Applying Matching Strategies in Climate Change Negotiations

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Abstract This paper aims to apply game theory matching mechanisms to international climate change negotiations using numerical analysis in order to overcome the free-riding problem without a central authority. The analysis found that the mechanisms can increase the reduction by 2.5 times compared to the case without the mechanisms. It also demonstrates that coupling it with an emission trading scheme could reduce total abatement costs, and improve countries' payoffs substantially. Matching mechanisms could be tabled in international climate change negotiations based on the conditional pledges which are currently proposed by the European Union and a few other countries.

Keywords Game theory · Climate change · International negotiations · Matching · Free riding

1 Introduction

The Conference of Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) agreed to limit the average global temperature rise to under 2° Celsius in December 2010 at Cancun, Mexico (UFCCC 2011). In addition, many countries have pledged their greenhouse gas (GHG) reduction targets for 2020 under the Cancun Agreements (UFCCC 2012a). However, recent studies show that the aggregated emission reduction pledges do not reach the level required to achieve the 2° target (Climate Analytics 2011). Therefore, raising targets pledged by those countries

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is one of the most important negotiation agendas. At COP at Durban in 2012, it was agreed to start a new comprehensive framework participated by all nations from 2020 (UFCCC 2012b). It means that the target year would be set for 2030 or later, which indicates that the window of the opportunity to achieve 2° target is closing (De Vit and Höhne 2012). GHG reduction is an issue of providing international public goods. Due to incentives for free-riding, the public goods are often underprovided—an issue long tackled by various studies. In addition, the North-South debate influences negotiation. The UNFCCC abides by a principle of "common but differentiated responsibility". In the negotiation over the future framework, developing countries insist that developed countries take a lead in emission cuts as majority of historical emissions come from the developed countries, and this issue is often referred to as climate justice while the developed countries assert the necessity of participation of the developing countries due to their large share of current and future emissions (Goodman 2012).

1.1 Literature Review

Game theory has been used to analyze the process of forming coalitions in climate change negotiations. Many studies have investigated it in a theoretical framework (e.g. Barrett 2001, 2003; Asheim et al. 2006; McGinty 2006; Asheim and Holtsmark 2009). A general principle that can be derived from these studies is that it is very unlikely that a stable coalition with a high participation level will materialize, because individual coalition members have an incentive to free-ride. In most of these modeling approaches, there lies an assumption that all countries are symmetric—at least *ex ante*—which seriously limits most practical applications of these models. There are two important reasons why this assumption of identical countries needs to be relaxed. Firstly, differences in abatement costs and benefits can themselves assist cooperation, because it gives an opportunity to exploit inexpensive abatement reduction options. Secondly, asymmetry in players' interests can make the transfer of payoffs effective, and it helps to stabilize the coalition. Theoretical devices such as integrated assessment models (IAM) have already been developed to incorporate heterogeneity of players into numerical analysis. Dellink et al. (2004), Finus et al. (2005) and Nagashima (2010) have used IAMs (so called "the STACO model") and derived results similar to those from game-theoretic models with empirical inputs. There are substantially larger global net benefits achieved in the fully cooperative case than in the non-cooperative case, but some countries are worse off, because they contribute more to reducing emissions than is in their own interest. This will eventually lead to the act of free-riding.

The efficiency of voluntary contbutions to the international public goods, when countries can commit themselves to their decisions, has been established by Guttman (1987), Danziger and Schnytzer (1991) and Boadway et al. (2007); Boadway et al. (2011). Recently, a number of studies have proposed mechanisms for implementing efficient contributions by countries to the international public goods, such as climate change mitigation. In particular, Guttman (1987) proposed a mechanism, which addresses the free-riding problem without an enforcing authority. In his approach termed 'conditional contribution' or 'matching', players voluntarily subsidize each

others' contributions to the supply of a public good. Each player individually finds it optimal to match other players' contributions, and this matching behavior leads to a Pareto-optimal outcome from the viewpoint of the whole group utility. In international climate change negotiations, some countries including the European Union (EU), Japan and Australia propose a higher reduction target conditional on other major emitters' comparable contributions (UFCCC 2012a). The recent analysis of EU's conditional commitment shows that such cooperative arrangements that would leave each party better off than its baseline policy could be established (Underdal et al. 2012). In principle, these mechanisms can be designed to implement any desired emission reduction objectives, although they require some prior cooperative agreement to establish such objectives, and to decide how to distribute the surplus across countries. In order to make such matching mechanisms functional, how to ensure players implement the contributions or "strategy-proofness" is one of the most important aspects to be considered.

What is lacking in the literature, however, are quantitative applications of matching mechanisms. Hence, this paper aims at filling the gap between the theoretical models (with general results and identical players) and empirical models (which allow for different costs and benefits from the abatement of GHGs across regions). The merit of our study is twofold: (1) that we develop an alternative model of a dynamic GHG abatement game; and (2) that we evaluate and compare the results achieved using different matching mechanisms with empirically relevant specifications and asymmetric players.

1.2 Objective

This study aims to apply a matching mechanism to international climate change negotiations and demonstrate that the mechanism can raise countries' current pledges under the Cancun agreements towards the required reduction to achieve the 2° Celsius target. In the Conference of Parties to UNFCCC in Durban in December 2012, it was agreed to establish the Durban Platform to negotiate a new global agreement by 2015. A mechanism to raise the reduction level of countries is thus required.

