Analysis of International Emissions Trading System Applying a Multi-Agent Model

-Considering the Kyoto Protocol-

Ken'ichi MATSUMOTO*

Abstract

In this study, a multi-agent simulation model is constructed and international emissions trading (IET) of CO_2 considering the Kyoto Protocol is analyzed applying it. Then, the results of the analysis are compared with the case of "no IET" and the case of "theoretical IET". Unlike traditional economic methods, multi-agent models make analysis of complex social systems like emissions trading possible without strong assumptions. In the model, each country (region) behaves as an independent agent in the interactions and tries to abate CO_2 emissions with minimum cost through decision making between self-abatement and IET depending on its local information. In the trade, offer price, the expected trade price, of each region is determined based on the marginal abatement cost function and strategies of the region, and offer amount, the expected trade amounts, of each region is determined based on CO_2 emissions and emissions rights of the region.

As a result, although the results of each simulation are similar, the states of trade are continuously fluctuating. From the comparisons with the case of no IET and the case of theoretical IET, it is revealed that the costs and the self-abatement amounts of the developed countries become smaller, the profit of economies in transition which holds emissions rights more than CO_2 emissions becomes larger, and the total cost becomes smaller by introducing IET assuming bounded rationality. However, these effects are far below those of the theoretical IET despite of the active trade in the simulations.

Keywords: Kyoto Protocol, CO_2 Emissions Trading, Multi-Agent Model, Bounded Rationality, Marginal Abatement Cost Function

---

* Affiliation: School of Policy Studies, Kwansei Gakuin University
JSPS Research Fellow
Address: 2-1, Gakuen, Sanda, Hyogo, 669-1337, Japan
E-mail: kenichimatsu@ksc.kwansei.ac.jp

1. Introduction

International emissions trading (IET) will be a core method to abate greenhouse gases (GHG) emissions efficiently under the Kyoto Protocol. Although a number of the related economic studies have been done, most of such studies have introduced traditional strong economic assumptions such as the representative individual and the perfect rationality to avoid difficulties in the analyses. As a result, equilibrium solutions are introduced under such assumptions using top-down models with sophisticated mathematical formulae, in which some important and complex conditions of real economic systems are ignored. However, the real world which is based on interactions among economic entities, and among economic entities and systems is extremely complex and the behavior of economic entities is bounded rational. Furthermore, it is not always in the equilibrium state. Therefore, while traditional economic methodologies are easy to operate and useful to observe rough results of such complicated behavior, they are not enough to analyze social and economic problems in detail. In addition, there is possibility that misdirected outcomes are drawn

To solve the problems of traditional economic methodologies, multi-agent simulation analysis, a bottom-up approach, is considered one of the useful approaches. It starts from micro-agents and they behave based on their own local information, namely bounded rationality of agents is considered. It can properly express the condition of social systems in which interactions among micro-agents and among micro-agents and macro-systems are observed. Recently, market analysis based on this approach is seen in some studies (Kaneda (2005), Palmer et al. (1994)) and it is also applied to analyze IET (Mizuta and Yamagata (2001, 2003), Kimura and Oda (2002), Oda et al. (2003))[1]. However, the framework of this methodology has not been consolidated, yet, in spite of its availableness.

In this paper, a unique multi-agent model is constructed and IET considering the Kyoto Protocol is analyzed. Then, the results of the simulations are shown and compared with the states brought by the "theoretical IET", that is perfectly rational IET, and the "no IET", that is all countries achieve the emissions (abatement) targets without IET.

---

[1] Multi-agent models are used to analyze various social and scientific phenomena. Studies about ecosystems, stock markets, traffic jams, political negotiations, and communications are the examples.

2. Methods

2.1 Assumptions of Analysis

The assumptions of this analysis are as follows. Countries participating in IET are developed countries and economies in transition ratifying the Kyoto Protocol, and they are aggregated into four regions. That is to say, developed countries withdrawing from it, the United States and Australia, are not considered here. Each region is thought an independent agent. Then, only CO_2 emissions and CO_2 emissions trading are considered (not all of GHG) in the analysis. Because the Kyoto Protocol is taken into account in this paper, the target period is the first commitment period and the emissions targets of the regions follow it.

