AN ANALYSIS OF CLIMATE CHANGE COALITION FORMATION

FROM A GAME THEORETIC PERSPECTIVE

by

Jinmi Kim

A dissertation submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Energy and Environmental Policy

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LIST OF ACRONYMS

AIM	Asia-Pacific Integrated Model
BAU	Business as Usual
CGE	Computable General Equilibrium
CBDR	Common but Differentiated Responsibilities
CFCs	Chlorofluorocarbons
COP	Conference of the Parties
DICE	Dynamic Integrated Climate-Economy model
EPPA	Emissions Prediction and Policy Analysis model
FUND	Climate Framework for Uncertainty, Negotiation an Distribution
GCAM	Global Change Assessment Model
GCF	Green Climate Fund
$GTCO_2$	Giga-ton of CO_2
IAM	Integrated Assessment Model
IEA	International Environmental Agreement
IMAGE	Integrated Model to Assess the Global Environment
INDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
MERGE	Model for Estimating the Regional and Global Effects of Greenhouse Gas Reduction
PAGE09	Policy Analysis for the Greenhouse Effect 09
PNNL	Pacific Northwest National Laboratory

RICE	Regional Integrated Climate-Economy model
UNFCCC	United Nations Framework Conventional on Climate Change
WIAGEM	World Integrated Assessment General Equilibrium Model
WITCH	World Induced Technical Change Hybrid model

MODEL ACRONYMS

AF	Africa and Middle East
CA	China and Pacific Asia
EE	Formal Soviet Union and Rest of Europe
EU	European Union
FRT	Feedback Response Time
IA	India and Southeast Asia
LA	Latin America
OT	Other OECD
TCR	Transient Climate Response
THC	Thermohaline Circulation
US	United States

ABSTRACT

Unlike traditional environmental problems that often involve conflicts over local resource distribution, climate change is a global externality problem that arises from common 'ownership' of the earth's atmosphere. Climate solutions call for internalizing externalities at a global scale, necessitating international agreement among sovereign states with differing national incomes, priorities, values, cultures and social attitudes toward risks and uncertainty. Diversity at the sovereign state level complicates the process of organizing stakeholders to create international and national solutions that could serve the public good.

This dissertation is a game theoretic analysis of decisions leading to the formation of coalitions to address the complexity of global climate change. Game theoretic approaches have been widely applied to analyze strategic behavior in international negotiations and strategic development, particularly in the context of international relations. The models are interdisciplinary, drawing upon the fields of management, economics and political science.

The dissertation concludes by discussing the uncertainties associated with the dangerous risks of climate change and how the presence of these uncertainties, in some instances, might lead regions to bargain with one another if free-rider incentives appear to be large. This qualitative investigation recognizes that net benefit and free-rider incentive measurements themselves may not fully capture the complex decision-making and negotiations that take place during the process of coalition formation.

Because climate change involves very large uncertainties (especially concerning the magnitude of damages), this dissertation encourages researchers to evaluate the findings of this study multi-dimensionally and with caution.

Chapter 1

INTRODUCTION

1.1 Climate Change as a Policy Problem

Climate change has several unique characteristics that distinguish it from other persistent environmental problems. These differences help to explain, in part, why the climate change problem has proven particularly difficult to solve. Both conventional environmental problems and climate change are fundamentally externality issues, but the spatial scales and time horizons they inhabit serve to set them apart. Indeed, climate change is a global externality problem arising from common 'ownership' of earth's atmosphere whereas traditional environmental problems involve local resources endowments spread across a multitude of regions. Solving climate change calls for internalizing externalities at global scale, which necessitates global agreement among sovereign states with differing national incomes, priorities, values, lifestyles, and attitudes toward risks and uncertainty. The diversity at the sovereign state level makes it difficult to organize stakeholders to support solutions that could serve the global public good.

Inertia in the natural and socioeconomic systems also complicates climate decision-making as the time horizon of impacts and other relevant parameters extends to decades or even centuries. Moreover, most climate change impacts are non-linear and irreversible (IPCC, 2014a, 2014b). These features of climate change problems challenge the conventional decision-making framework familiar to traditional environmental issues.[1]

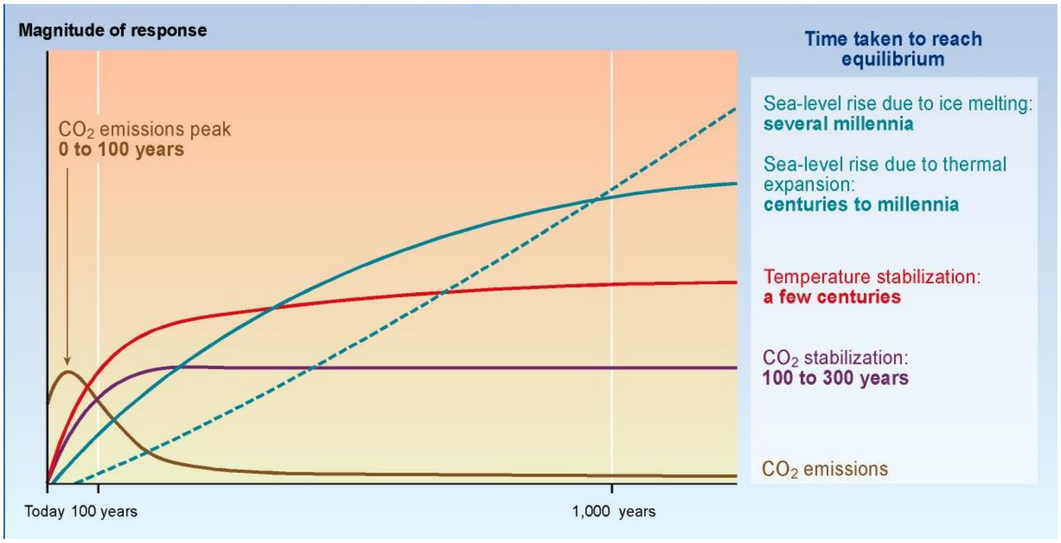

Figure 1-1: CO_2 concentration, temperature, and sea level continue to rise long after emissions are reduced[2]

Since 1992, parties to the United Nations Framework Convention on Climate Change (UNFCCC) have tried to achieve a binding international climate agreement to reduce GHG emissions. In 1997, the Kyoto Protocol was adopted and entered into

[1] The Montreal Protocol to control CFCs has been considered a successful model of international negotiation with parallels to the climate change problem. However, controlling CFCs does not require the same level of effort as controlling fossil fuel production and land uses needed for climate stabilization. Stabilizing the climate necessitates transformational change in global energy system and land use patterns whereas CFCs control is basically a single sector task (Benedick et al., 1991; Barrett, 2003).

[2] Source: IPCC Third Assessment Report (2001c), Fig 5-2

force in early 2005. However, one of the major GHG emitting countries, the U.S., refused to ratify the Protocol, and, in 2012, three countries (Canada, Japan and Russia) left the Protocol. During the COP18 in Doha in 2012, parties agreed to produce a universal emissions reduction agreement by 2015 that would include developed and developing countries. The agreement would become effective in 2020. According to IPCC assessments, achieving a 2℃ target would require global emissions to peak in 2015 and decline 80% relative to 1990 levels by 2050 (IPCC, 2007). Parties submitted their emissions reduction plans following the Copenhagen Accord and the Cancun Agreement, but the total planned emissions reduction implies a 3℃ temperature increase (UNEP, 2012). Thus, the challenge for the international community is to formulate a global agreement that raises the level of mitigation ambition to meet the 2℃ temperature target. One challenge is to overcome the free-rider problems inherent in the allocation of common pool resources, such as access to the global atmosphere (Ostrom et al., 1994).

An analysis of the coalition-building process used to adopt and implement climate change strategies must consider many quantitative and non-quantitative factors that encompass a myriad of physical, social, economic, and ethical concerns. The analysis provided in this dissertation focuses on only three factors that influence coalition formation—i.e., economic benefits/costs, free-rider incentives and damage risk. With this in mind, the results of this analysis must not be overstated. Rather, they must ultimately and properly be weighed in terms of the multidimensional nature of climate coalition formation. In other words, even if this analysis indicates that it is possible to form a stable coalition among regions that can greatly minimize damage risks, free-rider incentives and economic costs, such a coalition may not be desirable, justifiable, or practical on social environmental, ethical, or other grounds.

There are two main factors that influence the interpretation of game theory analysis as concluded in this dissertation: (1) the information each party has in deciding whether and when to join a coalition and which coalition it prefers; and (2) the social, political and economic inequalities which affect decision-making in any game involving actual existing parties, i.e., regions consisting of multiple countries. While this analysis generally captures the information uncertainty condition by specifying a high damage function, it does not consider how structural inequalities may impact the decisions of regions to join or abstain from coalitions. Indeed, the research literature on climate justice (Byrne et al., 1998, 2002; Okereke, 2010; Pettit, 2014) has shown that structural inequality significantly influences decision-making for climate related issues. For example, Byrne et al. (1998) argue that collective action cannot solve the climate change problem until inequalities are addressed and emissions reductions burdens are fairly distributed among the world's regions. Furthermore, as Okereke (2010) argues, the international arena in which climate coalition games are played is not a neutral space, but an imbalanced platform wherein actors possessing varying amounts of clout and leverage vie for power and influence. In the end, these power imbalances and sharp political economic realities create a complex backdrop to the coalition games that cannot be fully captured by this analysis.

1.2 The Role of Coalition Formation

A number of studies have analyzed the efficiency and equity aspects of particular climate decisions (Tol, 2002; Nordhaus, 2006; Stern, 2006; Hope, 2008;

Dannenberg et al., 2010; Kronik & Verner 2010; Nyborg 2012). Analyses of mitigation costs, adaptation costs, damage costs, and policy instruments like carbon taxes and tradable permits are also widespread (Weitzman, 2010, 2011, Pindyck, 2011). The primary focus of these studies is the welfare implications of a given climate decision at global, national or sub-national levels. In comparison, relatively few studies focus on climate decision-making itself (Aldy & Stavins, 2007; Barrett, 1994, 1999; Carraro, 1998, 1999; Bosetti et al., 2013) or climate negotiation (Pinto & Harrison, 2003; Van der Gaast, 2015; Gupta, 2012). This may be the case because climate change decision-making has to grapple with a panoply of constraints and requirements, not the least of which being that the assessment of climate risk is not uniform among countries; conventional decision tools are not appropriate for climate problems; mitigation action is required at global level; and the total required reductions are often more than the level individual countries are willing to reduce. Rigorous study would be complementary to understanding these and other complex climate change problems.

This dissertation is a game theoretic analysis of the decisions leading to the formation of coalitions designed to address global climate change. Game theoretic approaches have been widely applied to analyze strategic behavior in international negotiation and strategy development in international relations as well as in the areas of political science, management and economics. In environmental studies, the game theoretic framework has been used to analyze cooperation for environmental protection (Carraro and Siniscalco, 1998), coalition formation (Carraro, 2000), self-enforcing[3] strategies for international environmental agreements (Barrett, 1994; Heitzig, Lessmann, et al., 2011; Van der Gaast, 2015), and GHG mitigation pathways (Nordhaus and Yang, 1996; Jacob, Luderer, et al., 2012).

