Following the calculation similar to the derivation of the optimality for non-source market participants and considering the market clearing condition for the market contract, it is easy to show:

$$\bar{p} - f_p = \gamma Var(\tilde{p}).$$

Substituting the market contract for the total wealth per capita in the equation (10), we finally obtain the following forward pricing formula.

$$(13) \qquad F = \bar{S} - \left\{ m \cdot \frac{Cov(\tilde{p},\tilde{S})}{Var(\tilde{p})} - (1-m) \cdot \frac{Var(\tilde{S})}{Var(\tilde{p})} \cdot \frac{\bar{S}}{C''_{ave}} \right\} \cdot (\bar{p} - f_p)$$

Implications that the equation (13) yields are close to the same with those of the other equation (10). Emissions forward markets are contango by nature while they change the appearances as the size of non-emitter trade volume grows. However, the equation (13) tells more.

Suppose for a while that m is equal to one. The equation (13) is simplified as follows.

$$F = \bar{S} - \beta_S \cdot (\bar{p} - f_p) \text{ where } \beta_S \equiv Cov(\tilde{p},\tilde{S}) / Var(\tilde{p}).$$

This is the well-known Capital Asset Pricing Model (CAPM) for forward contracts.[13] In this sense, the equation (13) can be interpreted as an extended version of CAPM where the beta is modified as the following.

$$\beta_S^{Mdf} \equiv m \cdot \frac{Cov(\tilde{p},\tilde{S})}{Var(\tilde{p})} - (1-m) \cdot \frac{Var(\tilde{S})}{Var(\tilde{p})} \cdot \frac{\bar{S}}{C''_{ave}}$$

Again, the modified beta can be either positive or negative depending upon m, which would have never happened with the standard CAPM formula.

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[13] Although popular CAPM formula for securities would be written in terms of returns on assets, it is easy to show that the form here is equivalent to the popular one under the proper definition of "returns" on forward contracts.

It might be interesting for us to rewrite the modified beta in terms of standard deviations as follows.

$$\beta_S^{Mdf} = (1-m)\cdot\frac{\bar{S}}{C''_{ave}}\cdot\left\{\frac{m\rho C''_{ave}}{(1-m)\bar{S}}-\left(\frac{Sdev(\tilde{S})}{Sdev(\tilde{p})}\right)\right\}\left(\frac{Sdev(\tilde{S})}{Sdev(\tilde{p})}\right)$$

where ρ represents the correlation coefficient between prices of the market contract and emission permits.

Let us assume that the correlation coefficient, the standard deviation of the market contract and all other expected values are constant. It is easy to find from the above expression that the modified beta is a quadratic function in terms of the standard deviation of the emissions spot price. Thus, the modified beta is positive when the standard deviation of the emissions spot price is low while the modified beta becomes negative and the absolute value becomes larger as the standard deviation grows. FIGURE 1 illustrates the issue of whether emissions forward markets are contango or normal backwardation. For a fixed standard deviation of a future spot price, an emissions forward market can be either a contango or a normal backwardation depending upon the size of non-emitters trade volume. For a fixed size of non-emitters trade volume, a lower standard deviation of a future spot price would result in the market being a normal backwardation while a higher standard deviation would bring a contango market.

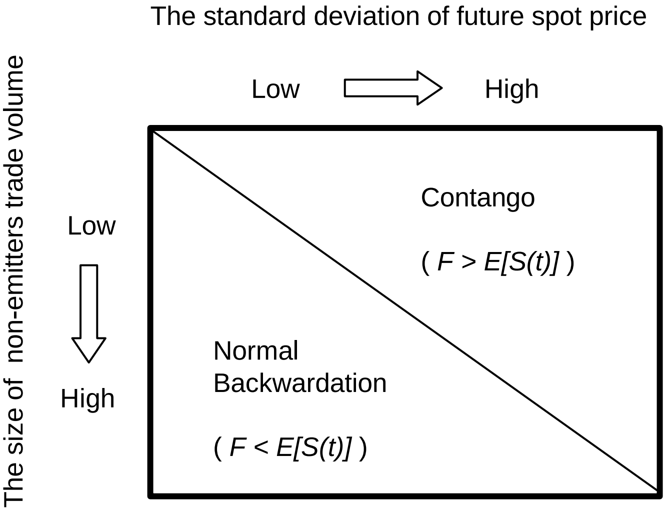

FIGURE 1. Are emissions forward markets contango or normal backwardation?