The BAU CO_2 emissions levels of the regions in 2008-2012 are estimated referring to the latest emissions data of Marland et al. (2006) and the expected growth rates of CO_2 emissions from IEA (2004). Then, the emissions rights assigned to each region are calculated from the Kyoto Protocol.

Table 1 shows the assumptions described above. JPN, E_U, and KPI are developed countries, and EFS is economies in transition.

Table 1 Structure of Regions, Emissions Targets (% from base year), and Total BAU CO_2 Emissions and Total Emissions Rights for 5 years (Mt-CO_2)

Code	Region	Target	CO_2 Emissions	Emissions Rights
JPN	Japan	94	6685.4	5035.8
E_U	EU	92	17183.8	14349.7
KPI	Rest of the OECD countries included in the Annex B of the Kyoto Protocol and ratifying it	94.5	3760.8	2456.4
EFS	Russia and Eastern Europe included in the Annex B of the Kyoto Protocol and ratifying it	98.1	14118.8	19949.8

*Since KPI and EFS are composed of multiple countries and regions, the target rates are the weighted averages of the rate of each country or region included by CO_2 emissions of the country or the region.

2.2 Multi-Agent Model

As described in the above section, there are some previous studies analyzing IET applying multi-agent models. Although Kimura and Oda (2002), Mizuta and Yamagata (2001, 2003), and Oda et al. (2003) give crucial hints to construct the model of this study, it also includes some unique and realistic characteristics. For example, unlike Kimura and Oda (2002) and Oda et al. (2003), marginal abatement cost (MAC) functions are adopted for decision making, whether to trade emissions rights or not, of each region[2]. Furthermore, real regions and their emissions rights and emissions are used instead of imaginary ones. Also, the constructed model can appropriately treat behavior of regions whose emissions rights are not less than the CO_2 emissions[3]. Then, unlike Mizuta and Yamagata (2001, 2003), bilateral trade is applied as the trade method[4] and trade is made multiple times in one year whenever an offer price, an expected trade price, to sell or buy is accepted by a target region, a trade partner[5]. Moreover, each region uses strategies for decision making. The details of this model are described below.

In this model, the trade method adopted is bilateral trade as mentioned above[6] and the purpose of each region is to abate CO_2 emissions below its emissions rights and minimize the cost (or maximize the profit) simultaneously. Each region behaves based on the local information of its own such as the MAC function, the CO_2 emissions, the emissions rights, and the strategies.

The flow of this model is as follows. Also, Fig.1 shows the structure of trade in the model.

1. Establishment of the annual plan
2. Offer to sell or buy, answer, and trade
3. Self-abatement of CO_2 emissions

---

[2] Kimura and Oda (2002) and Oda et al. (2003) consider that MAC of each region is constant.

[3] EFS comes under this example.

[4] Mizuta and Yamagata (2001, 2003) apply double auction as the trade method.

[5] Mizuta and Yamagata (2001, 2003) assume that trade is made once a year under the equilibrium state.

[6] Although some other trade methods such as double auction can be considered, bilateral trade is adopted because the number of traders is small in this study.