Chapter 2 of this dissertation contains a literature review to show the international negotiation of climate change and coalitions. Chapter 3 provides information on the research questions and methodology. Chapters 4 and 5 show the outcomes of climate science and economic impacts under the 450 and 580 ppm cases, while a discussion and comparison of the two cases is provided in Chapter 6. Finally, Chapter 7 concludes the research study.

[3] Self-enforcing (or strategically stable) strategy entails that “each player’s predicted strategy must be that player’s best response to the predicted strategies of the other players” (Gibbons. 1992; p.8).

Chapter 2

LITERATURE REVIEW

2.1 Conceptual Discussion of International Environmental Negotiations

Sovereign states have attempted International Environmental Agreements (IEAs) related to various global environmental problems, including biodiversity preservation, as well as stock externality issues such as global climate change (Kolstad & Ulph, 2008; Finus & Rundshagen, 2005). Due to the absence of property rights, these environmental problems face free-rider problems, a situation whereby self-interested states benefit from the ecologically responsible behavior of other states without making any national sacrifice (Barrett, 1999; Carraro 1999; Van der Gaast, 2015). In 1968, Hardin called this phenomenon the “tragedy of the commons.” The absence of an international central authority makes the formation of agreements such as IEAs difficult. Several researchers argue that self-enforcing treaties are required to overcome the barriers of achieving IEAs. Barrett (1999), Carraro (1999), Dutta & Radner (2004), and Hovi & Areklett (2004) have all studied issues related to self-enforcement of treaties.

Barrett (1999) argued that self-enforcement is mandatory to achieve full cooperation in the case of a global environmental problem. Assuming that full cooperation is individually and collectively rational, he demonstrated that the high degree of sustained cooperation was dependent upon a small number of signatories.

Dutta & Radner (2004) developed a mathematical dynamic strategy model to find Nash equilibria in order to lower GHG emissions. They examined not only

Business as Usual (BAU) but also Pareto-optimal strategies. The authors estimated the benefits of a self-enforcing agreement and found an equilibria in the BAU case, which was not Pareto-optimal.

Hovi & Areklett (2004) analyzed the Marrakesh Accords, developed at the 7th Conference of the Parties (COP) held in 2001, to examine the concept of non-cooperative equilibrium. The authors considered five equilibrium concepts[4]. They introduced the definition of "soft" and "hard" enforcement[5] for self-enforced IEAs. The Marrakesh Accords was evaluated as a "hard" instrument using different non-cooperation equilibrium concepts[6]. For example, the result of their evaluation based on the search for Nash equilibrium shows that setting the right level of the penalty is needed to deter non-compliance (Hovi & Areklett, 2004).

Van der Gaast (2015) pointed out multiple reasons to explain the difficulty of reaching agreements in climate change negotiations: (1) countries give more weight to addressing domestic than global issues and would join climate agreements only if such a decision produces benefits over costs; and (2) the climate target has become an object of negotiation as climate science has evolved since 1990. Furthermore, Van der Gaast presented three conditions for successful climate negotiations: (1) constraints facing individual countries must be recognized and the game theoretic aspects of

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[4] These concepts are the Nash equilibrium, the subgame perfect equilibrium, the perfect Bayesian equilibrium, the coalition and the renegotiation proof equilibrium.

[5] The "soft" enforcements are building capacity and supervision. The "hard" instruments include financial penalty and suspension.

[6] These concepts are the Nash equilibrium, the subgame perfect equilibrium, renegotiation proof equilibrium, coalition proof equilibrium, and perfect Bayesian equilibrium.

climate solution must also be recognized; (2) the process of negotiation should be "flexible with multiple trajectories"; and (3) such process should include "decisive tactical maneuvers at crucial moments". He indicates that successful climate negotiation requires finding options for climate resilient sustainable development pathways built upon the arrangement of an international support mechanism.

Post-Kyoto policy has been analyzed using a five-stage, sequential game theoretic framework. Two parties[7] would choose their strategies based on the previous decision of other players. Císcar & Soria (2002) ran the simple Dynamic Integrated Climate-Economy model (DICE) and Regional Integrated Climate-Economy model (RICE). The first mover is Annex B who chose their policy for the 2000 to 2010 time periods. Next, the non-Annex B countries decided their policy for 2010 based on policies of Annex B. They considered three policy options for GHG emissions reduction targets: 0%, 3%, and 5%. They found that non-Annex-B countries would be required to reduce GHG emissions by higher rates than those of Annex-B countries if a consensus was to form. Therefore, non-Annex B countries are likely to be against climate change agreement. The benefits would be positive for both parties. Their conclusion was that a so-called the Kyoto-forever scenario may not be supported due to a lack of participation by non-Annex B countries when their reduction rates would need to be higher than those for Annex B.

Forgo, Fülöp & Prill (2005) developed an extensive game (assuming perfect information) to analyze climate change negotiations. Their work is similar to research performed by Císcar & Soria (2002). Both studies assumed the same number of

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[7] Annex B and non-Annex B.

players for the Kyoto and post-Kyoto regimes. The difference lies in the segments of the time periods considered. Forgo et al. assumed three time periods—Kyoto (2000-2010), post-Kyoto (2011-2020), and forever Kyoto (2020)—while Císcar & Soria (2002) assumed five time periods. The results are that to achieve Kyoto targets in the near term, specific efforts between Annex-B and Non Annex-B countries are required. Their study confirmed that Non Annex-B countries would need to play a major role to achieve the equilibrium and stability conditions of a climate treaty. However, the Kyoto-forever polices do not seem to be reliable as they tend to be sensitive to exogenous variables such as discount rates.

2.2 Coalition Formation

Climate change coalition formation has been analyzed on the basis of various types of 2x2 games (DeCanio & Fremstad, 2013), Schelling's conjecture concept (Kroll & Shogren, 2008), the stability likelihood concept (Dellink, Finus, & Olieman, 2008) and the cost efficiency concept (Hoel, 1991, 1994; Hoel & Schneider, 1997). Chander & Tulkens (2006) assumed that an ultimate goal of coalition cooperation is to achieve efficiency. As such, they used a cooperative game theory[8] framework to determine the necessary conditions for the stability of a grand coalition.

DeCanio & Fremstad (2013) examined a total of 25 sets of 2x2 games to assess the strategies governments apply to improve their success during negotiations in

[8] Cooperative games "typically consider in addition to the strategies chosen jointly by groups of players, usually called coalitions, that is, subsets of players (including singletons and the all players set)" and "non-cooperative games consider strategies enacted by individual players; they lead essentially to the Nash equilibrium concept" (Bréchet, Gerard, & Tulkens, 2011).

international climate change meetings. These strategies include Prisoner's Dilemma (PD)[9], coordination, and chicken games. Through these games, the authors demonstrated fundamental barriers to achieving an international climate treaty. Whenever some parties agree to abate their emissions, other parties find incentives to pollute. This counter behavior significantly affects the accumulation of GHG emissions in the atmosphere. There researchers found a tendency, when chicken and PD games are included, for the result to end in "unhappy games". The authors were however optimistic about the prospect of achieving a climate change treaty. They proved that if all players recognized the serious risks caused by climate change, the abatement strategy would be the best solution.

Kroll & Shogren (2008) analyzed the impacts of domestic constraints on a government's decision or action on international negotiations, referred to as Schelling's conjecture. Based upon two games they developed for domestic constraints, ratification and election games, they found that domestic constraints do not always negatively affect governments' actions in international negotiations.

Dellink et al., (2008) examined the stability of all climate change coalition formations using a 'stability likelihood concept'. This approach allowed uncertatinty to be better understood in the context of the stabilitiy of climate change coalitions. Unlike other analyses, Dellink et al. examined the relationship between uncertainty

[9] "The "dilemma" faced by the prisoners here is that, whatever the other does, each is better off confessing than remaining silent. But the outcome obtained when both confess is worse for each than the outcome they would have obtained had both remained silent" (Kuhn, S. 1997. p.1).

and learning for stabilization to be realized through coalitions. The authors found that the expected payoff from learning was greater than otherwise.

While research on climate change regimes has typically relied upon static games and sequential move games, two research papers adopted a non-cooperative game theoretic framework. Hasson, Löfgren, & Visser (2010) showed the experimental results drawing from the work of Carraro & Siniscalco (1998) who had previously identified the analytical approach.

Hasson et al., (2010) analyzed the relationship between mitigation and adaptation options for climate change on the basis of a one-shot game using behavioral experimental methodology. The game included two types of impact groups: low-vulnerability and high-vulnerability impact groups. The experimental results showed that the mitigation action from the high-vulnerability impact group is lower than the low-vulnerability group. Even though the high-vulnerability group has high costs of damages from climate change, the high-vulnerability group does not take sufficient mitigation actions to meet treaty needs. The belief held by the high-vulnerability group that the other group will act to mitigate emissions is higher than the actual performance by the low-vulnerability group. The experiment showed that there is not a meaningful difference in mitigation levels between the two groups. The low-vulnerability group showed that the mitigation actions were affected by incentives for free-riders and adaptation decisions. The researchers explained the significance of the combination between mitigation and adaptation strategy in addressing climate change, indicating a need to realize a balance of incentives.

Carraro & Siniscalco (1998) developed a one-shot coalition game, a type of non-cooperative game, to analyze the role of incentives in the IEAs. Among the non-cooperative games, they focused on a one-shot game because a discount rate and collective rationality are not required. They also developed a two-stage game. In the first stage they assumed that states would decide whether or not to join the treaty. After that, the states play the emission game. They determined that players tend to prefer both multiple agreements and partial coalition treaties. The number of signatory states also depends upon the design of the treaty.

Finus & Rundshagen (2003) analyzed the global coalition structures with six kinds of coalition games[10]. They developed a reduced-stage model with a two-stage game that assumed symmetrical countries would make membership decisions simultaneously. They assumed various membership compositions and equilibrium concepts. A sequential membership decision was simulated by a sequential move game and an equilibirum-binding game. The comparison between sequential and simultaneous games showed that sequential formation games can more easily realize equilibrium coalition formations than simultaneous games.

Finus et al., (2005) analyzed IEAs with a two-stage game framework assuming symmetric countries. They also compared the results between the simultaneous game and the sequential game. They found that an equilibrium coalition for the simultaneous game is Pareto-optimal and the grand coalition is stable. A sequential move game led to lower abatement of emissions and consequently lower global payoff. They examined the role of a hypothetical regulator with advisory functions but no enforcement power giving recommendations to the parties. They identified conditions

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[10] The six different models are: Cartel formation game, open membership game, exclusive membership Δ-game, exclusive membership Γ - game, sequential move unanimity game, equilibrium binding agreement game.

under which the regulator could increase the global expected welfare in the simultaneous game.