III-D. An illustration: the US SO_2 market

The above result tells us that in GHG forward markets, we would have either a contango or a normal backwardation depending on certain conditions. Since there is currently no GHG marketplace that is established and has been operated by some legislative body in any country, we will not be able to conduct statistical tests on actual data to find evidences that would support the theoretical model presented here. Our model is intended to describe GHG markets and is not directly applicable to SO_2 markets. Some critical assumptions that the paper makes, for instance, correlation among potential emissions through some macroeconomic indicators, may not apply. Keeping in mind that the model may not apply to any emissions markets other than GHG, it might still be helpful and interesting to examine actual trade data for SO_2. We briefly look at the U.S. Acid Rain Program allowance auction data.[14]

Even if we have actual data at hand, we still face a difficulty in testing our model. It is because the estimation of expected values of future spot market prices itself would be a big project and would contain many issues still needed to be discussed.[15] Clearly, a future spot price would be subject to the target set by the authority. Thus, a spot price in a year might have little to do with another spot price in another year assuming that abatement cost function is not path-dependent.

Keeping the difficulty in mind, let us assume, for the purpose of an illustrative analysis, that a growth rate of a spot price is a realization of a random variable that satisfies the ordinary least squares (OLS) conditions. That is: growth rates from year to year have the same expected values, the same variances, and no serial correlation. With this OLS assumption on the growth rate, we define $\tilde{\mu} \equiv S_{t+1}/S_t - 1$ as a random variable that follows a normal distribution. Using the expected growth rate, μ, we have the following.

(14) $S_t \cdot (1+\mu)^{T-t} = E_t[S_T]$

On the other hand, it is known that an arbitrage-free condition between present spot markets and forward markets requires the following equality.

(15) $F_{t,T} = S_t \cdot (1+r-y)^{T-t}$

where $F_{t,T}$ represents forward price at time *t* for time *T*, and

y and *r* represent the "convenience yield"[16] and the annual risk-free rate, respectively.

The equations (14) and (15) yield the following.

(16) $E_t[S_T]/F_{t,T} = (1+\mu+y-r)^{T-t}$

Therefore, the issue of whether the forward market is a contango or a normal backwardation can be reduced to that of whether the sum of the expected growth rate and the convenience yield is greater or less than the current risk-free interest rate.

The U.S. EPA allowance auction data of the acid rain program is summarized in TABLE 1. Note that, in the auction, actual trades are made on spot and advance. Also, note that the ratio between a spot price and an advance price implies the convenience yield. That is:

$$S_t / A_{t,T} = (1+y)^{T-t}$$

This relation allows us to estimate the convenience yield in average based on the data in TABLE 1. Next, from the time series data of spot prices, we estimate the expected value of the growth rate. Finally, using the interest rate date offered by the U.S. Federal Reserve,

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[14] Some private companies provide forward market data, such as Cantor Fitzgerald Environmental Brokerage Services. Because of two reasons that the analysis of SO_2 markets is not a main focus here and that the only official - in a sense of being operated by the US Environmental Protection Agency (EPA) - data source on forward trades is that of EPA, we will limit our attention to the EPA auction data.

[15] In the US SO_2 trading program, actual spot trade prices turned out to be lower than initially expected. Many studies try to explain the reasons. For example, see Conrad and Kohn (1996), Ellerman and Montero (1998), and Klaassen and Nentjes (1997).