This paper is organized as follows. Section 2 provides a description of matching mechanism models for international climate change negotiations using quantitative figures from the STACO model. Section 3 reports on the main results of the modeling analysis. In Sect. 4, we investigate the findings from the modeling analysis with a view to contributing to the international climate change negotiations. Section 5 provides conclusions.

2 Models

This section describes the models used in this study. They are matching mechanisms based on Guttman (1987), a quantity–contingent Mechanism based on Boadway et al. (2007); Boadway et al. (2011), emission trading and the STACO model based on work by the Wageningen University team (Dellink et al. 2004; Finus et al. 2005) and Nagashima 2010).

2.1 Matching Mechanisms

2.1.1 Two-Country Model

Guttman (1987) shows that matching mechanisms can realize a Pareto-optimal outcome. His mechanism consists of two stages. In the first stage, player i announces rates, b_i, at which they will match the contribution of other player j. Player j also announces rates, b_j. In the second stage, given the announced matching rates, player i choose its own contribution, a_i and player j also determine its contribution a_j. So player i's total contribution, q_i, is expressed as Eq. (1).

$$q_i = a_i + b_i \sum_{j \neq i} a_j \tag{1}$$

The payoff for player i, denoted as $\prod_i$, is a function of the combined contributions of all players, $B_i(Q)$, minus the cost of i's own contribution, $C_i(q_i)$, where $Q = \sum_{i=1}^{n} q_i$ (n is number of countries)

$$\prod_i = B_i(Q) - C_i(q_i) \tag{2}$$

All equilibria are assumed to be subgame perfect, so they are deduced through backward induction. In stage 2, given the matching rates from stage 1, player 1 chooses a_1 to maximize $\prod_1$. The first order condition is

$$\frac{\partial \prod_1 (a_1, a_2, b_1, b_2)}{\partial a_1} = (1 + b_2) \frac{\partial B_1(Q)}{\partial a_1} - \frac{\partial C_1(q_1)}{\partial a_1} = 0 \tag{3}$$

$$\frac{B_1'(Q)}{C_1'(q_1)} = \frac{1}{1 + b_2} \tag{4}$$

Similarly player 2 chooses a_2 to maximize $\prod_2 (a_1, a_2, b_1, b_2)$.
The first-order condition is:

$$\frac{\partial \prod_2 (a_1, a_2, b_1, b_2)}{\partial a_2} = (1 + b_1) \frac{\partial B_2(Q)}{\partial a_2} - \frac{\partial C_2(q_2)}{\partial a_2} = 0 \tag{5}$$

$$\frac{B_2'(Q)}{C_2'(q_2)} = \frac{1}{1 + b_1} \tag{6}$$

Guttman has found that the relationship of the reaction curve in the two player case has to satisfy $b_1 b_2 = 1$. An interior equilibrium in Stage 1 cannot be reached if $b_1 b_2 \neq 1$. In particular, when $b_1 b_2 < 1$, both players would want to increase their matching rates until $b_1 b_2 = 1$. When $b_1 b_2 > 1$, an interior equilibrium would be unstable. Both players would want to increase their matching rates if they anticipated that unstable equilibria would realize in Stage 2. In that case, such increases would eventually lead to $a_1 = a_2 = 0$, where neither direct nor indirect contributions to the public good are made. Such an allocation is dominated by an allocation involving

a positive value of at least one of a_1 and a_2. It might be reasonable to rule out this equilibrium, since it requires that both countries anticipate that an unstable equilibrium would occur in Stage 2. If q_1 is so large that this marginal benefit is less than the effective price of the public good, the player sets its unconditional contribution, a_1, equal to zero. $b_1 b_2 = 1$ is thus the condition characterizing the efficient levels of emissions by the two countries. These relationships are formulated in the following equations:

$$b_1 b_2 = 1 \Leftrightarrow \frac{1}{1+b_1} + \frac{1}{1+b_2} = 1 \Rightarrow \frac{B_1'(Q)}{C_1'(q_1)} + \frac{B_2'(Q)}{C_2'(q_2)} = 1 \qquad (7)$$

As the equation below shows, each player's effective costs of direct and matching abatements are equal.

$$\frac{1}{1+b_2}Q = \frac{(1+b_2)a_1 + (1+b_1)a_2}{1+b_2} = a_1 + \frac{1+b_1}{1+b_2}a_2 = a_1 + b_1 a_2 = q_1 \quad (8)$$

In stage 1, anticipating $a_1(b_1, b_2)$, $a_2(b_1, b_2)$, players 1 and 2 choose b_1, b_2 simultaneously.

Thus, player 1's total contribution equals its marginal rate of substitution, $\frac{1}{1+b_1}$, applied to Q. The same applies for player 2. Thus, the total abatement each country makes can be seen as its quasi-Lindahl abatement effort.

Finally, in equilibrium, player 1 and 2 are indifferent as to whether they make direct abatements or matching abatements. The effective cost to player 1 of direct abatements is $\frac{1}{1+b_2}$, whereas its effective cost of matching abatements is $\frac{b_1}{1+b_1}$. When $b_1 b_2 = 1$, $\frac{1}{1+b_2} = \frac{b_1}{1+b_1}$ and $\frac{1}{1+b_1} = \frac{b_2}{1+b_2}$. Thus the costs to either player of reducing emissions by one unit through direct abatement efforts or through matching abatement efforts are equal.