2.2.1 Grand and Regional Coalitions

Barrett (1994), and Carraro & Siniscalco (1993) analyzed the concept and formation of coalitions leading to IEAs. Chander & Tulkens (2001) examined international air pollution agreements in the context of the core-cooperative game frameworks. The authors analyzed a financial transfer scheme that leads to achieving equilibrium status for the global coalition. Considering that asymmetrical countries try to minimize their abatement costs, the researchers used the concept of the γ-core equilibrium. The γ-core equilibrium assumes that if a country defects from the grand coalition in the first stage of the game, the remaining countries will decide to defect from full cooperation. This research focused on how transfer schemes could improve the stability of the cooperation. Transfers can lower net costs for full cooperation compared to partial cooperation results.

Yang (2003) analyzed the problems of "stock externality" in closed-loop systems that were simulated using a modified RICE model. He demonstrated the viability of closed-loop[11] frameworks in analyzing climate change compared to the open-loop[12] approach. The open-loop approach cannot analyze complex issues such as climate change because the model is based on broad economic and environmental

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[11] "The closed-loop strategies allow the agents to condition their decisions at time t on the history of nature up to the time t" (Yang, 2003: p.1567).

[12] "In open-loop solutions, agents' strategic decisions for the entire time horizon are made at the beginning" (Yang, 2003: p.1565).

interactions. In this research, Yang developed a sequential game, incorporating the impact of providing information and the attendant implication on the efficiency of the grand coalition. However, the introduction of new information leads to a change in the viability of the coalition since existing policy design depends on the same underlying information, thus the previous agreement would require renegotiation. For a stable coalition, he proved that strong incentives are required in the first stage.

In an analysis of regional coalition formation, De Zeeuw (2005) found that equilibrium of the deterministic stable coalition type, large or small, depends upon time, as benefits and costs occur at different points in time. Noting that the states require time to detect the other party's decision, he proved that threat is not a sufficient condition for coalition stability in a dynamic repeated game.

Burke & Parthemore (2009) analyzed strategic options available for climate change cooperation among four major GHG emitting countries: China, the EU, the U.S. and India. The analysis showed that the role of the U.S. and China is most important for potential climate change cooperation. Cooperation between China and India—two large developing countries—however, is not required to achieve a climate change agreement. Nevertheless, cooperation between two developed parties, notably the EU and the U.S., is significant to realize an agreement.

Regional coalitions were analyzed under three kinds of coalition formation using a modified RICE model. Buchner et al.,(2005) developed the two bloc coalitions: the Annex B bloc and non-Annex B bloc[13]. Under the non-Annex B bloc, a coalition between the U.S. and China showed significant results. China plays a major

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[13] The two-party climate coalitions include EU + Russia and EU + Japan. The non-Annex B block includes China and the U.S.

role in coaltion formation as a dominant emissions permit seller. With China's collaboration, the U.S. demand that developing countries participate meaningfully in a climate change agreement is fulfilled, making the prospect of reaching an international binding treaty more certain. In return, China was able to decrese its abatement cost through permit sales.

A comparison between non-cooperation and cooperation was analyzed by Labriet & Loulou (2008), Hammitt & Adams (1996), and Dockner & Van, L. N. (1993). These studies examined the conditions necessary for stable coalitions.

Cooperative and non-cooperative strategies for climate change treaties was analyzed using an integrated model called MARKAL[14]. To analyze abatement costs and climate damages from each strategy, Labriet & Loulou (2008) developed a model with 15 regions and a modified AIM-A1B scenario by IPCC. This research identified reasons for the difference in results between these two strategies for the common goal of stabilizing climate change. The grand coalition is not stable in terms of internal stability because a group of developing countries tends to have incentives to leave the coalition at any time. The grand coalition is stabilized by different allocations of the emissions budget and transfers. The free-rider incentives proved to be dependent upon the number of asymmetric countries, and, as such, an introduction of a cartel system may help to stabilize the coalition without a costly transfer scheme.

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[14] "MARKAL (an acronym for MARKal Allocation) is a mathematical model of the energy system of one or several regions that provides a technology-rich basis for estimating energy dynamics over a multi-period horizon" (Loulou, Goldstein, & Nobel, 2004, p.9).

Bosetti et al., (2009) used the WITCH (World Induced Technical Change Hybrid) model to evaluate the stability of coalitions to achieve GHG concentrations of 550 ppm by 2100. Their assessment found that both grand and smaller coalitions were unstable under these circumstances because the estimated amount of welfare expected for each coalition was insufficient for offsetting the estimated free-rider incentive.

Dockner & Van, L. N. (1993) also compared cooperative and non-cooperative strategies of emissions reduction by developing a dynamic game between two players. They showed that the grand coalition is not achievable due to the incentives to leave the agreement, even though it is Pareto-efficient.

2.2.2 Emission Trading

Scheffran (2004) analyzed emission trading using a dynamic game theory framework. The models included the benefits and costs of emissions reduction and emissions permit trading. It analyzed two assumed cases. In Case 1, two regions join the emissions trading scheme. In Case 2, emissions from all countries are asumed to be stable in the absence of trading, thereby allowing total emissions reductions to decline modestly by year with trading, reaching 50% in 25 years. In Case 2, the permit price will reach 40 $/tonC from 25 $/tonC in 25 years. In Case 1, emissions per capita in the EU and the Pacific OECD regions will increase as these countries purchase permits. The total emissions will decline and permit prices will increase from $60 to $80 per ton of C.

Kemfert, Lise, & Tol (2004) analyzed impacts of international trade on the optimal amount of GHG emissions reduction and emissions reduction cooperation using computable general equilibrium (CGE) models. The trade effects of other countries' actions allow countries to easily cooperate for GHG emissions reduction.

Bernard, et al. (2008) analyzed an emission trading game between Russia and China as representative of one between developing countries, using a CGE model. Particiatipation of China in the post-Kyoto period depends upon transaction costs. If transaction costs[15] are low, China would agree to abate emissions in the post-Kyoto period with permit trading. Setting a “resonable” target for GHG emissions would induce developing countries as well as Annex B countries to join the international emission trading system to benefit from the emissions reduction.

2.3 Conditions for a Coalition to Form

The role of incentives was studied by Barrett & Stavins (2003), Chou & Sylla (2008), Carraro, Eyckmans, & Finus (2006). Broadly, the incentives for a party to join a coalition included financial transfers, technology investments or transfers, and penalty. Barrett & Stavins (2003) divided incentives between positive and negative incentives. Financial transfer scheme supports a stable coalition because all parties derive benefits from the coalition (Germain et al., 2003).

Barrett & Stavins (2003) proved that incentives are necessary to induce countries to join binding international climate change agreements. They argued that current climate change negotiations focus on the cost-effective method of GHG mitigation whereas a climate change regime requires not only cost-effectiveness strategies but also participation and compliance with the regime. The authors proved the necessity of incentives to achieve compliance and participation in the regime. Their research showed that a cost-effective approach by itself fails to attract

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[15] Transaction costs include negotiation costs, search costs, validation costs, review costs, registration costs, monitoring costs, verification costs, and certification costs.

significant participation of countries and that alternative approaches can lead to a high level of participation by countries even when cost-effectiveness may suffer.

Chou & Sylla (2008) analyzed an international environmental agreement using a two-stage game with a transfer system and found that it is difficult for the environmental treaty to attract a grand coaltion at the beginning. The first stage of the game consists of a single developed country willing to join the treaty. However, the transfer system encourages developing countries to join the treaty thereby enticing other developed countries to join as well. This two-stage model can be used to explain the process that led to the ratification of the Montreal Protocol and its subsequent success in phasing out the production of harmful substances that are responsible for ozone depletion. In addition, the model can be used to explain the difficulty in reaching a grand coalition under the Kyoto Protocol.

Germain et al. (2003) analyzed how transfers lead countries to join a pollution cooperation game in the context of a closed-loop game framework. A financial transfer system allows countries to get interested in optimal pollutant levels for all periods. The transfer scheme supports the convergence of a stable climate treaty due to the benefits to cooperating nations.

Carraro et al. (2006) analyzed several cases, using a modified RICE model, in which a transfer scheme encourages all countries to join the self-enforcing international agreement. The authors considered both financial and technology transfers. Noting that the analysis of transfer schemes to encourage participation in IEAs had been neglected in non-cooperative game theory applications, the authors examined how potential transfer schmes lead to outcomes which maximize global benefits while also realizing the internally and externally stable IEAs.

Issue linkage is a tactic used to deter free-rider problems and encourage states to join IEAs by linking environmental negotiation to other issues, including trade, technological cooperation, etc. (Carraro & Siniscalco, 1998). Studies show that issue linkage not only increases the number of countries willing to form a stable coalition but also reduces barriers between asymmetric parties (Carraro & Siniscalco, 1998; Carraro 1999; Buchner et al., 2005; Kemfert, 2004).

Buchner et al. (2005) analyzed the role of issue linkage using a modified RICE model, and examined whether issue linkage would force the U.S. to join the Kyoto protocol. Their research showed that issue linkages between climate change and an R&D coalition would not be effective to encourage the U.S. to rejoin the protocol. However, issue linkage leads to strong incentives for technological cooperation among the coalition parties of the Kyoto protocol.

Technological development and climate change cooperation can encourage non-cooperating nations to join a climate change cooperative because incentives to join would be higher than to remain outside the coalition (Kemfert, 2004). The author analyzed the application of issue linkage in the IEAs using the World Integrated Assessment General Equilibrium Model (WIAGEM), and found that the spillover effects from technological innovation led to benefits such as energy efficiency being granted to non-cooperative nations. Moreover, the larger the number of countries joining the cooperative technology development coalition, the larger the spillover effects expected from a cooperative technology development based coalition.

2.4 Conclusion

Negotiating agreements to control environmental problems such as climate change is difficult, as self-interested states often attempt to free ride by taking advantage of the atmosphere's lack of property rights (Barrett, 1999; Carraro, 1999; Dutta & Radner, 2004; Van der Gaast, 2015). Adding to the problem is the fact that no central international authority exists to adjudicate between competing interests or to forge a global agreement that would be acceptable to all sovereign states. Given these conditions, game theory can be a useful tool for analyzing the strategic decisions of nations driven by their own self-interest. Since Barrett (1999)'s analysis on climate decision-making, researchers have used a variety of game theoretic frameworks to analyze what would make self-enforcing treaties for climate change mitigation (and international environmental agreements in general) possible, as well as what it would take for individual nations to engage in self-enforcing emissions reduction strategies that could lead to an international agreement and/or coalition for climate stabilization.

In addition, research has assessed the performance of climate coalitions by combining internally consistent integrated assessment models (IAMs) in the context of game theory, i.e., static or dynamic games. Typical studies have analyzed non-cooperation and grand coalition by evaluating the cost of climate change via the RICE model (Buchner et al., 2005) and/or the stability of partial coalitions via MARKAL (Labriet & Loulou, 2008). Moreover, a stability test for 550 ppm coalitions has been conducted via the top-down WITCH model (Bosetti et al., 2009), and a number of studies have examined the role of coalition incentives in climate change negotiations (Barrett & Stavins, 2003; Chou & Sylla, 2008; Carraro et al., 2006; Hasson et al., 2010).