[16] For the definition of the convenience yield and its economic meaning, see standard textbooks on futures markets including Duffie (1989).

we estimate an average risk-free interest rate for slightly long-term maturity, say 5 to 7 years. The estimated values are also shown in TABLE 1. On average, μ+y-$r \cong 13$ percent as an annual rate. The result shows that the market is clearly a normal backwardation, which implies that the presence of non-emitter traders may not be negligible, or rather may have significant influences on the market making. In fact, some private brokerage services report that trade volumes of brokers, energy traders, and marketers are growing in these days. Assume that SO_2 forward markets are similar to possible GHG markets, in a sense that they might be contango by nature without non-emitter market participants. Then, we could conclude, from the above results, that the current SO_2 market in the U.S. Acid Rain Program is functioning well as a typical asset market.

TABLE 1. U.S. Acid Rain Program; EPA data and analysis

US acid rain program: EPA auction results unit: $/ton

	1993	1994	1995	1996	1997	1998	1999	2000	2001
spot			130.00	66.05	106.75	115.01	200.55	126.00	173.57
1y-advance		150.00							
2y-advance	131.00								
3y-advance									
4y-advance									
5y-advance									
6y-advance		140.00	128.00	64.14	105.15				
7y-advance	122.00	140.00	126.00	63.01	102.15	108.30	167.55	55.27	105.72

Source: http://www.epa.gov/airmarkets/auctions/index.html

Convenience Yield									
y (percent)	1.43	1.27	0.35	0.58	0.44	0.86	2.60	12.49	7.34

Growth rate of exp. spot			96/95	97/96	98/97	99/98	00/99	01/00	
mu (percent)			-49.19	61.62	7.74	74.38	-37.17	37.75	
Average	15.85								

Annual interest rate									
r (percent)	5.19	6.03	7.12	6.14	6.62	5.71	5.36	6.51	4.88

Caluculated from data avairable at http://www.federalreserve.gov/releases/

E[S]/F-1									
mu+y-r	12.10	11.10	9.09	10.30	9.67	11.01	13.10	21.84	18.31
Average	12.95								

IV. Banking Impacts

As discussed in Section I, banking is redundant in a sense that a regulated emission source would be able to make the same arrangement to transfer the emissions right of a year to that of another year thereafter by the use of swap trades. Whether the regulatory authority would allow sources to bank their permits or not would not affect individuals' behavior regarding abatement and permit trading. However, the permission of banking might have significant impacts on permit markets because it could change the total amount of permits of each vintage year. This section focuses on these impacts.

IV-A. Arbitrage opportunity

We continue to work on the single-period model presented in the previous section. We consider time 0 and time 1, which represent the present year and a future year, respectively. Suppose an emitter wants to bank some amount of current-year vintage permits for the future. We write the amount of banking as $B_i(0)$. Due to the banking, its total permit holdings for time 0 and 1 change to $T_i(0)$-$B_i(0)$ and $T_i(1)$+$B_i(0)$, respectively. Total net profit that accrues from selling residual permits and/or buying necessary permits would be evaluated at time 0 as an expected value as follows.

$$S(0)\cdot\{(T_i(0)-B_i(0))-(G_i(0)-X_i(0))\}+\frac{F}{1+r}\cdot\left\{(T_i(1)+B_i(0))-\left(\overline{G}_i(1)-\overline{X}_i^{\,*}(1)\right)\right\}$$

where r represents risk-free interest rate between time 0 and 1.

Rearranging the above gives us the following:

$$\left(\frac{F}{1+r}-S(0)\right)\cdot B_i(0)+S(0)\cdot(T_i(0)-G_i(0)+X_i(0))+\frac{F}{1+r}\cdot\left(T_i(1)-\overline{G}_i(1)+\overline{X}_i^{\,*}(1)\right)$$

The above expression gives conditions that exclude arbitrage opportunities as follows.