If the equilibrium generated by a matching mechanism is to be the desired Pareto-optimal outcome, it is necessary for every player to be at an interior solution at that equilibrium. A precise condition for existence of interior matching equilibria is discussed by Buchholz et al. (2011).

2.1.2 Multi-country model

Boadway et al. (2011) show that all the results of the basic two-country model can be generalized to the case, where there are more than two countries. Let us now assume that there are n countries denoted by $i, j = 1, \ldots, n$, and let $b_{i,j}$ be the matching rate offered by country i on the direct abatement commitment of country j. In this way, countries can commit to matching the direct abatements of all other countries at different rates. As in the two-country case, countries simultaneously choose their matching rates in Stage 1, and then set their direct abatement commitments in Stage 2. We solve it with backward induction in the same way as for the two-country case.

Stage 2: choosing direct abatements a_i. Matching rates are determined at this stage, and all countries take the price of quotas as given. The direct abatement commitment of country i is obtained by solving the following equation:

$$\frac{B_i'(Q)}{C_i'(q_i)} = \frac{1}{1 + \sum_{j \neq i}^{n} b_{ji}} \tag{9}$$

The effective cost at which country i can increase world abatements by one unit depends on the total rate at which its direct abatement will be matched by all other countries. Country i chooses a_i such that this effective cost is equal to the ratio of marginal costs and marginal benefits of emission reductions.

Stage 1: choosing matching rates b_{ij}. The equilibrium matching rates turn out to satisfy similar properties to the two-country case. In fact, with n countries, matching rates are such that $b_{ij}b_{ji} = 1$ and $b_{ki}b_{ij}b_{kj} = 1$ (or equivalently $b_{ki}b_{ij} = b_{kj}$) for all i, j, k. Since the equilibrium is analogous to that in the two-country case, we need not go through its full derivation. It is shown that with n countries, no country would have an incentive to change its matching rates, when the earlier conditions are satisfied.

The other properties of the equilibrium matching rates derived in the two-country case apply here as well. In particular, with matching rates satisfying $b_{ij}b_{ji} = 1$ and $b_{ki}b_{ij}b_{kj} = 1$, it is also the case that

$$\sum_{i=1}^{n} \frac{1}{1 + \sum_{j \neq i}^{n} b_{ji}} = \sum_{i=1}^{n} \frac{B_i'(Q)}{C_i'(q_i)} = 1 \tag{10}$$

Thus, equilibrium abatements are efficient and the marginal benefits of emissions are equalized across all countries. The total abatements of each country are again quasi-Lindahl abatement efforts. To see this, note that country i's quasi-Lindahl price $\frac{B_i'(Q)}{C_i'(q_i)}$ is equal to $\frac{1}{1 + \sum_{j \neq i}^{n} b_{ji}}$ by Eq. (10). Using Eq. (1), which implies that $b_{ij}b_{ji} = 1$ and $b_{ki}b_{ij} = b_{kj}$, country i's quasi-Lindahl abatement effort simplifies to the following after straightforward simplification:

$$\frac{1}{1 + \sum_{j \neq i}^{n} b_{ji}}(q_1 + \cdots + q_n) = a_i + \sum_{j \neq i}^{n} b_{ij} = q_i \tag{11}$$

2.2 Quantity–Contingent Mechanism

Boadway et al. (2007) has developed Guttman's mechanism with the condition that only one country can commit to a matching contribution in the two-player case. Further he extends the case that the matching plan involves discrete quantities as opposed to continuous quantities. Under the extended mechanism, one country commits to a contribution contingent on others' contribution of at least some threshold amount. The fallback situation is thus important in determining the parameters of the mechanism and therefore the payoffs attained by each country. The mechanism is called a quantity–contingent mechanism (QCM). If the other player does not meet the threshold, the proposed country no longer provides its committed amount, and the outcome reverts to some fallback situation, which depends on the ability of the two countries to commit. The proposed country takes into consideration the fallback situation and designs the

QCM to induce the other player to participate. Boadway has proved that a QCM yields efficient provision of the public goods.

The QCM consists of three stages. In the first stage, player 1 announces that it will reduce g_h of emissions if player 2 contributes more than r and otherwise reduce g_l. In the second stage, player 2 announces its contribution. Finally in stage 3, players 1 and 2 make their contributions based on the conditions set by the previous stages. It is straightforward to find that the QCM leads to an equilibrium in which player 1 reduces g_h and player 2 reduces r. In the case of player 1, it is assumed that a commitment to the QCM is binding, so q cannot be reduced beyond $g_h.$. If player 2 decides to reduce by less than r, anticipating player 1's response as specified by the announced commitment, player 1 acts according to the commitment and each holds its reservation utility. Thus player 2 cannot be better off by lowering its reduction below r, implying that g_h and r are sustained as equilibrium. Boadway has proved that the QCM equilibrium is efficient and satisfies the Samuelson condition:

$$\frac{B_1'(Q)}{C_1'(q_1)} + \frac{B_2'(Q)}{C_2'(q_2)} = 1 \tag{12}$$

Here, player 2 gets the reservation utility level while player 1 gets the remaining surplus from internalizing the free-rider problem. The allocation of reservation utility depends on the commitment ability of each player in Stage 3.