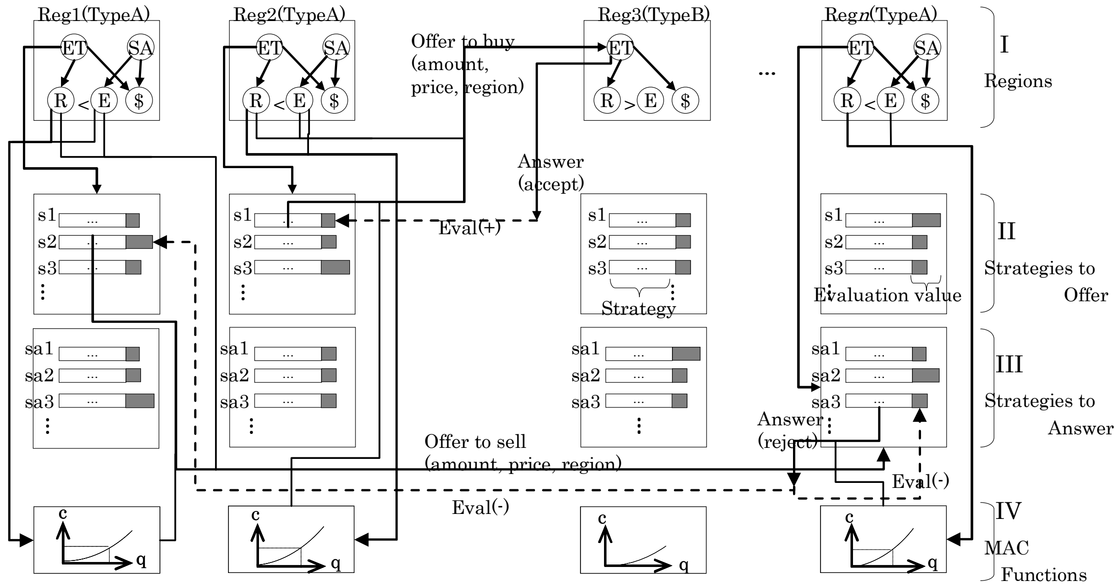

Fig.1 Structure of Trade

*Reg: region, ET: emissions trading, SA: self-abatement, R: emissions rights, E: CO_2 emissions, $: money, s: strategy to offer, sa: strategy to answer, Eval(+): positive evaluation, Eval(-): negative evaluation

The first stage is a process to determine a CO_2 amount each region expects to abate and trade in the year. There are two types of choices according to the CO_2 emissions and the emissions rights of each region (Fig.1-I). If a region has the emissions rights less than the CO_2 emissions (Type A), it can be either a buyer or a seller of emissions rights. It determines the expected amount to abate by itself and through IET in the year based on its self-abatement rate, its deficient emissions rights, and remaining years. It also determines the expected amount of the emissions rights it is willing to sell and buy where the amount to buy is thought to be larger than that to sell. If a region has the excess emissions rights (Type B), it only can be a seller and determines the expected amount it is willing to sell based on the excess amount and remaining years.

This process is implemented once at the start of a year.

The second stage is a process to trade. Concerning Type A, each region selects a strategy to offer (Fig.1-II), determines an offer amount (Fig.1-I), which is an expected trade amount, and calculates MAC (Fig.1-IV) to determine an offer price. Each strategy is composed of a position (2 options), which determines to be a buyer or a seller, a range of offer price (10 options), which determines how much to add on (to reduce from) the MAC when offering to sell (buy) in percentages 1-10%[7], and a target (3 options), which is to determine a trading partner. That is to say, each region has 60 (2 × 10 × 3) kinds of strategies. In addition, an evaluation value, which indicates how superior the strategy is, is assigned to it and it is selected randomly with the probability proportional to the evaluation. The offer amount is determined according to the expected buying or selling amount obtained in the first stage. The offer price to sell (to buy) is determined to be able to gain profit (reduce cost) from trade and self-abatement. Therefore, the offer price to sell (buy) is calculated by adding (reducing) the range of offer price obtained from the selected strategy on (from) the MAC. Then, the information about the offer price and offer amount is sent to the trading partner determined by the selected strategy. When a region of Type A receives the offer message, it determines whether to accept or reject it by selecting a strategy to answer (Fig.1-III). Each strategy is composed of a target (3 options), which is to determine a trading partner, and a range of price (10 options), which determines how much to add on (reduce from) MAC when receiving offers to buy (sell) in percentages 1-10% like strategies to offer. That is to say, each region has 30 (3 × 10) kinds of strategies to answer. If the offer price to buy (sell) from the determined trading partner is higher (lower) than the MAC plus (minus) the range of price of the receiver, the offer message is accepted and the entire offer amount is traded. The offer price is treated as the trade price. On the contrary, the offer message is rejected if the offer price to buy (sell) is lower (higher) than the MAC plus (minus) the range of price of the receiver.

Concerning Type B, they do not send any offer messages and only receive the messages. Because each region only can be a seller, it does not use strategies to determine the behavior and it accepts offers to buy and rejects those to sell. The offer price is treated as the trade price and the entire offer amount is traded.