This dissertation analyzes various climate coalition formations to achieve two alternative climate stabilization goals: 450 ppm and 580 ppm. The outcomes of each coalition, which will be an IAM-driven estimation, will be evaluated according to two criteria: economic feasibility and stability. Testing the economic feasibility of a coalition consists of examining its net benefits; i.e., the costs of mitigation compared to its socio-economic benefits. The stability test involves assessing potential free-rider incentives. Conducing this second test is important because even an economically feasible coalition may fail to be effective if it is vulnerable to participants withdrawing. In such cases, coalitions cannot reach the goal of mitigating global climate change at the stabilization target they had set. Model-driven free-rider incentives will be examined to evaluate coalition stability.

Numerical assessments of the effects of coalition games will be conducted using the PAGE09 model. Unlike the WITCH model used by Bosetti et al. (2009) that estimates the cost-effectiveness of climate coalitions, the PAGE09 model allows us to analyze coalition performance on the basis of the net benefits expected from coalition actions. Secondly, the PAGE09 model is capable of quantifying the uncertainty of key parameters associated with climate change and its physical and economic impacts via a probability distribution. The PAGE09 model's treatment of uncertainty sets it apart from other IAMs including RICE, and this dissertation uses it as the main estimation tool.

While climate damage estimates are critical for evaluating the performance of coalitions, estimating the potential damage from climate change is subject to large uncertainty. The PAGE09 model enables this dissertation to quantitatively account for the relationship between the uncertainty inherent in climate damage assessments and the decisions associated with climate coalition formation. In order to further delineate the significant effects different climate damage estimates can have on potential coalitions, this dissertation takes advantage of the PAGE09 model's ability to compare two types of climate damage estimates: model-driven damage estimates and a priori information-driven damage estimates. Comparing the two reveals how coalition performance is subject to differences in climate damage estimates, which ultimately affects how potential benefits—i.e., global emissions reductions—are calculated. Analyzing the effects of the uncertainty of climate damage estimates can enrich our understanding of the ways in which climate coalitions make decisions in light of the complexities of the problem. Furthermore, this dissertation's method of analyzing net benefits to test the economic feasibility and stability of coalitions is more likely to capture the real world dynamics of coalition decision-making than an approach solely rooted in cost-effectiveness that has been attempted in other studies. Together, these two aspects of this dissertation's analytical approach—uncertainty analysis and net benefit assessment—differentiate it from other studies that have previously examined climate change issues and coalition formation.

Chapter 3

GAME THEORETIC MODEL FOR STOCK EXTERNALITY PROBLEM

This dissertation seeks to explore the rationale behind voluntary, unilateral actions to address the risks of climate change and how such actions might affect the willingness of different nation-states to join global coalitions that could help achieve climate stabilization goals, such as 450 ppm and 580 ppm GHG concentrations, by 2100. Understanding these actions from a game theoretic perspective may provide new insight into the processes influencing the formation of climate coalitions aimed at global emissions reductions. This dissertation is concerned with modeling coalition formation under top-down target-setting conditions (such as 450 ppm and 580 ppm). The goal of this dissertation is to identify effective, economically feasible, and stable coalitions that would facilitate action to significantly lower GHG emissions globally. The details are as follows:

1. **Identification of effective coalitions**: This research will focus on identifying effective coalitions that are economically feasible for achieving the GHG stabilization goal of 450 ppm and the alternative goal of 580 ppm. The concept of net benefit will be used to evaluate the economic feasibility of both grand and partial coalitions for achieving these climate goals.
2. **Measures to increase membership of coalitions:** The efficiency of a mitigation effort depends on the participants involved. This research will examine the available options for broadening the membership of a

coalition so that large emitters from the developing world will participate in the global mitigation effort. The research will examine potential incentives for participation by assessing abatement costs and the potential benefits associated with abatement actions.

3. **Identification of coalition stability**: Coalition participants have a tendency to exploit the opportunity to free ride if they find that they stand to gain more by leaving the coalition. Because the atmosphere is a common pool resource and the benefit of climate change mitigation is a public good, capturing such a benefit without payment can be an alluring. If every region attempts to free ride on the emissions reductions of others, however, there will be no benefit left for anyone to appropriate. The incentive to free ride is positive only when the welfare gained from leaving the coalition exceeds the welfare gained from participating in it. This difference in the magnitude of welfare is known as the free-rider incentive. With a positive free-rider incentive, a coalition becomes unstable and its continued existence becomes threatened. This dissertation will assess the free-rider incentives of coalitions and analyze what measures are required to offset free-rider incentives and in so doing increase coalition stability.
4. **Characteristics of Coalitions**: This dissertation will analyze the different climate and economic outcomes expected from different coalitions. These outcomes will include temperature changes, changes in CO_2 concentrations, socio-economic impacts of climate change, and net benefits of mitigation. The PAGE09 model will be used for these

analyses and Section 3.3 will address the detailed methodology and explain the model in more detail.

3.1 Game Theoretic Framework of Stock Externality

The IPCC Third Assessment Report (TAR) mentions several decision-making frameworks (DMFs) as tools for handling the climate change problem. As indicated in Chapter 1, climate change differs from other environmental problems in several key ways due to the long time scale and high level of uncertainty involved. As a result, climate policy decisions must be made in the face of these uncertain and complex conditions. Decision-making frameworks help to eliminate some of the inherent complexity as (IPCC 2001b; p.606):

> Analytical techniques aimed at synthesizing available information from many (broader or narrower) segments of the climate problem to help policymakers assess the consequences of various decision options within their own jurisdictions.

The IPCC TAR introduced nine types of decision-making frameworks that deal with climate change problems, which the scientists further classify according to six characteristics[16]. Game theory is one of the DMFs that considers "global" and "relevant to institutional framing" problems.

Osborne and Rubinstein define game theory as "a bag of analytical tools designed to help us understand the phenomena that we observe when decision-makers

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[16] In IPCC (2001b, p.610-611), the nine types of DMFs are decision analysis, cost-benefit analysis, cost-effective analysis, tolerable windows and/or safe landing approach, game theory, portfolio theory, public finance theory, ethical and cultural prescriptive rules, policy exercises, focus groups, and simulation gaming. The six problem characteristics are defined as global, long-term, pervasive human activities, uncertainty, irreversible, and relevant to institutional framing.

interact" (Osborne & Rubinstein, 1994, p.1). Game theory is one of the most useful tools analysts have for dealing with complex economic and policy problems—such as those relating to the environment—where interactions among diverse stakeholders, domestic as well as international, play a crucial role (Ostrom et al., 1994; Barrett, 1994; Carraro, 1998, 1999). According to Carraro & Fragnelli (2004), game theory analyses can help enhance our understanding of the interrelations between the economy and the environment and also provide practical suggestions for policy interventions.

Since 1992, many sovereign states have been making efforts to prevent global climate change. A main theme of these efforts, as witnessed during international conferences and negotiations, has been to achieve global GHG emissions reductions through enhanced global cooperation, a tactic referred to as "grand coalition" in game theory models. Grand coalition as discussed in this dissertation can be characterized as a top-down approach because it aims to create a global treaty for reducing GHG emissions that would involve the participation of all parties to the convention. Thus far, the parties of the UNFCCC have not been successful in negotiating this type of global climate change treaty. The difficulties of achieving a global climate change treaty have been attributed to factors such as the power asymmetries between countries, incentives to free ride, and an absence of international authority (IPCC, 1996). Van der Gaast (2015) explained that a global coalition is difficult because "countries may have incentives for free-rider behavior while countries cannot be excluded from the benefits of GHG emission reduction efforts by other countries" (p.221). Game theory analyzes how climate decisions can be made under these constraints. The 2100 global atmospheric stabilization targets our hypothetical coalitions aim to achieve are set at 450 ppm of GHG concentration and 580 ppm as an alternative. These emissions pathways are consistent with scenarios discussed in the IPCC Fifth Assessment Report's SPM (IPCC, 2014d).

To achieve the GHG concentration at 450 ppm CO_2eq, global emissions should decrease by 80% relative to 2010 levels by 2050 and 99% by 2100[17]. As an alternative global climate target, the 580 ppm atmospheric concentration of CO_2 requires a less stringent 30% reduction of GHGs relative to 2010 levels by 2050 and a 50% reduction by end of the century.

This dissertation sets up a global climate change game for the purpose of achieving the two GHG concentration targets mentioned above. According to game theory, a game consists of three elements: player(s), strategy or action, and payoff. In the context of our climate change game, a player is an individual region a strategy concerns the decision of whether or not to mitigate (participate in a coalition); and the payoff represents the avoided damage or net benefit obtained from participating or non-participating. In this dissertation, there are eight players representing eight regions[18] defined in the PAGE09model, each of whom face strategic choices as to whether it benefits them more to join the emissions-reduction coalition or not join and

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[17] The IPCC AR5 SPM Table 1 shows that the 450 ppm stabilization target requires GHG emissions to decline by 41% - 72% relative to 2010 levels by 2050, and close to 100% by 2100 with a range between 78% and -118%. In order to avoid the necessity of negative emissions in 2100, this dissertation assumes that more ambitious reductions of emissions would occur in the first half of this century (IPCC, 2014d).

[18] The eight regions are defined in the PAGE09 model as EU, US, OT (other OECD), EE (Former Soviet Union & Rest of Europe), CA (China & Central Pacific Asia), IA (India and South East Asia), AF(Africa and Middle East), and La (Latin America).

attempt to free ride. Payoff in this case refers to the net benefit[19] of coalition participation as estimated by the PAGE09 model. Net benefit estimates are derived by estimating and comparing the benefits[20] and abatement costs required to stay in the coalition. Benefits in this analysis represent the amount of damage avoided by reducing global GHG emissions (an obligation for coalition members), and represent the difference between the estimated costs of socio-economic impacts before and after the abatement actions are taken. In this dissertation, the estimation of socio-economic impacts is based upon the model-driven damage functions embedded in the PAGE09. Any estimation of climate change damage is subject to large uncertainty and is highly sensitive to the choice of assumptions used to define the key parameters of the damage function. To better account for this uncertainty, a higher damage function is also applied and discussed as an alternative to the model-driven damage function. It should be noted that it is not the intention of this dissertation to propose that we have definitive findings about what drives mitigation and coalition formation. As Norgard (2001) indicates, there are strategies such as "… energy savings, which are not cost-effective in the conventional sense, but attractive to society because of their

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[19] In benefit cost analysis, there are many ways to compare the benefits and costs, such as benefit-cost ratio and net benefit. Benefit-cost ratio is "the ratio of benefits to cost", and net benefit is "total benefits minus cost" (Field & Field, 2002. p121). In this research, net benefit is the focus of analysis and its estimates are derived from simulations of PAGE09 model. The net benefit to Region r from its participation in the coalition is the sum of total benefit to Region r, Br, net of total abatement costs paid by Region r, Cr.

$$\text{Net Benefit} = \sum (B_r - C_r)$$

[20] "The benefit associated with a climate policy is meant to represent what the avoided damage from the policy is worth to people." (Goulder, 2003. p74)

environmental benefits" (Norgard, 2001, p.268). This dissertation offers a new conceptual framework and method that can be used to explore factors such as uncertainty about damage, which might make a difference in arriving at a stable coalition.