We need to define how to set g_h, g_l, and r. It is straightforward to set g_l to the Nash equilibrium, when no player cooperates. As the aim of this study is to identify a mechanism to realize the maximum total reduction by coalition countries, we assume that player 1 reduces emissions as much as possible, while maintaining its payoff at g_l. All surpluses from raising the reduction level go to Player 2. The level of r can be determined where the Samuelson condition is satisfied.

We extend the QCM to a multi-country case based on the study by Boadway et al. (2011). One country or a coalition of countries commits to the QCM in which its reductions are contingent on the level of reductions by each country in the coalition. The QCM's assumption that not all countries are able to commit seems to be more practical considering the reality of climate change negotiations. Currently only a limited number of countries announce conditional commitments.

2.3 Emission Trading

Emission quota trading provides an instrument for achieving an optimal allocation. The matching mechanism with emission trading involves three stages (Boadway et al. 2011). The matching rates and the direct abatements chosen in the first two stages determine the emission quotas to which countries are committed. In the third stage, countries can trade these quotas at the equilibrium price, which we assume is competitively determined. Note that in the absence of a central government with the authority to administer a quota trading system, the three-stage abatement process with quota trading requires a stronger form of commitment from countries than the two-stage process of the previous section. Again, we assume a subgame perfect equilibrium, so that they are derived from backward induction, starting at Stage 3.

Stage 3: emissions quota trading

At this stage the total abatement commitment of country i is $q_i = a_i + b_i \sum_{j \neq i} a_j$. The demand for emission quotas by country i maximizes;

$$\prod_i = B_i(q_i) - C_i(q_i - p_i) - p_c \cdot p_i \tag{13}$$

The first-order condition is $C_i'(q_i - p_i) = p_c$, and the solution is country i's demand for emission quotas $p_i(p_c, q_i)$, for $i, j = 1, \ldots, n$. In the equilibrium, $\sum p_i = 0$, and the price is such that $p_c(q_i, \ldots, q_n) = C_i'(q_i - p_i)$ for all i. Emission trading therefore leads to an equalization of the marginal cost of emission reductions across all n countries.

Emission trading is applied to the QCM as well, whose step will be added to the QCM as its Stage 4.

2.4 STACO Model

The STACO model has been developed to quantify each country's costs and benefits from CO_2 reduction in order to analyze the stability of a coalition of countries. Here we focus on the main features of the model. Details of the model can be found in Dellink et al. (2004).

It considers twelve world regions; USA, Japan (JPN), the European Union-15 (EU15), other OECD countries (OOE; including Canada, Australia and New Zealand), Eastern European countries (EET; including Hungary, Poland and Czech), former Soviet Union (FSU), energy exporting countries (EEX; including Middle East countries, Mexico, Venezuela and Indonesia), China (CHN), India (IND), dynamic Asian economies (DAE; including South Korea, Philippines, Thailand and Singapore), Brazil (BRA) and rest of the world (ROW; South Africa, Morocco, most South American countries, other Asian countries and African countries). The model's horizon is set at 100 years, ranging from 2011 to 2110, long enough to assess the benefits from abatement. The STACO model captures the net present value of the stream of payoffs generated between 2011 and 2110. Data for each year between 2011 and 2110 are used to calculate the stock of CO_2 in 2110 and to calculate the net present value of benefits and abatement costs.

The model's basic equations are presented below. An overview of the model's parameters is presented in Table 1. Benefits from abatement are the avoided damage, which, in turn, depends on the accumulated (stock) level of CO_2. Damage is derived from the damage cost module of the DICE model which is a dynamic integrated assessment model (Nordhaus 1994) and the climate module by Germain and van Steenberghe (2001). The stock of CO_2 for each period M_t is given in Eq. (14).

$$M_t(q_{2010}, \ldots, q_t) = \overline{M} + (1 - \delta) \cdot (M_{t-1} - \overline{M}) + \omega \cdot \sum_{i=1}^{n} (\overline{e}_{i,t} - q_{i,t}) \tag{14}$$

The stock depends on the stock in the previous period M_{t-1}, a natural equilibrium stock $\overline{M}$, a decay rate δ, baseline (or uncontrolled) emissions $\overline{e}_{i,t}$, abatement $q_{i,t}$ and

Table 1 Global parameters of the STACO model

Symbol	Description	Value	Unit	Source
M	Pre-industrial level of	590	GtC	Nordhaus (1994)
M_{t0}	Stock of CO2 in 2010	835	GtC	Nordhaus (1994)
σ	ä Natural annual removal	0.00866	–	Nordhaus (1994)
ω	Airborne fraction of emissions remaining in the atmosphere	0.64	–	Nordhaus (1994)
r	Discount rate	0.02	–	Assumption
θ_i	Share of region i in global benefits	see Table 2		Own calculation based on Fankhauser (1995) and Tol (1997)
α_i	Abatement cost parameter 1 of region i			Own calculation based on Ellerman and Decaux (1998)
β_i	Abatement cost parameter 2 of region i			Own calculation based on Ellerman and Decaux (1998)
γ_D	Scale parameter of damage and benefit function	0.027	–	Tol (1997)

the airborne fraction of emissions that remains in the atmosphere ω. Data from the EPPA model was used for CO_2 emissions. The damage function is a function of the stock of CO_2 and can be approximated by a linear function. In Eq. (15), y_t denotes global GDP in year t.

$$d_t M_t(q_{2010} \ldots, q_t) = \left[\gamma_1 + \gamma_2 \cdot \left(\frac{M_t}{\overline{M}} \right) \right] \cdot \gamma_D \cdot y_t \tag{15}$$

A GDP growth rate is assumed at about 2 % annually, using data from the DICE model. Parameter γ_2 is estimated by OLS-regression; for the global damage parameter γ_D, Tol (1997)'s estimate was used in the STACO model. It assumes that damage amounts to 2.7 % of GDP with a CO_2 stock more than double of the pre-industrial levels. Equation (15) shows the global benefits of abatement depending on the stock.