When a trade is made, the evaluation value on the selected strategy (both the strategy to offer and answer) is updated. Since success of trade means success of the selected strategy, the evaluation on it is raised. On the contrary, since failure of trade means failure of the selected strategy, the evaluation on it is lowered. The evaluation is changed proportionally to the range of price. That is, the updated value is calculated by [original value ±

[7] A range of price is useful to determine whether the region can reduce cost (or get profit) certainly from trade.

range of price]. This is reinforcement learning. Because regions of Type B do not use strategies, this process is implemented only for regions of Type A.

This process is repeated 365 times a year.

The third stage is a process of self-abatement (Fig.1-I). This model assumes that each region abates its CO_2 emissions over its emissions rights by itself as a result of IET and it is implemented every year. Although the self-abatement amount is determined according to the self-abatement rate, the rate is updated every year and the CO_2 emissions become equal to the emissions rights in each region in the end of the simulation[8].

This process is implemented once in the year-end.

The model is constructed using a simulator, KK-MAS, developed by KOZO KEIKAKU ENGINEERING Inc..

2.3 Marginal Abatement Cost Functions

As described above, MAC functions are used to calculate MAC. They are estimated using a general equilibrium model, the GTAP-E model (Burniaux and Truong (2002)). Each of them is a function of the abatement levels and each region has a unique function. In order to construct each one, the GTAP-E model is run under different abatement levels of the corresponding region[9] and MAC against each abatement level is obtained. Then, a MAC function (a quadratic function: $c = aq^2 + bq$, where c is the MAC in \$/t-CO_2, q is the abatement level in Mt-CO_2, and a and b are the coefficients) of each region is approximated by the least squares method. Table 2 shows the coefficients, a and b. All coefficients of determination in the approximations are 0.99. In this study, identical MAC functions are applied every year to make the analysis simple.

Table 2 Coefficients of Estimated MAC Functions ($c = aq^2 + bq$)

Region	a	b
JPN	0.00023	0.12395
E_U	0.00002	0.03623
KPI	0.00036	0.10782
EFS	0.00002	0.02988

[8] However, there is possibility that emissions rights are larger than CO_2 emissions.

[9] In this study, 1%, 5%, 10%, 15%, 20%, 25%, and 30% abatement of the CO_2 emissions are used to estimate.

3. Results and Discussions

For the analysis, the above multi-agent simulation model is run for 50 times[10]. In this section, at first, the results of the simulations are shown and then, they are compared with the calculated results of the no IET and the theoretical IET.

The results of the simulations are summarized in Table 3 and Table 4. Also, Fig.2 shows one simulation result.

Table 3 Summary of Simulation Results (Trade)

	Value
Average Price ($/t-$CO_2$)	26.66 (0.36)
Traded Amount (Mt-CO_2/y)	468.56 (8.38)
Annual Trade Frequency	278.86 (3.47)

*The values are averages and standard deviations.

Table 4 Summary of Simulation Results (Regional Influences)

Region	Cost (M$/y)	Self-Abatement (Mt-CO_2/y)
JPN	7819.67 (47.86)	185.49 (1.89)
E_U	6272.20 (53.93)	430.27 (5.70)
KPI	4931.88 (30.21)	160.582 (1.70)
EFS	-9328.99 (86.49)	0 (0)
Total	9694.77 (153.24)	3881.42 (45.46)

*The values are averages and standard deviations.

[10] Because some variables such as offer price and offer amounts take random values in each trial and different results might be brought, the simulation is implemented 50 times to obtain the average of the trials.