A group of eight coalitions, in addition to non-cooperation and grand coalition, are selected for analysis from a total possible 255 coalitions on the basis of political and institutional feasibility. Coalitions excluding developed countries are considered unrealistic and infeasible due to the fact that most of the historical responsibility for emissions falls upon developed countries, and the ambitious goal of achieving a mere 2°C increase in global atmospheric temperature by the end of the century requires their participation. Coalitions that include the African region are also considered unrealistic and infeasible due to their low level of economic development and small contribution to global emissions. The resulting ten coalitions/cases are as follows. Non-cooperation or BAU represents a case in which no climate action is undertaken. In contrast, the grand coalition represents a case in which every region undertakes abatement. Coalition 1 is the case in which only developed countries undertake abatement. Coalition 2 - 8 represent cases in which both developed and developing countries join coalitions in different combinations. The role of developing countries in climate stabilization will be assessed by comparing the results of Coalition 1 with the results of Coalitions 2 - 8. Table 3-1 summarizes the membership of the eight coalitions and the two other cases.

Table 3-1: Coalition Formation

	Participating region[21]
Grand coalition	Participating all regions (EU, US, OT, EE, CA, IA, AF, LA)
Non-cooperation	All singleton
Coalition 1	Participating: all developed regions (EU, US, OT, EE) Not participating: CA, IA, LA, AF
Coalition 2	Participating: all developed regions + CA Not participating: IA, LA, AF
Coalition 3	Participating: all developed regions + IA Not participating: CA, LA, AF
Coalition 4	Participating: all developed regions + LA Not participating: CA, IA, AF
Coalition 5	Participating: all developed regions (EU, US, OT, EE) + CA, IA Not participating: LA, AF
Coalition 6	Participating: all developed regions (EU, US, OT, EE) + CA, LA Not participating: IA, AF
Coalition 7	Participating: all developed regions + IA, LA Not participating: CA, AF
Coalition 8	Participating: all developed regions +CA, IA, LA Not participating: AF

[21] The eight regions are defined in the PAGE09 model as EU, US, OT (other OECD), EE (Former Soviet Union & Rest Of Europe), CA (China & Central Pacific Asia), IA (India and South East Asia), AF(Africa and Middle East), and La (Latin America).

3.2 Integrated Assessment Model: PAGE09

3.2.1 Integrated Assessment Model (IAMs)

Integrated assessment models (IAMs) provide internally consistent estimations of climate change, its impacts, and the mitigation potential of particular greenhouse gas emissions scenarios. IAMs have been widely used to analyze optimal solutions based on cost-benefit comparisons; cost-effective solutions to meet concentration targets; and the sensitivity of key variables including technology options, price mechanisms, and regulatory constraints. The outcome of IAM analyses help policy makers and researchers understand the complex interactions behind the factors contributing to climate change, as well as the impacts on adaptation and the necessary mitigation responses (Kelly & Kolstad, 1999).

Integrated assessment models are used to analyze the interaction between climate policy actions and the economy in an integrated framework. IAMs such as RICE (Regional Integrated Climate-Economy model), DICE (Dynamic Integrated Climate-Economy model), MERGE (a model for estimating the regional and global effects of greenhouse gas reductions), GCAM (Global Change Assessment Model), AIM (The Asia-Pacific Integrated Model), and PAGE09 have been used to conduct climate-economy analyses during the last two decades. Some IAMs are optimization models (RICE/DICE, MERGE), while others are partial equilibrium (GCAM) or bottom-up models (AIM). The strength of IAMs lies in their ability to conduct internally consistent analyses of the nexus between climate change, its impacts, and mitigation.

IAMs are divided into three categories by Yang (2008): computable general equilibrium (CGE) models, intertemporal optimization models, and scenario simulation models. The CGE model is a flexible model to build or disaggregate sectors or regions. Examples include the EPPA model and PNNL's Second General Model (SGM). Intertemporal optimization models include RICE and MERGE. According to Yang, intertemporal optimization models are more flexible, powerful, and transparent than CGE models due to the former' capacity to handle intertemporal economic relationships. Scenario simulation models, including IMAGE and GCAM, reflect systems of relations as assessed by modelers without any formal involvement of assumptions as to the behavioral aspects of the decision-making entity.

Using game theory combined with IAMs can provide useful information to decision makers. The global benefits and costs derived from IAMs can function as important benchmarks for strategy development by players in the greenhouse gas emissions reduction game. Likewise, the game theoretic approach can provide rich insight into the quantitative outcomes of IAM analyses.

Yet despite the potential for combining game theory and IAMs, efforts to integrate and apply these two approaches to climate change analysis have only a short history (Hammitt & Adams, 1996; Císcar & Soria, 2002; Yang, 2003; Buchner et al., 2005; Carraro et al., 2006; Labriet and Loulou, 2008; Bernard et al., 2008). In 2002, Císcar & Soria emphasized that game theory is an appropriate tool for analyzing the conditions for cooperation and conflict in addressing climate change problems, considering that the payoffs of certain strategies are calculated by IAMs, which also provide information on global as well as regional climate damages and the amount of GHG emissions abatement. Nordhaus and Yang (1996) analyzed climate change strategies using the RICE model to calculate an emissions reduction path to reflect the outcomes of a cooperative approach and compared it to the path expected from a non-cooperative approach.

Analyzing the economic feasibility and stability of emission reductions coalitions requires obtaining information about climate impacts and the costs of avoiding these impacts. Integrated Assessment Models are analytic tools designed to provide information on climate impacts and responses, among other variables. This dissertation uses the PAGE09 (Policy Analysis for the Greenhouse Effect) model, one of the most widely used integrated assessment models for climate policy analysis, to merge its game theory approach with analyzing emission reductions coalitions.

3.2.2 The PAGE09 Model

The PAGE09 model (Policy Analysis for the Greenhouse Effect 09) model, an updated version of PAGE02, is an integrated assessment model that is designed to help decision makers understand climate change problems (Plambeck, Hope, & Anderson, 1997; Hope, 2011a, 2011b). The model estimates impacts from climate change and calculates the abatement and adaptation costs of climate change policy (Hope, 2011b)The PAGE09 model helped provide information on the impacts of climate change for the Fourth Assessment Report of the IPCC (IPCC, 2007).

PAGE09 uses simple equations to illustrate the results of complex climate change issues through scientific and economic modeling (Plambeck et al., 1997, Hope, 2009, 2011a). The model results of PAGE09 are represented by probability distributions created by repeatedly running random sampling input data based on triangular probability distributions (minimum, mode, and maximum). This kind of model is called a stochastic model and is especially useful for representing the uncertainties inherent in climate change. Not only does the model use probabilities to help estimate its results, it also determines its input variables through probabilities based on "Latin hypercube sampling[22]" (Hope, 2006).

The PAGE09 model can run two policy scenarios simultaneously. Thus, in addition to showing the estimated outcomes of each scenario, the model can also show differences between the two scenarios' outcomes (e.g. differences in prevention costs, climate impacts, and adaptation costs). As there are many possible ways of responding to climate change, it is useful to be able to compare two different adaptation and/or abatement policies as made possible by the model (Hope, 2011b).

In the PAGE09 model, the BAU scenario is based on the A1B[23] scenario from "Special Report: Emissions Scenarios" by IPCC. Each IPCC policy scenario regarding emissions reduction or climate change intervention is described by the percentage change of emissions relative to the base year 2008 (Plambeck et al., 1997). The percentage change of emissions in the model covers all Kyoto-identified GHGs, represented by the four gases CO_2, CH_4, N_2O, and Lin (SF_6, CFCs, PFCs). PAGE09

[22] "Latin Hypercube sampling is preferred to "random" Monte Carlo sampling since it provides a better coverage of the underlying PDFs" (Pycroft et al., 2011, P.1).

[23] The A1 scenario assumes rapid economic growth, population peaking in mid-century and then followed by a decline, and the rapid penetration of new technology. A1B is a part of the A1 scenario family that assumes using all technologies do not depend on a specific source (IPCC, 2001a, 2001b).

includes eight regions[24] and four impact sectors[25] from 2008 to 2200 with 10-year time periods[26] (Hope 2011a, Hope 2011b).

The volume of emissions reduction needed to achieve a certain temperature decrease is determined by the amount of cumulative CO_2 emissions in the atmosphere. In other words, higher cumulative concentrations of CO_2 requires greater emissions reductions to lower atmospheric temperature by a set amount; e.g. 1℃. Each IAM arrives at different estimations for cumulative CO_2 emissions, which in turn affects the estimated emissions reduction volume necessary to lower atmospheric temperature. Table 3-2 compares the relationship between the estimated volume of emissions reduction and cumulative emissions among the selected IAMs. The PAGE09 model estimates that the cumulative BAU emissions in 2100 will be 4,559 $GtCO_2$, which would require a reduction of 1,311 $GtCO_2$ to reduce the temperature by 1℃. Alternatively, the DICE/RICE and WITCH models estimate that 2100 BAU cumulative emissions will be 6,286 $GtCO_2$ and 6,202 $GtCO_2$, respectively, which would require reductions of 2,987 $GtCO_2$ or 1,859 $GtCO_2$ to achieve a 1℃ temperature decrease. Of the three models, the DICE/RICE provides the highest estimate for the volume of emissions that would need to be reduced to lower atmospheric temperature and PAGE09 provides the lowest estimate.

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24 EU, US, OT (other OECD), EE (FSU&ROE), CA(China & Asia), IA, (India and South Asia), AF (Africa & ME), LA (Lain America)

25 Economic and non-economic, sea level, and discontinuities

26 Time period: 2008 (base year), 2009, 2010, 2020, 2030, 2040, 2050, 2075, 2100, 2150, 2200.

Table 3-2: Comparison of Emissions and Temperature in selected IAMs

	PAGE	DICE/RICE	WITCH
Cumulative emissions in BAU ($GtCO_2$)	4,559	6,286	6,202
Temperature increase in BAU (degree C)	3.90	3.88	4.13
Cumulative emissions in Low emission scenario ($GtCO_2$)	2,394	3,325	4,194
Reduction in emissions ($GtCO_2$)	2,165	2,961	2,008
Decrease in temperature from BAU (degree C)	1.65	0.99	1.08
Emission reductions ($GtCO_2$) per 1 ℃	1,311	2,987	1,859

The PAGE09 model uses a 1.03% discount rate to estimate the future streams of benefits and costs, while the DICE/RICE model uses a 1.5% discount rate and the WITCH model uses a rate of 3% (see Table 3-3). The lower discount rate used by the PAGE09 model would indicate that the resulting present value of future benefits/costs estimates are relatively higher for this model.

Table 3-3: Discount Rate

	PAGE09	DICE/RICE	WITCH
Discount Rate	1.03%	1.5%	3%[27]

[27] Bosetti et al. (2006).

3.2.2.1 Input Values in PAGE09

PAGE09 estimates greenhouse gas effects and radiative forcing by tracking the accumulation of GHG emissions in the atmosphere. The model assumes that a high concentration of CO_2 among the GHG emissions in the atmosphere is a main driver of anthropogenic climate change. Concentration of GHG emissions in the atmosphere consists of the concentrations of greenhouse gases during the pre-industrial era plus the base year's excess concentrations multiplied by the remaining emissions divided by the base year's remaining emissions (Hope, 2006). Major input data of CO_2 is shown by triangular proportional distribution. Table 3-3 shows the major triangular distributions for CO_2 in the model.