Each region receives a share s_i of the global benefits, as displayed in Table 2. Benefits are the sum of per-period benefits discounted at rate r. Equation (16) gives the marginal benefits from current abatement (discounted back to period t). Note that q_i is the *sum* over the periods for region i, not the level for an individual year. The abatement level for individual years is assumed to equal the century abatement level divided by the number of years: $q_{i,t} = q_i/100$.

$$B_i(q_i) = s_i \cdot \gamma_D \cdot C \cdot q_i \sum_{t=2011}^{\infty} \left\{ (1+r)^{-(t-2010)} \left(\sum_{s=2011}^{t} (1-\delta_M)^{t-s} \cdot 0.64/100 \right) \right\} \tag{16}$$

The abatement cost functions are specified following the estimates of the EPPA model. In Eq. (17), α and β are the regional cost parameters displayed in Table 2.

Table 2 Regional parameters in the emission function of the STACO model

| Regions	Emissions in 2010 GtC (share)	Parameters		
		Share of global benefits θ_i	Abatement cost α_i	Abatement cost β_i
USA	1.763 (0.238)	0.2263	0.0005	0.00398
JPN	0.344 (0.046)	0.1725	0.0155	0.1816
EU15	0.943 (0.127)	0.236	0.0024	0.01503
OOE	0.36 (0.049)	0.0345	0.0083	0
EET	0.226 (0.03)	0.013	0.0079	0.00486
FSU	0.774 (0.104)	0.0675	0.0023	0.00042
EEX	0.469 (0.063)	0.03	0.0032	0.03029
CHN	1.127 (0.152)	0.062	0.00007	0.00239
IND	0.344 (0.046)	0.05	0.0015	0.00787
DAE	0.316 (0.043)	0.0249	0.0047	0.03774
BRA	0.122 (0.016)	0.0153	0.5612	0.84974
ROW	0.637 (0.086)	0.068	0.0021	0.00805
World	7.425 (1)	–	–	–
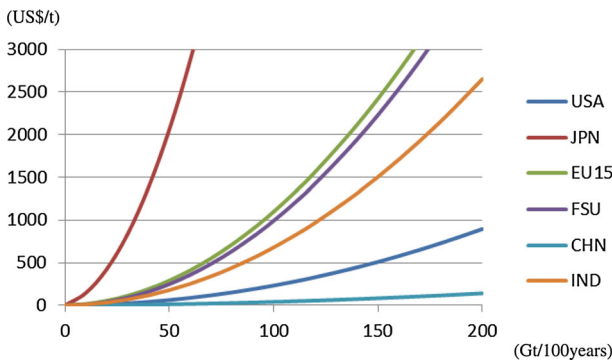
Fig. 1 Marginal abatement cost curves for six countries/regions

Equations (17) and (18) specify discounted abatement costs and marginal abatement costs, respectively. Marginal abatement cost curves for six countries/regions are presented in Fig. 1.

$$C_i(q_i) = \sum_{t=2011}^{2110} (1+r)^{-(t-2010)} \cdot \left(\frac{\alpha_i}{3} q_i^3 + \frac{\beta_i}{2} q_i^2 \right) \tag{17}$$

$$MAC_i(q_i) = \sum_{t=2011}^{2110} (1+r)^{-(t-2010)} \cdot (\alpha_i q_i^2 + \beta_i q_i) \tag{18}$$
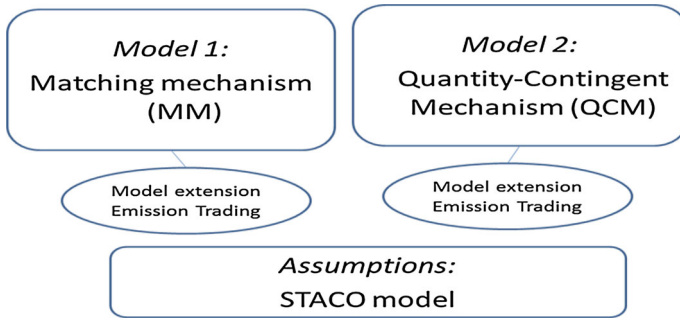
Fig. 2 Model framework of this analysis

Based on this specification of benefits and costs, Eq. (19) gives the gross payoff in net present value.

$$\prod_i = B_i(q_i) - C_i(q_i) \qquad (19)$$

It is assumed that signatories and singletons play Nash equilibrium with regard to their abatement strategies. Non-signatories choose their abatement level by maximizing their own payoffs, taking the other regions' abatement levels as given. On the other hand, signatories choose the abatement levels that maximize the sum of the payoffs of the signatories, taking the abatement levels of non-signatories as given.