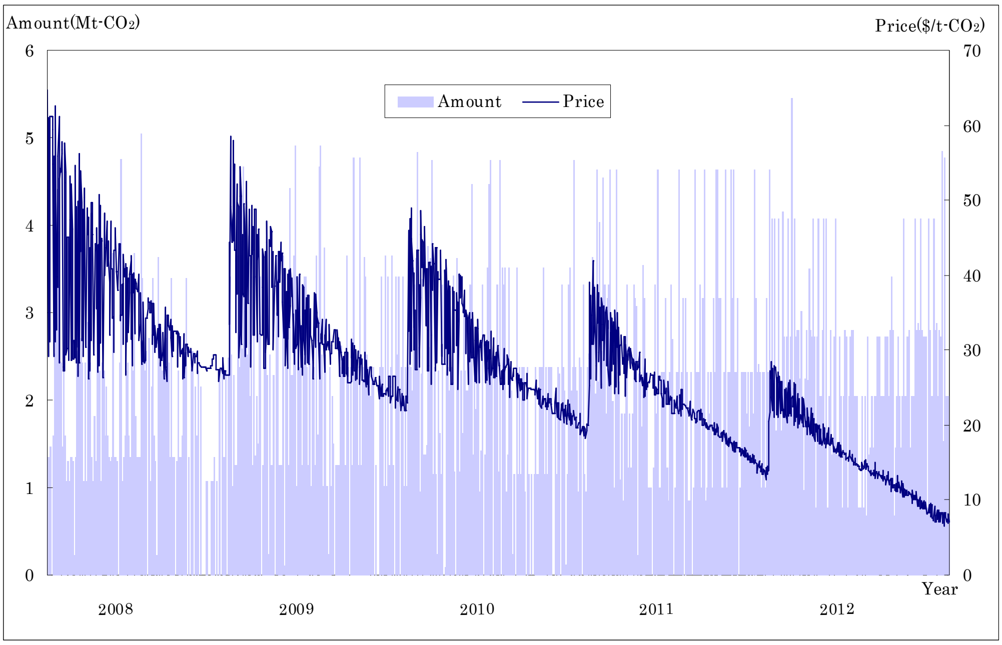

Fig.2 One Simulation Result

On the whole, as Table 3 and Table 4 indicate, no big differences are seen among the simulations. Standard deviations of the items in the tables are relatively small. However, as Fig.2 represents, trade price and trade amount fluctuate widely in each simulation. In this case, trade is implemented 1394 times in 5 years. The average trade price is \$26.34/t-CO_2, whereas the standard deviation is \$10.18/t-CO_2 (the highest one is \$64.68/t-CO_2 and the lowest one is \$6.51/t-CO_2), and the average trade amount in one time is 1.74Mt-CO_2, whereas the standard deviation is 1.02Mt-CO_2 (the largest one is 5.46Mt-CO_2 and the smallest one is zero). The trade price tends to decrease in each year and year by year[11] [12], and the trade amount tends to increase year by year[13]. The cause of the first tendency is that the more the cumulative purchase amount of emissions rights of each region in a year, the lower the demand price, namely the offer price to buy. The cause of the second tendency is that because the regions which hold insufficient amount of emissions rights tend to demand more emissions rights as years pass to achieve the targets and one region, EFS, holds sufficient

[11] The average trade price is \$36.84/t-CO_2 in the first year, \$32.47/t-CO_2 in the second year, \$28.83/t-CO_2 in the third year, \$23.05/t-CO_2 in the fourth year, and \$15.65/t-CO_2 in the final year.

[12] These tendencies are true for the other simulation results.

[13] The trade amount is 373.74Mt-CO_2 in the first year, 473.30Mt-CO_2 in the second year, 460.96Mt-CO_2 in the third year, 529.69Mt-CO_2 in the fourth year, and 582.14Mt-CO_2 in the final year.

amount of emissions rights to sell, the average demand price is decreased. Then, the cause of the third tendency is that because the average price is declined year by year, the demand is increased in later years. Concerning the trade frequency, as trade is realized about 75% probability, it is due to the continual behavior of EFS, which has a considerable amount of excess emissions rights, as a seller.

Concerning the influences on each region, it costs the developed countries to achieve the targets. On the other hand, because EFS holds a large amount of excess emissions rights, it gains some profit through IET and abates no CO_2 emissions by itself at all.

Next, comparisons of the above results with the no IET and the theoretical IET show some interesting results. The latter two are calculated from the MAC functions and the calculated results are shown in Table 5. Concerning the no IET, each self-abatement amount is [(emissions – emissions rights) / 5] of the region[14] and each cost is calculated by [$\int(aq_i^2 + bq_i)\, dq_i$] where q_i is the self-abatement amount of region i. Concerning the theoretical IET, because the total emissions rights are larger than the total CO_2 emissions[15] in the world, the cost and the self-abatement amount of each region and the world are zero. In this case, the trade price is zero as well.