Suppose that $F/(1+r)-S(0)$ is strictly positive. The emitter could make an infinitely large profit with no risks by banking large amount of permits, which is arbitrage. Thus, $F/(1+r)-S(0)$ must be non-positive. Suppose, on the contrary, $F/(1+r)-S(0)$ is strictly negative. In this case, the emitter would make a loss with a positive amount of banking. If borrowing would be allowed, a negative amount of banking would make a profit. Otherwise, the best thing that the emitter can do is to bank nothing. The above discussion yields the no-arbitrage condition for the case where banking is allowed, as follows.

$$(17)\qquad \begin{array}{ll} \dfrac{F}{1+r}=S(0) & with\quad B_i(0)>0 \\ \dfrac{F}{1+r}<S(0) & with\quad B_i(0)=0 \end{array}$$

IV-B. Spot market equilibrium under a banking regime

A banking opportunity connects the present spot trade market and the forward market through the no-arbitrage condition. Since the forward market reflects expectations on the future spot trade market, the banking opportunity leads to a direct interaction between these present and future spot trade markets. For example, the increase of uncertainty on the future spot market would change the price of forward contracts, which then might create permit transfer between the present and the future. The result would be a change in the total amount of present-year vintage permits in the market as well as a change in the equilibrium price. In order for us to analytically examine these banking impacts on the present market equilibrium, let us assume that all regulated emission sources are identical in that they have a same abatement cost function and same potential emissions. This assumption would be too simple to discuss market equilibrium in one year, but would be satisfactory for us to focus on the interaction between two markets in different years. With this assumption, we omit the subscript that represents individual agent i.

In addition, we assume that marginal abatement cost functions can be approximated by linear functions as follows.

$$MC(X(t),t)\equiv c_t X(t)\qquad for\quad t=0,1$$

Substituting the forward price formula (13) for the price in the no-arbitrage condition of (17) above, we obtain the optimal banking amount. Then, it yields the equilibrium price for the present spot trade market as follows. The detail of the above derivation is described in Appendix B.

(18) $S(0) = max\{S^+, S^{NB}(0)\}$,

where

(19) $$S^+ = c_0 \cdot \left(X^{NB}(0) + \overline{X}^{NB}(1)\right) \cdot \left\{1 - \frac{(1+r)}{(1+r) + c_1/c_0 + (1-m)\gamma\sigma_S^2/c_0}\right\} - \frac{m\gamma\rho\sigma_p\sigma_S}{(1+r) + c_1/c_0 + (1-m)\gamma\sigma_S^2/c_0},$$

$S^{NB}(0) = c_0 X^{NB}(0)$, and $X^{NB}(t) = G(t) - T(t)$.

$\sigma_S, \sigma_p, and\ \rho$ are standard deviations of the emission spot trade market price at time 1, the market contract price at time 1, and the correlation coefficient between the two. *Xs* represent emission abatements while the superscript *NB* indicates that it is the value that would be realized if no banking would be allowed.

It is worth to point out that the equation (18) indicates that the present spot market price has a lower bound. The lower bound is the price that would be realized if no banking would be allowed. In this sense, the permission of banking can only contribute to the increase of the present spot price, but never to the decrease.

IV-C. The impacts on the present spot market price

Let us examine the implications of the equations (18) and (19). Our interests are the impacts of uncertainty, technology progress, changes in potential emissions and emission endowments, and the ratio of emitter and non-emitter market participants.

The impact of uncertainty:

When we observe the equation (18), the impact of uncertainty of the future on the present spot price would seem complex at a glance. Basically, it contains two forces. One of them is due to regulated emitters while the other is due to non-emitter market participants. For the purpose of identifying these forces, let us first consider the case with no non-emitter market participant. Namely, *m* is to be zero. The equation (19) is reduced to the following.

(20) $$S^+ = c_0 \cdot \left(X^{NB}(0) + \overline{X}^{NB}(1)\right) \cdot \left\{1 - \frac{(1+r)}{(1+r) + c_1/c_0 + \gamma\sigma_S^2/c_0}\right\} \qquad \text{(when } m=0\text{)}$$

It is easy to find that the equation (20) is hyperbolic and strictly increasing with respect to the variance σ_S^2. It approaches to $c_0 \cdot \left(X^{NB}(0) + \overline{X}^{NB}(1)\right)$ as σ_S^2 approaches to infinity, which is the upper bound of the function.