2.5 Model Framework

Two different models of the comparable mechanisms, each employing the matching mechanism and the QCM, respectively, are applied to international climate change negotiations in this research. This research makes the following assumptions in applying these two mechanisms. The target countries for this analysis are the top six largest GHG emitters: China, United States, the European Union, India, Russia, and Japan. Emissions from these countries accounted for 68 % of world emissions in 2009, and are expected to maintain a similar share in 2020. As Guttman shows that the feasibility of matching behavior decreases with group size, it is both theoretically and practically advantageous to limit the number of countries. The matching mechanism needs information on costs and benefits related to GHG reduction. Based on the STACO model described in Sect. 2.4, the authors set simplified functions for marginal abatement costs and marginal benefits from the abatement. Emission trading is applied for both the matching mechanism and the QCM in order to improve cost-efficiency. The framework of the analysis is shown in Fig. 2.

One of the important things to be considered about the QCM as well as the matching mechanism is strategy-proofness. In the third stage there could be incentives for players to deviate from their conditional commitments made in the previous stages. How the mechanism deals with the issue of strategy-proofness, however, exceeds the scope of the current paper and needs to be considered in a future study.

3 Results

This section presents the result of numeric analysis using the proposed models described in the previous section. Each country's reduction level is calculated through the conditions set by the corresponding models. The outcome of the analysis for STACO model has been reproduced in this study.

3.1 Matching Mechanism

The Guttman's matching mechanism has been applied to a negotiation between the six countries/regions set out in the previous section. Different reduction levels for each coalition member as well as the total reduction amount may be observed between the STACO model and the matching mechanism. The STACO model produces a total reduction of 181Gt, while the matching mechanism decreases by 137 Gt over the next 100 years (Table 3). Compared to the singleton case, STACO produces 3.3 times the reduction and the matching mechanism produces 2.5 times the reduction. STACO requires extremely high reductions from China and India. When we assume that the annual reduction amount is constant over the 100 years, they have to reduce by 75 and 56 % of their current emissions, respectively. Developed countries such as Japan and the EU need moderate reductions of 9 and 15 %, respectively. On the other hand, the required reduction level for the six coalition countries are relatively close, when using the matching mechanism compared to the STACO model. Only 33 % for China and 40 % for India are required. Japan and the EU need to reduce by 22–23 %, which is more than under the STACO. Japan's marginal abatement cost (MAC) is very high, so a 23 % reduction means quite high costs. In fact, the reduction amount for the matching mechanism is ten times higher compared to the singleton case. USA's reduction level is almost the same for STACO and the matching mechanism, which is only twice as the singleton case.

The STACO model assumes that coalition members reduce their emissions to the level at which their marginal costs equal the sum of the marginal benefits of coalition members. It means that marginal benefits for a country become higher compared to the singleton case. On the other hand, under the matching mechanism, the marginal cost

Table 3 Comparison of reductions by six countries in coalition using STACO and the Matching Mechanism

	STACO (Gt)	% from BaU	c.p. All Singleton	Matching (Gt)	% from BaU	c.p. All Singleton
USA	33.8	19.2	2.1	34.5	19.6	2.1
JPN	3.1	9.0	4.0	8.0	23.1	10.3
EU15	14.3	15.2	2.2	20.3	21.6	3.1
FSU	17.4	22.5	3.5	14.8	19.2	3.0
CHN	84.9	75.3	5.5	37.2	33.0	2.4
IND	19.3	56.0	5.7	13.9	40.5	4.1
Global	180.7		3.3	136.7		2.5

Table 4 Matching rate

	USA	JPN	EU15	FSU	CHN	IND
USA		4.35	1.82	2.38	0.91	2.13
JPN	0.23		0.43	0.55	0.21	0.49
EU15	0.54	2.35		1.31	0.52	2.18
FSU	0.42	1.80	0.76		0.39	1.11
CHN	1.08	4.64	1.88	2.54		2.33
IND	0.47	2.04	0.45	0.90	0.42	

of an individual country is subsidized by the other countries' matching contribution. It means that their effective marginal cost is lower than the singleton case. Therefore, marginal costs for coalition members become lower, although the marginal benefits for coalition members are unchanged.

Matching rates are summarized in Table 4. USA's matching rate for Japan's unconditional reduction, for example, is 4.35. USA commits to reducing more than 4 times against Japan's reduction amount. Japan receives the highest matching rates from all the other countries, while China is the lowest. A country's matching rates become large, when the reduction benefit for the country is low and the reduction cost for the country is high. As has been mentioned, a matching rate is a kind of subsidy. If a country receives less benefit per unit of reduction than other countries, the country will be more subsidized. If the reduction cost per unit of CO_2 is expensive, the country will be more subsidized too. The equation below shows that relationship.

$$\frac{B_i'(Q)}{C_i'(q_i)} = \frac{1}{1 + \sum_{j \neq i}^{n} b_{ji}} \Rightarrow \sum_{j \neq i}^{n} b_{ji} = \frac{C_i'(q_i)}{B_i'(Q)} - 1 \tag{20}$$

As a result, the matching rate of Japan is the highest and that of China is the lowest. The regional sharing of benefit and marginal abatement cost curves are shown in Table 2 and Fig. 1.

3.2 Quantity–Contingent Mechanism

Annex I countries could form a collective group to propose a QCM, since not only the EU but other Annex I countries such as Japan and Australia have also announced ambitious conditional pledges. In the UNFCCC negotiations, developed countries have in the past agreed to take the lead, while all countries including developing countries make the utmost efforts to reduce GHG emissions. Although it is unlikely that the USA will join those countries offering conditional pledges in the short term because of their current political situation, it is desirable that all major Annex I countries including USA should propose conditional pledges towards major developing countries such as China and India. Therefore, this study assumes that Annex I countries (USA, Japan, EU, FSU) propose conditional pledges to China and India.