Table 5 Calculated Results of No IET and Theoretical IET

Region	No IET		Theoretical IET	
	Cost (M$/y)	Self-Abatement ($Mt\text{-}CO_2/y$)	Cost (M$/y)	Self-Abatement ($Mt\text{-}CO_2/y$)
JPN	9527.33	329.92	0	0
E_U	7285.72	566.81	0	0
KPI	5815.69	260.88	0	0
EFS	0	0	0	0
Total	22628.74	1157.61	0	0

Comparing the simulation results with the no IET, the costs and the self-abatement amounts of the developed countries are smaller, and EFS gains some profit through IET. Consequently, the total cost is smaller as well. Comparing with the theoretical IET, on the other hand, the costs and the self-abatement amounts of the developed countries are larger. Also, the trade price is higher. However, EFS gains profits because it does not sell the entire amount it can sell and the trade price becomes much higher as a result.

[14] If the solution is below zero, it means that the region does not abate emissions.
[15] The total amounts of emissions rights and CO_2 emissions are the sum of emissions rights and CO_2 emissions of four regions respectively.

Consequently, the total cost becomes larger as well. The reasons that the simulation results are inferior are as follows. Concerning the theoretical IET, since trade is implemented to equalize MAC of all regions by the top-down approach, one exactly optimum trade price is determined and just a optimum quantity of emissions rights determined by the price are traded. With regard to the simulation, however, regions take the initiative of the trade and they never know the overall optimality. In addition, trade is implemented repeatedly in a year, and trade price and amount fluctuate depending on the market conditions (see Fig.2). Consequently, the optimum trade is not realized unlike the theoretical IET.

From these comparisons, it is indicated that the simulation results are placed between the no IET and the theoretical IET, and the actual cost reduction effects brought by IET are much smaller than the theoretical expectation.

4. Concluding Remarks

In this study, a multi-agent model for emissions trading analysis was structured and international emissions trading was simulated. Then, by comparing the simulation results with the "no IET" and the "theoretical IET", the effects of IET under the condition of bounded rationality were clarified. As a result, because emissions rights were sold to developed countries, the total cost to achieve the targets of the Kyoto Protocol was reduced even under bounded rationality of regions (agents) through IET. However, the realized efficiency was far from that brought by the theoretical IET, in spite of the vigorous trade.

Since theoretical IET never exists in reality, it is expected that this study and the constructed multi-agent model will help analyzing and finding effective and efficient IET systems reflecting reality.

For the future investigation, it is important to analyze the influences when different trade methods are adopted and when the number of regions participating in IET is different. In addition, since the constructed model was a simple framework and only IET under simple assumptions was analyzed, it is necessary to study methods to analyze IET by incorporating some realistic assumptions, for example trading costs and various climate change policies, into the model. Furthermore, investigation of more efficient IET is necessary as well.

References

Burniaux, J.M. and Truong, T.P. (2002) GTAP-E: An Energy-Environmental Version of the GTAP Model. GTAP Technical Paper 16.

IEA (2004) World Energy Outlook 2004. IEA Publications: Paris.

Kaneda, T. (2005) Simulation & Gaming of the Social Design. Kyoritsu shuppan: Tokyo (in Japanese).

Kimura, K. and Oda, M. (2002) Formation of the International Environmental Regime -Searching for Desirable Emissions Trading System. In Yamakage, S. and Hattori, S (eds.) Artificial Society in the Computer. Kyoritsu Shuppan: Tokyo, 195-210 (in Japanese).

Marland, G., Boden, T.A., and Andres R.J. (2006) Global, Regional, and National Fossil Fuel CO_2 Emissions. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A., http://cdiac.ornl.gov/. Cited December 4, 2006.

Mizuta, H. and Yamagata, Y. (2001) Agent-based Simulation and Greenhouse Gas Emissions Trading. Proceedings of the 2001 Winter Simulation Conference, 535-540.

Mizuta, H. and Yamagata, Y. (2002) Simulation and Gaming for International Emissions Trading IEICE Technical Report 101(536), 65-71 (in Japanese).

Oda, M., Kimura, K., and Tamada, M. (2003) A Study of International Emissions Trading Using Multi-Agent Simulation. IEICE Technical Report 102(613), 43-46 (in Japanese).

Palmer, R.G., Arthur, W.B., Holland, J.H., LeBarone, B., and Taylerf, P. (1994) Artificial Economic Life: a Simple Model of a Stockmarket. Physica D 75, 264-274.