Table 3-4: CO_2 Parameter

	Mean	Min	Mode	Max	Unit
Percent of CO_2 emitted to air[1)]	62.0	57	62	67	%
Stimulation of CO_2 concentration[2)]	9.7	4	10	15	%/degC
CO_2 stimulation limit[3)]	53.3	30	50	80	%

Source: 1) Results of A2 and 450 scenarios from FUND, RICE and MERGE models (PAGE09)
2), 3) the developer input the size data feedback (PAGE09)

Radiative forcing equations of CO_2 comprise the base year's radiative forcing plus a concentration logarithmic function. Radiative forcing equations of N_2O and a CH_4 follow the same format, and amount to the base year's forcing plus the forcing slope given by the model multiplied by the square root of each gas concentration. The concentration of the 4th gas, LIN (SF_6, CHCs, PFCs), is calculated using a linear equation to account for the distribution of radiative forcing (Hope, 2011b). Total radiative forcing is the sum of radiative forcing from all four GHG gases plus excess forcing from other gases. Other contributors to radiative forcing include O_3, black carbon, and oleoresin capsicum aerosol. Together, these represent exogenous variables that can be adjusted for in policies (Hope, 2011a).

Table 3-5: Default Value of Four Gases

	mean	min	mode	max	
Percent of CO_2 emitted to air	62.00	57	62	67	%
Half-life of CO_2 atmospheric residence	73.33	50	70	100	years
Half-life of CH_4 atmospheric residence	10.5				years
Half-life of N_2O atmospheric residence	114				years
Half-life of Lin atmospheric residence	1,000				years
Forcing slope of CO_2	5.5				
Forcing slope of CH_4	0.036				
Forcing slope of N_2O	0.12				
Forcing slope of Lin	0.2				

The climate sensitivity (SENS) is estimated using two forms of uncertain input data: the transient climate response (TCR)[28] and the feedback response time (FRT)[29].

28 Transient climate response (TCR) means that "the temperature rise at the end of 70 years of CO2 concentration rising at 1% per year, corresponding to a doubling of CO2 concentration." (Hope. 2011b. P.5)

29 The feedback response time (FRT) "indicates how many years GHGs persist in the atmosphere." (Pycroft et al. 2011. P.6)

In the PAGE09 model, the half-life of global warming represents the feedback response time.

Table 3-6: TCR and FRT Parameters

	Mean	Min	Mode	Max	Unit
Transient climate response	1.7	1	1.3	2.8	degC
Half-life of global warming[1)]	35	10	30	65	years

Source: 1) The developer reduced from PAGE02

Climate change impacts estimated by the PAGE09 are divided into four sectors: economic, non-economic, sea level rise, and discontinuity. These impacts, shown as a proportion of GDP, are calculated from a polynomial equation with an uncertain exponent (Hope, 2011a). The estimated impacts of climate change reported in Chapters 4 and 5 reflect these categories of economic and non-economic impacts.

Table 3-7: Default Value of Sea Level Impact

	Mean	Min	Mode	max	
Sea level impact at calibration sea level rise	1.00	0.5	1	1.5	%GDP
Sea level impact function exponent	0.73	0.5	0.7	1	
Sea level exponent with income	-0.30	-0.4	-0.3	-0.2	

Economic impacts[30] include agricultural losses, as well as heating and cooling costs that are directly included in GDP. Non-economic impacts[31] include ecosystem losses and declines in human health that are not represented in GDP (Hope, 2011b). Non-economic impacts represent situations wherein market prices cannot be applied due to lack of markets (Stern, 2006). The estimated impacts of climate change reported in Chapters 4 and 5 reflect both these categories of economic and non-economic losses. PAGE09 estimates climate impacts on market and non-market categories using temperature rise, in contrast to most other damage estimate methods in the research literature that use the doubling of CO_2 concentrations in the atmosphere. In this model, the impacts of climate change are assumed to correlate with global mean temperature rises above 2.5℃, called the tolerable temperature level in PAGE09 (Hope, 2006). Table 3-8 shows the default values used to estimate climate impacts.

[30] Economic impacts are defined as: "market impacts where prices exist and a valuation can be made relatively easily, such as in agriculture, energy use and forestry" (Stern, 2006, P. 150).

[31] Non-economic impacts focus "directly on human health and the environment, where market prices tend not to exist and methods are required to create them" (Stern, 2006, p.150).

Table 3-8: Default Value of Economic and Non-Economic Impacts

	Mean	Min	Mode	Max	
Economic impact at calibration temperature	0.50	0.2	0.5	0.8	%GDP
Economic impact function exponent	2.17	1.5	2	3	
Economic exponent with income	-0.13	-0.3	-0.1	0	
Non-econ impact at calibration temperature	0.53	0.1	0.5	1	%GDP
Non-economic impact function exponent	2.17	1.5	2	3	
Non-economic exponent with income	0.00	-0.2	0	0.2	

Discontinuity impacts account for damages such as ice sheet melting and thermohaline circulation (THC) (Hope, 2011a, 2011b). The PAGE09 model assumes that discontinuity impacts occur when the global mean temperature increases 3℃ above the pre-industrial level (Hope, 2011b). The mean chance of discontinuity as recorded in Table 3-8 signifies that there is a 20% chance of discontinuity impacts occurring relative to the temperature rising about 1℃.

Table 3-9: Default Value of Discontinuity

	Mean	Min	Mode	Max	unit
Tolerable before discontinuity (TDIS)	3.00	2	3	4	degC
Chance of discontinuity (PDIS)	20.00	10	20	30	% per degC
Loss if discontinuity occurs (WDIS)	15.00	5	15	25	% GDP
Half-life of discontinuity (DISTAU)	90.00	20	50	200	year

3.2.2.2 Comparison of Damage Estimates

Comparing the various climate damage estimates provided by the models reveals the large uncertainties inherent in quantifying future damage. Due to the difficulty of quantifying non-economic damages, for example, some models choose not to include them in their evaluation. The large gap between the PAGE09 and IPCC damage estimates can be partly explained this way, as the PAGE09 estimate includes economic and non-economic damages while the IPCC considers economic damages only. Moreover, the difference between the two IPCC estimates reflects the significant increase in damages that are expected to occur if no action is taken to limit temperature rise, as opposed to if mitigation action limits the temperature increase to 2.5℃. Ultimately, the wide range of climate damage estimates indicates that the results of the model simulations presented in Chapters 4 and 5 should be interpreted with caution.

Table 3-10: Damage Estimates

	PAGE09		IPCC AR4	IPCC AR5
	Model driven function (BAU)	High damage function (BAU)	No Action	RCP4.5[32]
World GDP loss(%)	10%	32%	1-5%	0.2-2.0%
Projected Δ Temperature	3.8	3.9	4	~2.5

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[32] According to IPCC AR5 SPM (2014d), CO_2-eq concentration will be between 580 ppm and 720 ppm in 2100.

Chapter 4

ANALYSIS OF STATIC GAME OF STOCK EXTERNALITY UNDER THE CASE 1: 450 ppm

This chapter examines the climate and economic outcomes found by the PAGE09 model for different coalitions under the 450 ppm target. Each outcome chapter notes the differences between non-cooperation and grand coalition as well as the differences between the partial coalitions as compared to grand coalition and non-cooperation. Climate outcomes examined in this chapter include CO_2 emission pathways, CO_2 concentrations, and atmospheric temperatures in 2100. Economic outcomes are used to assess the economic feasibility of different coalitions by estimating net benefits and stability.

4.1 Climate Science Outcomes

4.1.1 Non-cooperation and Grand Coalition

This section describes the outcomes of non-cooperation and grand coalition given the 450 ppm by 2100 global emissions target. As mentioned in Chapter 3, grand coalition represents a scenario in which all eight regions as defined in the PAGE09 model, agree to reduce their emissions to a level necessary to achieve the chosen climate target. By contrast, non-cooperation means that no region joins the climate agreement. In other words, the non-cooperation emissions pathway reflects the BAU emissions trajectory as defined in the PAGE09 model.

Figure 4-1 shows the world's CO_2 emissions under grand coalition and non-cooperation. Under grand coalition to achieve 450 ppm CO_2eq in 2100, the global CO_2 emissions peak in 2020 then decline until the end of the century. The emission path under non-cooperation shows that global CO_2 emissions grow until about the mid-21st century and then slightly decrease because of the declining energy intensity and increasing energy efficiency assumed by the model. In 2100, CO_2 emissions will be 49,452 Mton under non-cooperation and 403 Mton under grand coalition.

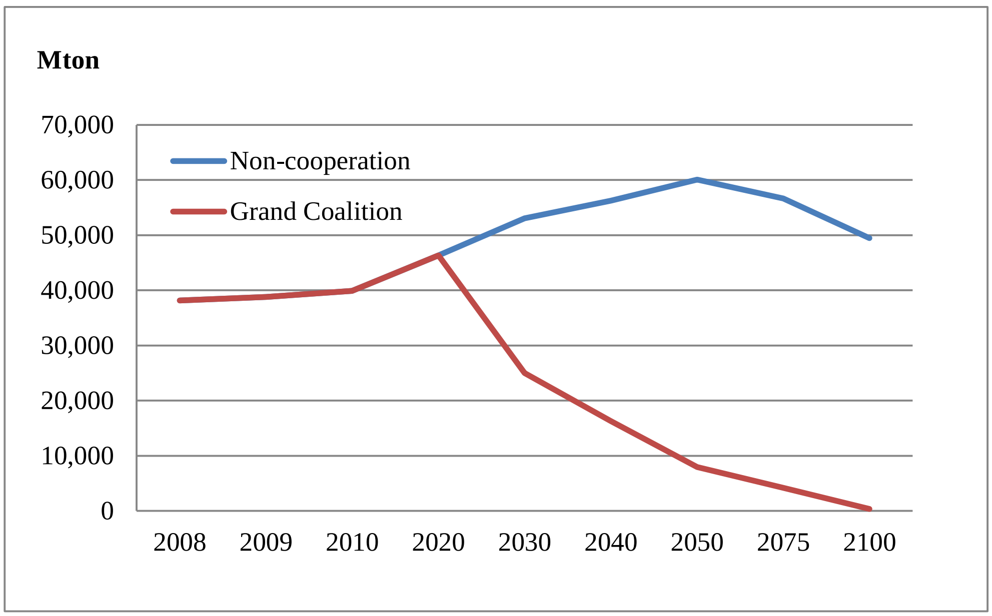

Figure 4-1: CO_2 Emissions

Figure 4-2 shows the CO_2 concentration from 2008 to 2100 for non-cooperation and grand coalition with probability distributions. After 2050, the CO_2 concentrations under non-cooperation rapidly grow until the end of the 21st century. The mean CO_2 concentration in 2100 is 704 ppm with a 95% confidence interval of

640 ppm - 779 ppm. The grand coalition pathway for achieving the 450 ppm target has CO_2 concentrations increasing gradually until about 2020 and then declining through 2100. The mean CO_2 concentration peaks at 457 ppm in 2050 and decreases to 431 ppm in 2100. The 95% confidence interval for the CO_2 concentration at the end of this century is 410 ppm - 455 ppm.