Table 5 Comparison of the reduction by six countries in coalition by STACO, Matching Mechanism and QCM

	STACO (Gt)	% from BaU	c.p. Singleton	Matching (Gt)	% from BaU	c.p. Singleton	QCM (Gt)	% from BaU	c.p. Singleton
USA	33.8	19.2	2.1	34.5	19.6	2.1	43.8	24.9	2.7
JPN	3.1	9.0	4.0	8.0	23.1	10.3	9.6	27.8	12.3
EU15	14.3	15.2	2.2	20.3	21.6	3.1	25.4	26.9	3.8
FSU	17.4	22.5	3.5	14.8	19.2	3.0	18.7	24.2	3.8
CHN	84.9	75.3	5.5	37.2	33.0	2.4	29.5	26.2	1.9
IND	19.3	56.0	5.7	13.9	40.5	4.1	5.2	15.1	1.6
Global	180.7		3.3	136.7		2.5	140.0		2.5

Here, we assume that proposers will not take any surplus from the additional reduction. All the surplus will be shared among the rest of the coalition members. Although various sharing rules are possible, what is assumed here is that the surplus will be equally divided between China and India. Common but Differentiated Responsibilities (CbDR) is one of the foci in the climate change negotiations. Sharing the surplus only between developing countries can be interpreted as one way of addressing CbDR.

When Annex I countries propose their conditional pledges to China and India, the reduction rates by Annex I countries become similar in the range of 24–28 % (Table 5). Non-Annex I countries' reduction rates become substantially smaller compared to under the matching mechanism. China's reduction rate in the QCM (26 %) is smaller than that under the matching mechanism (33 %). India's reduction rate in the QCM (15 %) is much smaller than that under the matching mechanism (40 %). For Japan, compared to the singleton case, the additional reduction amounts to 12 times under the QCM, which is more than under the matching mechanism (10 times higher than the singleton case).

3.3 Emission Trading

Emission trading reduces MAC substantially as summarized in Table 6. In the matching mechanism, Japan's MAC amounts to $105 and the EU's amounts to $56. The MAC of China and India are $8 and $17, respectively. With an emission trading scheme, China and India can sell their emission quotas to the developed countries. From a global perspective it is cost efficient to reduce emissions in China and India where the MAC is low. As a result the global payoff becomes 4,208 billion dollars with emission trading. It is 17 % larger compared to 3,607 billion dollars without trading. That corresponds to almost all of the gains produced in Japan (39 %), the EU (28 %) and China (24 %). The payoffs for different cases are shown in Table 7 and Fig. 3.

The improvement in payoffs with emission trading is much more significant in the case of the QCM. The assumption under the QCM is that the proposing countries' payoffs remain equal to those in the singleton case. It may reflect 'the common but differentiated responsibility,' but it substantially reduces the payoffs of the proposing countries as well as the global payoff. Interestingly, the QCM with emission trading can increase the global payoff to a similar level (5,515 billion dollars) to the matching

Table 6 Comparison of the marginal abatement costs (US$t)

	Singleton	STACO	Matching	Matching with ET	QCM	QCM with ET
USA	8	30	32	18	49	19
JPN	6	30	105	18	136	19
EU15	9	30	56	18	83	19
FSU	3	30	22	18	35	19
CHN	2	30	8	18	6	19
IND	2	30	17	18	4	19

Table 7 Comparison of the pay-offs for six countries in coalition under STACO, Matching Mechanism and QCM (billion US$)

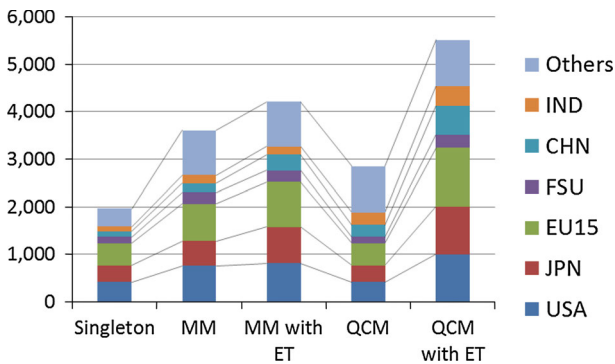|	Singleton	STACO	Matching mechanism	Matching mechanism with ET	QCM	QCM with ET
USA	415	1, 151	759	815	415	1, 001
JPN	356	1, 126	524	757	356	1, 007
EU15	464	1, 428	783	950	464	1, 234
FSU	136	281	238	240	136	277
CHN	112	−567	194	335	254	607
IND	101	121	164	165	254	415
OOE	72	236	178	178	183	183
EET	27	88	66	66	68	68
EEX	62	202	153	153	157	157
DAE	52	169	128	128	131	131
BRA	31	101	77	77	79	79
ROW	137	456	344	344	356	356
Global	1,963	4,791	3,607	4,208	2,854	5,515

Fig. 3 Comparison of the pay-offs for six countries in coalition under STACO, Matching Mechanism and QCM (billion US$)

mechanism, although the payoff under the QCM (2,854 billion dollars) is much lower than under the matching mechanism without emission trading. The STACO model assumes that marginal abatement costs are equalized across participating countries, so that there is no room for applying emission trading. China does not have any incentive to join the coalition under STACO, as China's payoff becomes negative in a six country coalition under STACO.