The economic interpretation of the increasing spot price will be the following. When the uncertainty regarding the future increases, the forward market price goes up due to the formula of the equation (11). The arbitrage-free condition then gives rise to the increase of the present spot market price. At the same time, the increase of the uncertainty on the future makes regulated emitters rush the banking of their permits to the future year. This leads them to start expecting an excess supply of permits in the future. An excess supply would cause the decline of the expected future spot market price. Through the forward pricing formula and the arbitrage-free condition, the present spot price would also decline, which yields equilibrium.

Suppose next that the number of non-emitter market participants overwhelms that of source participants. We can consider such a case by setting *m* to be nearly one, which leads to the following.

$$(21)\qquad S^{+} \cong c_0 \cdot \left(X^{NB}(0)+\bar{X}^{NB}(1)\right)\cdot\left\{1-\frac{(1+r)}{(1+r)+c_1/c_0}\right\}-\frac{\gamma\rho\sigma_P\sigma_S}{(1+r)+c_1/c_0}\qquad \text{(when } m\cong 1\text{)}$$

We can easily find that the equation (21) is linear and decreasing with respect to the standard deviation σ_S assuming that the correlation coefficient is positive. The increase of the standard deviation leads to the decline of the spot trade price, which is completely opposite to the case of no non-emitter market participants. Since we have the lower bound as we see above, the decline is limited.

The total impact of the increase of uncertainty is the sum of the two; the positive impact with the case of *m=0* and the negative impact with the case of *m≅1*. Since the first force that gives rise to the increase of the present spot price depends on the square of the standard deviation, the first one overwhelms the second one, as the standard deviation gets large. Thus, a typical example of the total impact can be depicted as in FIGURE 2. The increase of uncertainty on the future gives rise to the declines of the present spot price first and then contributes to the increases of them.

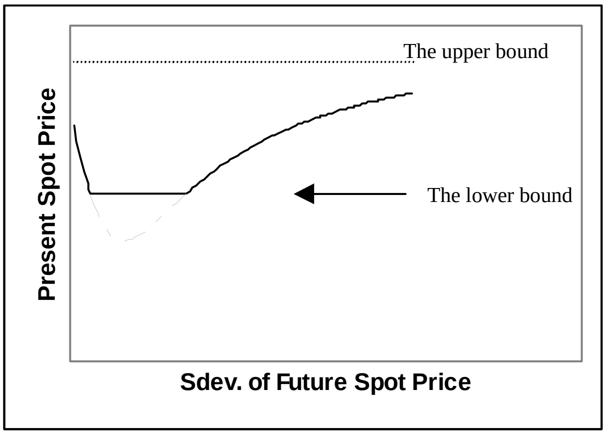

FIGURE 2. An example of the impact of uncertainty on the present spot price

The impact of technology progress:

Technology is entirely represented by the coefficients of linear marginal abatement cost functions. Technology progress can be considered as the change in the ratio of these coefficients. In fact, the decline of c_1/c_0 describes technology progress in our model. We find that the equation (19) is a hyperbolic function of c_1/c_0 and is increasing with respect to c_1/c_0. It indicates that technology progress would contribute to the decline of the present spot market price. The direction of the impact is not affected by the ratio of emitter and non-emitter market participants.

The impact of the growth of potential emission:

The growth of potential emissions leads to the increase of emission abatement required. Thus, it gives rise to the increase of the present spot price. The equation (19) tells us that the impact is linear in the future potential emission.

The impact of the increase of future emission endowment:

The increase of the endowment of future emission permits is mathematically equivalent to the decline of the future potential emission in the equation (19). Thus, the impact is the opposite.

The impact of the change in the proportion of non-emitter market participants:

The equation (19) is hyperbolic and strictly increasing with respect to 1-*m*. Thus, it is decreasing with respect to *m*. The increase of the ratio of emitter and non-emitter market participants leads to the decline of the present spot price.

The impacts discussed above are summarized in TABLE 2.