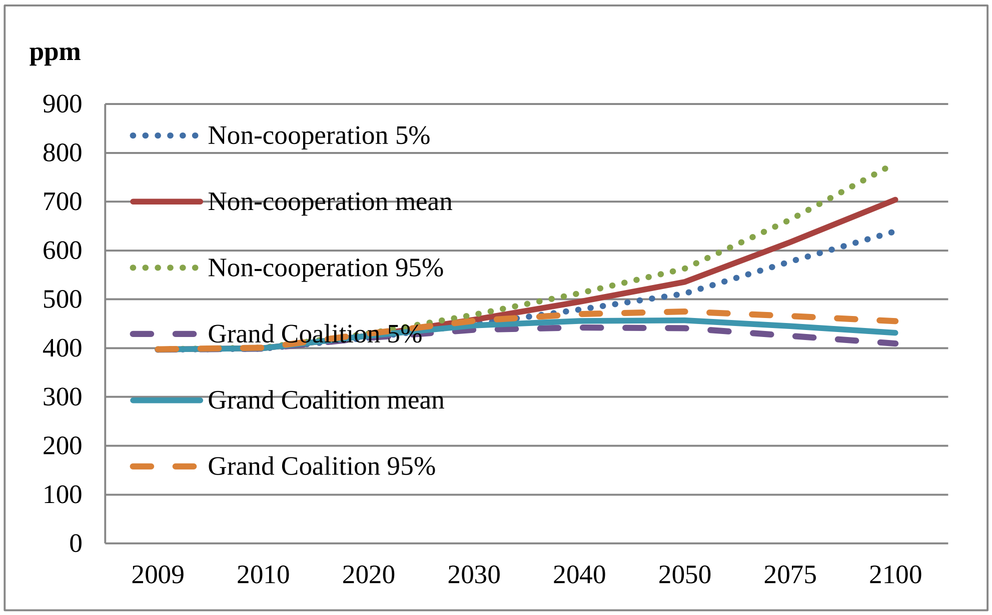

Figure 4-2: CO_2 Concentration

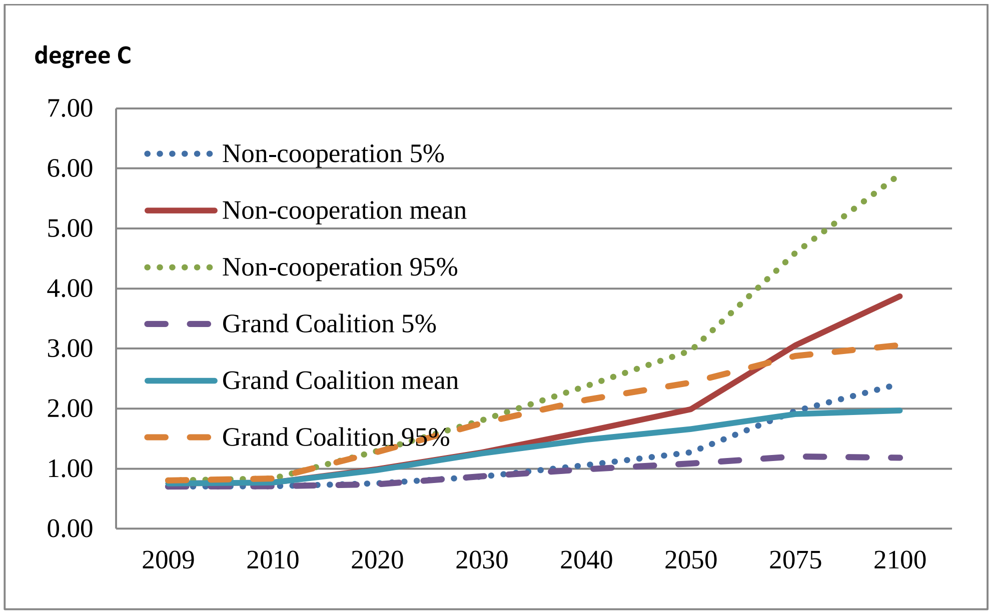

Figure 4-3: Global Mean Temperature

Under non-cooperation, the mean value for the global mean temperature is 3.87℃ above the pre-industrial level in 2100. The 95% confidence interval for the temperature increase in 2100 is 2.41 - 5.9℃, with a 5% chance that the global mean temperature under non-cooperation exceeds 5.9℃ in 2100. Under grand coalition, the mean value of global mean temperature in 2100 rises 1.97℃ above the pre-industrial level. The 5% confidence interval for this value is 1.18 - 3.06℃ relative to the pre-industrial level.

4.1.2 Partial Coalitions

This section presents the climate outcomes, i.e., CO_2 emissions and their climate consequences, for the period of 2008 - 2100 for the eight partial coalitions. Specific comparisons of the climate and emissions are made for two distinct cases:

Coalition 1 and Coalition 5. The outcomes of the other coalitions are described in Appendix A.

Coalition 1 models what would happen if all developed regions participate in a climate stabilization agreement. Coalition 5 evaluates the outcomes when two of the major emitting regions in the developing world, CA and IA, participate in an agreement with developed regions.

Figure 4-4 illustrates the CO_2 emissions paths of the eight coalitions for the period of 2008 - 2100 along with the emission paths expected from grand coalition and non-cooperation. Coalition 1 consists only of developed regions, with all developing regions remaining outside the coalition. The CO_2 emissions under Coalition 1 are 46,186 Mton in 2050 and 38,966 Mton in 2100. These represent a 23% drop in emissions relative to the non-cooperation emission path in 2050 and a 21% drop relative to that path in 2100.

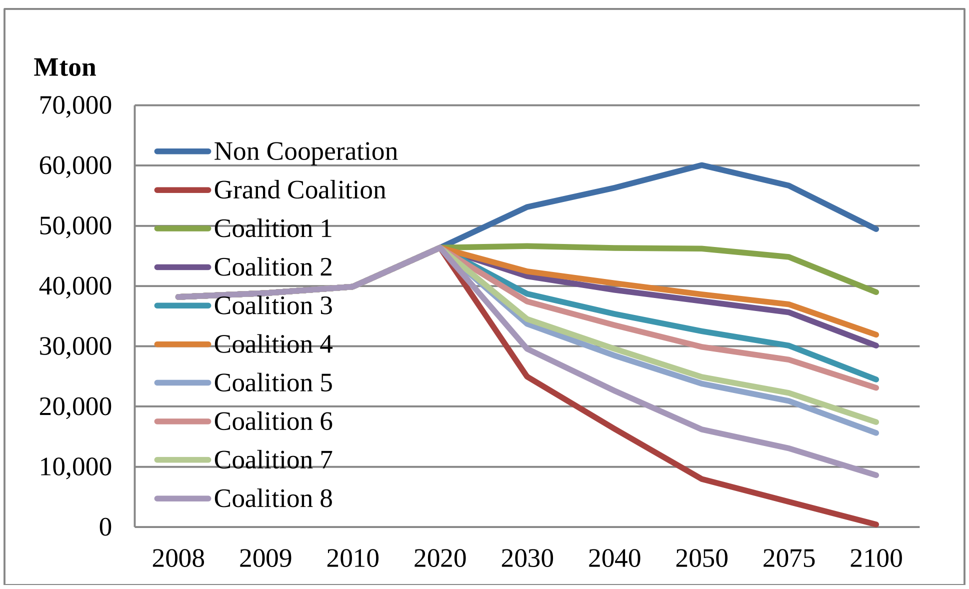

Figure 4-4: CO_2 Emissions under Coalitions

The CO_2 emissions of Coalition 8 (all developed regions and all developing regions except the AF region) are 16,208 Mton in 2050 and 8,593 Mton in 2100. The amount of CO_2 under Coalition 8 is less than the CO_2 generated during non-cooperation by 73% by 2050 and 82% in 2100. CO_2 emissions under Coalition 5 are 23,802 Mton in 2050 and 15,633 Mton in 2100, which is less than the CO_2 under non-cooperation by 60% in 2050 and 68% in 2100.

Figure 4-5 shows the CO_2 concentrations from 2008 to 2100 for all eight coalitions, as well as for grand coalition and non-cooperation. When only developed regions join the climate agreement (Coalition 1), the CO_2 concentration are 514 ppm in 2050 and 630 ppm in 2100, which is 5% lower than the concentration under non-cooperation by 2050 and 10% lower by 2100. However, the concentration of Coalition 1 is 12% higher than the grand coalition by 2050 and 46% higher by 2100. Coalition 5 in which all developed regions and two developing regions join the climate agreement is estimated to result in CO_2 concentrations of 480 ppm in 2050 and 509 ppm in 2100. The CO_2 concentration of Coalition 5 is 5% higher than the concentration under grand coalition by 2050 and 18% higher by 2100. Under Coalition 5, the global target of stabilizing GHG emissions by 450 ppm at the end of this century cannot be achieved, even with all developed regions and two major emitting developing regions participating. This would suggest that achieving the ambitious climate target of 450 ppm would require a coalition to have the participation of as many developing regions as possible.

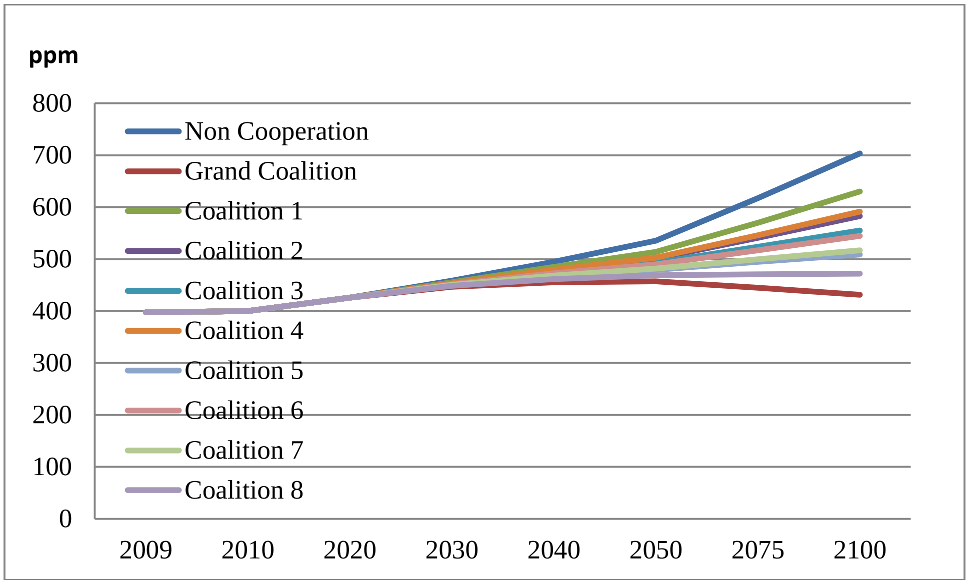

Figure 4-5: CO_2 Concentration under Coalitions

Table 4-1 describes the CO_2 concentrations and global mean temperature for all eight coalitions along with concentrations for grand coalition and non-cooperation. The uncertainty range for CO_2 concentrations and global mean temperatures are shown in the next table.