4 Discussion

The objective of this study is to investigate, in a quantitative way, promising mechanisms which can overcome the free-rider problem, so that they fill the gap between current pledges by countries and the required level of reduction to limit the average global temperature rise to less than 2° Celsius.

With a six country coalition the STACO model shows that the coalition countries reduce a large amount of their emissions. However, the STACO model assumes that coalition members reduce their emissions to the level at which their marginal costs equal the sum of marginal benefits of coalition members, while the matching mechanism enables emission to be reduced to the level of marginal cost having been subsidized by the other countries' matching contributions. The assumption of the matching mechanism is more realistic than that of the STACO model. Generally, countries are not supposed to consider coalition members' benefit as their own. It should also be noted that China's payoff becomes negative with the STACO model. If redistribution of the payoff across countries was not guaranteed, China would never accept any such reduction that would decrease their payoff substantially.

The matching mechanism can realize Pareto-efficient outcomes without any enforcing authority, if countries understand the costs and benefits of participating countries. Compared with the reduction level of participating countries under STACO, the matching mechanism as well as the QCM set more realistic and balanced reduction levels. The disadvantage of the matching mechanism, on the other hand, is that matching rates need determining against each other country. In the case of six countries, a country has to decide five matching rates, which in practice is difficult for a country to obtain a domestic consensus on. Since countries cannot identify exact contributions before starting the mechanism, emission reduction targets will only be determined *after* implementing the mechanism. As emission reduction targets have strong implications for its industry's international competitiveness and social welfare, it is difficult for a country to build a consensus across industries on a certain parameter set for a matching equation.

The QCM is a more promising mechanism than the matching mechanism. The QCM's assumption that not all countries are able to commit seems to be more practical considering the reality of climate change negotiations. Currently only a limited number of countries announce conditional commitments. The challenge for the QCM lies in how to set the threshold for the conditional commitments. There has seemingly been no theoretical or analytical basis for determining an appropriate level of threshold. In our study, the threshold is set based

on the assumption that payoffs of developed countries remain the same as under the singleton case and the surplus is divided between China and India. What principle is more acceptable for setting a threshold is an issue left for future study.

In order to decide a reduction level, the costs and benefits attributable to those reductions are the basis for calculating payoffs. More grounds could perhaps be provided by recent literature for rigorous assessment of these costs and benefits. The authors just make the point that any such assessment needs to be regarded as realistic by the negotiating countries. Our analysis also suggests that the countries should consider their contributions relative to the reduction amounts from 'Business as Usual' (BaU) levels. The current negotiation practice of making comparison against the 1990 base year makes it difficult to understand the real costs and benefits of the reduction targets.

It is obvious from our results that emission trading is quite effective at improving global and individual countries' payoffs. Without emission trading the QCM imposes quite high marginal abatement costs on developed countries, resulting in smaller payoffs for the reduction. The large variation in marginal abatement costs across countries could produce a win-win situation with emission trading.

To adopt the matching mechanism or the QCM is a realistic proposal, as they are similar to the conditional pledges announced by some developed countries (UFCCC 2011). The EU has committed to emission reductions of 20 % below 1990 levels unconditionally, and will commit to a 30 % reduction, if other developed countries commit to comparable emission reductions and developing countries contribute adequately according to their responsibilities and respective capabilities. Australia has decided unconditionally to reduce its emissions by 5 % on 2000 levels by 2020. Australia will reduce emissions by up to 15 % by 2020, if there is a global agreement, which falls short of securing atmospheric stabilization at 450 ppm and under which major developing economies commit substantially to restrain emissions and advanced economies take on commitments comparable to Australia's. If the world agrees to an ambitious global deal capable of stabilizing levels in the atmosphere at 450 ppm or lower, Australia will reduce emissions by 25 % compared with 2000 levels by 2020. Conditional pledges can address concerns about international competitiveness. In UNFCCC negotiations, comparable targets are one of the most controversial issues. Countries fear to bear the burden of unfair higher emission reduction targets compared to other countries and lose their international competitiveness. Such anxiety prevents the countries from reaching an ambitious agreement.

5 Conclusion

In this paper, we have applied the matching mechanism and the QCM to international climate change negotiations. The study has shown that those mechanisms have potential to reduce emissions from countries in theory. We have investigated to what extent those mechanism can realize further reductions compared with the singleton case by using the STACO model framework. The results showed that the mechanisms could

produce reductions by about 2.5 or 3.3 times the size of those under the case without the mechanisms. Such mechanisms can be applied in climate change negotiations, since similar conditional commitments have been proposed by the EU, Australia and a few other countries.

As with any model analysis, the results need to be examined with caution, as the model includes a number of contextual assumptions. Nonetheless, our numerical analysis with a larger number of heterogeneous regions allows the identification of some general features that cannot be analyzed in models with symmetric players.

Future study needs to refine the assumptions and figures in order better to reflect the real situation. One immediate step would be to use the latest version of the STACO model. This paper has used the basic STACO model for the sake of simplicity. The revised STACO model considers equilibrium every year (not for 100 years collectively) and technological development, and utilizes updated benefit parameters reflecting the current study and updated country groupings such as EU27 and Russia. Also how the mechanism deals with the issue of strategy-proofness is important and thus has to be considered.

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