TABLE 2. The impacts of banking on present spot trade market prices

Factors	Present spot price
Uncertainty on future prices and emissions ↑	↓ at first, then, ↑
Technological progress ↑	↓
Expected emission volume ↑	↑
Emission endowment (target set by the authority) ↑	↓
The size of non-emitter traders ↑	↓

V. Conclusion

The paper presented a forward pricing model that helped analyze domestic greenhouse gas emissions trading markets with/without banking. It highlighted the specific nature of forward markets and the impacts of banking.

Greenhouse gas (GHG) emissions are closely related to domestic economic activities in a country. Thus, spot trade market prices might be correlated to some macroeconomic indicators, which would create a systematic risk in future spot prices. It was pointed out that the stochastic nature of future spot prices was not self-explanatory because potential emissions from individual emitters could be negatively correlated to each other and thus could be canceled out. This point should not be underestimated because the uncertainty of future spot trade prices is the only reason for the need for forward contracts and other derivatives trades.

In Section III, we developed an analytical model that describes risk-hedging behaviors of regulated emitters and non-emitters, and a forward market equilibrium. The model suggested a forward pricing formula. We also related the formula to the well-known capital asset pricing model (CAPM) and examined both similarities and differences. The most important implication obtained was the following. GHG emission forward markets are by nature contango in a sense that the expected future spot market prices are less than the present forward price. One possible explanation is that emitters' motivation for holding emission permits is simply for the purpose of compliance, not for that of earning dividends. The meaning of the asset for emitters is thus completely different from that of typical financial assets. The emitters are obliged to hold the permits that are exposed to a systematic risk. The use of forward contracts gives them a way to hedge such risk. On the other hand, for non-emitters who are not under the regulation, emissions trading may provide opportunities for speculative trades as well as risk hedging. For non-emitters, emissions trades are similar to typical financial trades. In this sense, it is natural to see that the increase of the trade volume traded by non-emitter market participants changes the nature of the markets into normal backwardation which is the opposite to contango. The increase in uncertainty on future spot prices would be a reverting force from a normal backwardation to a contango.

Another important implication of the forward pricing formula is related to economic consequences of banking. When banking is allowed, the present spot market equilibrium and that of a future spot market are connected to each other. The forward pricing formula combined with the arbitrage-free condition between spot and forward markets allows us to calculate the amount of permit banking and the spot market equilibrium prices. It is found that the increase of uncertainty on future spot market prices and potential emissions may contribute to the decline of the present spot price at first, but soon give rise to the increase of them. Other factors including technological progress, the decline of emission growth, and the size of trade volume by non-emitter traders turn out to have negative impacts on the present spot. However, the present price with the authority's permission of banking would not be less than that without the permission of banking. In this way, the permission of banking by the authority can only contribute to the increase of the present spot price but never contribute to the decline.

In most environmental policy debates, the debate on whether setting a target each year (or period) is necessary or not would be followed by the debate on the choice of policy instruments. In fact, the introduction of the Kyoto mechanisms was proposed as one of the possible ways to achieve GHG abatements by each compliance period that have been agreed under the Framework Convention on Climate Change (FCCC). Thus, allowing banking after setting targets does not seem to make sense in light of the original purpose of environmental regulations. Some advocates, however, insist that allowing banking would give regulated sources flexible options and thus contribute to the decline of prices. In the ongoing markets of SO_2 and NO_x in the US, banking has actually been allowed. In the debate of domestic or regional carbon trading, a consensus has not been reached. The result of the paper could motivate pros and cons on the banking argument depending on their interests.

Appendix A: Derivation of the Equation (6)

Using the equations (2), (3) and (4) and the notion $\overline{S} = MC_i\left(\overline{X}_i^*\right)$ in equilibrium under the assumption of linear marginal cost function, we can rewrite all variables in terms of spot trade price as follows.

$$\tilde{G}_i = \overline{G}_i + \beta_i/Z \cdot \left(\tilde{S} - \overline{S}\right) + \tilde{\varepsilon}_i$$

$$\tilde{X}_i^{\,*} = \overline{X}_i^{\,*} + 1/C_i''\left(\overline{X}_i^{\,*}\right) \cdot \left(\tilde{S} - \overline{S}\right)$$

$$C_i\left(\tilde{X}_i^*\right) \cong C\left(\overline{X}_i^*\right) + \overline{S}/C_i''\left(\overline{X}_i^*\right) \cdot \left(\tilde{S} - \overline{S}\right) + \frac{1}{2} \cdot 1/C_i''\left(\overline{X}_i^*\right) \cdot \left(\tilde{S} - \overline{S}\right)^2$$

Substituting the above for the variables in the equation (5), we obtain the following.

(A1)
$$\begin{aligned}\tilde{R}_i^F = {} & \left(\tilde{S} - \overline{S}\right) \cdot \left\{\left(T_i - \overline{G}_i + \overline{X}_i^*\right) - \overline{S}\beta_i/Z - \tilde{\varepsilon}_i\right\} + \left(\tilde{S} - \overline{S}\right)^2 \cdot \left\{1/\left(2C_i''\right) - \beta_i/Z\right\} \\ & + \overline{S} \cdot \left\{\left(T_i - \overline{G}_i + \overline{X}_i^*\right) - \tilde{\varepsilon}_i\right\} - C_i\left(\overline{X}_i^{\,*}\right) + h_i \cdot \left(\tilde{S} - F\right)\end{aligned}$$

Taking the expectation of the equation (A1) yields the following.

$$E\left[\tilde{R}_i^F\right] = Var\left(\tilde{S}\right) \cdot \left(1/\left(2C_i''\right) - \beta_i/Z\right) + \overline{S} \cdot \left(T_i - \overline{G}_i + \overline{X}_i^*\right) - C_i\left(\overline{X}_i^{\,*}\right) + h_i \cdot \left(\overline{S} - F\right)$$

The variance is also calculated from the above equation as follows.

$$Var\left(\tilde{R}_i^F\right) = Var\left(\tilde{S}\right) \cdot \left\{\left(h_i + T_i - \overline{G}_i + \overline{X}_i^* - \overline{S}\,\beta_i/Z\right)^2 + Var\left(\tilde{\varepsilon}_i\right)\right\} + 2 \cdot \left(Var\left(\tilde{S}\right)\right)^2 \cdot \left(1/\left(2C_i''\right) - \beta_i/Z\right)^2 + \overline{S}^{\,2} Var\left(\tilde{\varepsilon}_i\right)$$

We finally obtain the equation (6).

Appendix B: Derivation of the Equation (18)

We continue to assume that all regulated sources are identical and write the amount of banked permits for each individual as *B(0)*. The banking opportunity would change equilibrium spot prices for time 0 and time 1 as follows.

(A2)
$$\begin{aligned} S(0) &= S^{NB}(0) + c_0 B(0) \\ S(1) &= S^{NB}(1) - c_1 B(0)\end{aligned}$$

Thus the equations (13) and (17) yield the following inequality.

$$(1+r) \cdot \left(S^{NB}(0) + c_0 B(0)\right) \geq \overline{S}^{NB}(1) - c_1 B(0) + \gamma(1-m)\sigma_S^{\ 2}\left(\overline{X}^{NB}(1) - B(0)\right) - m\gamma\rho\sigma_p\sigma_S$$

Rearranging the above in terms of *B(0)*, we obtain:

$$\left\{(1+r)c_0 + c_1 + \gamma(1-m)\sigma_S^{\ 2}\right\}B(0) \geq \overline{S}^{NB}(1) - (1+r)S^{NB}(0) + \gamma(1-m)\sigma_S^{\ 2}\,\overline{X}^{NB}(1) - m\gamma\rho\sigma_p\sigma_S$$

which yields,

$$B(0) = max\left\{B^+, 0\right\},$$

where

$$B^+ = \frac{c_1\overline{X}^{NB}(1) - (1+r)c_0 X^{NB}(0) + (1-m)\gamma\overline{X}^{NB}(1)\sigma_S^2 - m\gamma\rho\sigma_p\sigma_S}{(1+r)c_0 + c_1 + (1-m)\gamma\sigma_S^2}.$$

Substituting the *B(0)* for that in the equation (A2), we obtain the equation (18).

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