Table 4-1: CO_2 Concentration and Global Mean Temperature by all Coalitions

	2050	2100	
	CO_2 Concentration (ppm)	CO_2 Concentration (ppm)	Global mean temperature (degree C)
Non-cooperation	535	704	3.87
Grand Coalition	457	431	1.97
Coalition 1	514	630	3.22
Coalition 2	501	583	2.93
Coalition 3	493	555	2.76
Coalition 4	506	592	3.05
Coalition 5	480	509	2.43
Coalition 6	490	545	2.73
Coalition 7	482	517	2.55
Coalition 8	469	472	2.21

Figure 4-6 shows the CO_2 concentrations under Coalitions 1 and 5, with the non-cooperation and grand coalition results, for the period of 2008 - 2100. The concentrations of Coalition 1 are shown to continue to increase until the end of this century. The mean value of CO_2 concentrations under Coalition 1 is 630 ppm in 2100 with a 95% confidence interval of 579 - 690 ppm. There is also a 5% chance that the CO_2 concentration of Coalition 1 will exceed 690 ppm by 2100. The CO_2 concentration of Coalition 5, which assumes the participation of CA, IA and developed regions, keeps increasing until the end of this century, but it is less than the CO_2 concentration under Coalition 1. Coalition 5's CO_2 concentration reaches 480 ppm in 2050 and 509 ppm in 2100. The 95% confidence interval for the coalition's CO_2 concentrations at the end of this century is between 477 ppm and 546 ppm.

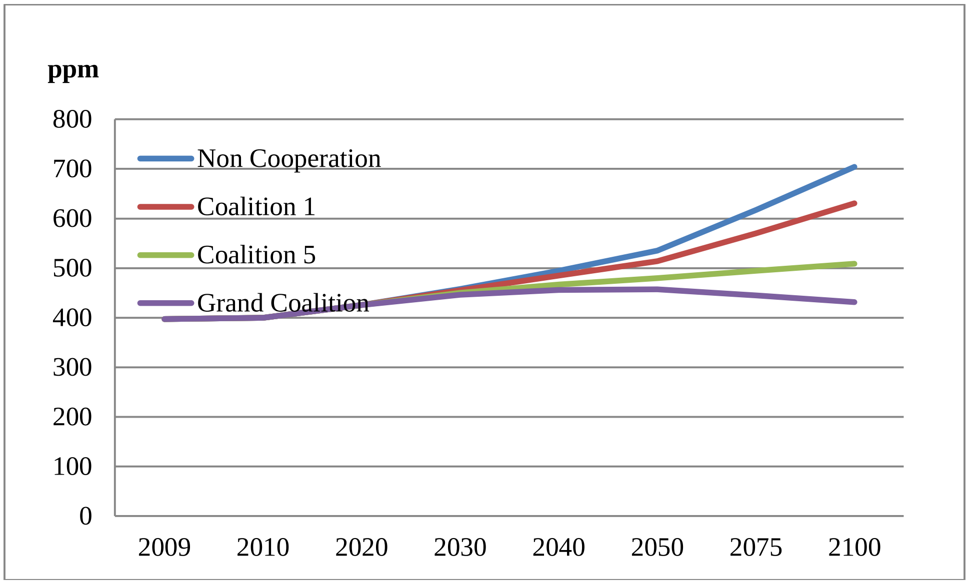

Figure 4-6: CO_2 Concentration of Coalition 1 and 5

Figure 4-7 compares the global mean temperature under Coalitions 1 and 5. Under Coalition 1, which includes only developed regions, the global mean temperature is 3.22℃ in 2100. The 95% of confidence interval for the global mean temperature at the end of the century is 2.00 - 4.96℃. Coalition 5 leads to lower global mean temperature than Coalition 1. If CA and IA join the coalition with developed regions, the global mean temperature is 2.43℃ in 2100. The 95% confidence interval for the global mean temperature under this coalition at the end of this century is 1.49 - 3.77℃, indicating that there is a 5% chance that the global mean temperature will exceed 3.77℃ in 2100.

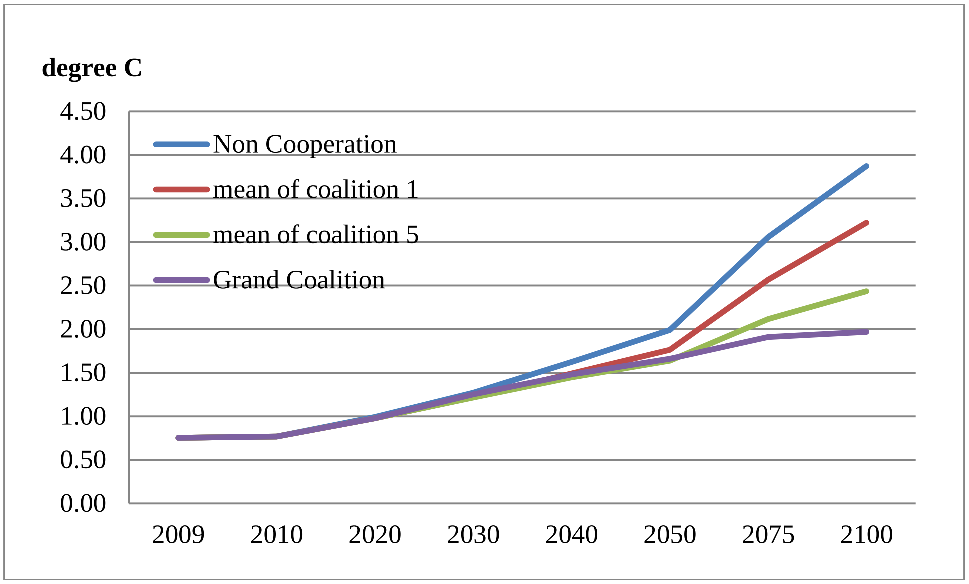

Figure 4-7: Global Mean Temperature of Coalition 1 and 5

4.2 Economic Outcomes

The main focus of this chapter is to analyze the results of the PAGE09 model simulations to determine if various coalition formations can achieve the goals of climate stabilization at the levels of 450 ppm or 580 ppm as an alternative. First, we assess the economic feasibility of the modeled coalitions—both grand and partial—by using three key criteria: socio-economic impacts, abatement costs, and net benefits. We then assess the stability of coalitions by analyzing what incentives are necessary for coalition formation and continuation. This assessment of economic feasibility and coalition stability will identify what coalitions would be effective for achieving certain climate targets and also help to define the conditions necessary for such coalitions to be stable.

4.2.1 Economic Feasibility

This section analyzes the conditions under which grand coalition is economically feasible. First, we examine the benefits that grand coalition would generate, i.e. the amount of socio-economic impacts reduced due to the grand coalition's ability to stabilize the climate. Second, we examine the costs of mitigating GHG emissions to achieve climate stabilization under grand coalition. An assessment of net benefits will follow.

Estimating the benefits of grand coalition begins with estimating the socio-economic impacts of non-action, i.e. estimating the level of climate damage that would occur if the world continues on a Business as Usual (BAU) path and does not adopt a global climate policy. This is the world of non-cooperation. Any action on climate will produce an alternative path, with a lower damage estimate, that will deviate from the BAU path. The extent of deviation from BAU is identical to the benefits of climate policy as mentioned in the previous chapter.

There are a number of studies that estimate the expected damages from climate change by assuming a doubling of atmospheric CO_2 concentrations relative to the pre-industrial level (Hope, 2009; Nordhaus, 2010). The range of estimates using this approach is large because there is great uncertainty regarding the relationship between atmospheric CO_2 concentration and temperature increase[33]. Other factors that contribute to variations in damage estimates include differences in the valuation of non-market impacts; treatment of potential non-linearity, discontinuity and irreversibility in impacts; and the discount rates applicable to impacts falling upon future generations. Most studies focus on the socio-economic impacts expected from

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[33] The equilibrium climate sensitivity is in the range of 1.5℃ - 4.5℃.

the temperature increase of 2°C, and there are very few that analyze the impacts of temperature increases beyond 3°C (Nordhaus, 2010). The socio-economic impacts of a 2°C temperature increase are estimated to be in the range of 0.2 - 2.0% loss in annual global income[34]. However, these estimates do not take into account catastrophic, irreversible impacts and thus may underestimate the magnitude of climate damages.

The social cost of carbon (SCC) provides another method for measuring the economic impacts of climate change. The SCC is the societal cost resulting from each additional ton of CO_2 emissions released into the atmosphere. The uncertainties and limitations regarding the estimation of socio-economic impacts are also applicable to SCC estimates. The IPCC's 4th Assessment Report (AR4) found that the SCC for 2005 had a mean value of $43 per ton of carbon with an uncertainty range of $10 - $350 per ton[35]. The SCC estimates are particularly sensitive to discount rates applied to future climate impacts. Table 4-2 shows the value of SCC with discount rates in the range of 0 - 3%. The table shows that a 3% discount rate results in $40 per ton of carbon, while a 1% discount rate yields a per ton price of $209 or an increase in the SCC by a factor of five[36].

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[34] Summary for Policy Makers, IPCC AR5, Working Group II Assessment Report (IPCC, 2014c, p.19).

[35] Summary for Policy Makers, IPCC AR5, Working Group II Assessment Report (IPCC, 2014c, p.17).

[36] IPCC AR5, Working Group II Assessment Report (IPCC, 2014a, p.80).

Table 4-2: Selected statistical characteristics of the social cost of carbon: average (Avg) and standard deviation (SD), both in dollar per tonne of carbon, and number of estimates (N; number of studies in brackets)

Interest Rate	Post-AR4		Pre-AR4		All studies	
	Avg	SD	Avg	SD	Avg	SD
0%	270	233	745	774	585	655
1%	181	260	231	300	209	284
3%	33	29	45	39	40	36
All	241	233	565	822	428	665

Source: IPCC (2014a, p.80)

4.2.1.1 Non-cooperation and Grand Coalition

The estimates of socio-economic impacts analyzed for various coalition formations in this dissertation are based upon the PAGE09 model, one of the few models that incorporates the possible effects of extreme events that may occur at temperatures higher than a 2℃ increase. The PAGE09 uses information the IPCC's Third Assessment Report recognizes as key to understanding the severity and pervasiveness of impacts corresponding to increasing warming. These are labeled by the IPCC as five "Reasons for Concern", and include risks to unique and threatened systems; risks from extreme climate events; distribution of impacts; aggregate impacts; and risks from future large-scale discontinuities (IPCC, 2001a).

A grand coalition to achieve climate stabilization below 450 ppm CO_2eq would reduce the magnitude of climate impacts below what would be expected under BAU.

The outcomes of grand coalition and non-cooperation for 450 ppm reflect an uncertainty range that incorporates the effects of extreme impacts, including non-linear, discontinuous and irreversible impacts. If regions do not reduce their emissions from the BAU emissions path, which would be expected under the non-cooperation scenario, the mean present value of socio-economic impacts is \$13 trillion in 2050 with a 95% confidence interval of \$2 - \$34 trillion or a 6% loss in annual global income. In 2100, the mean present value of the socio-economic impacts under non-cooperation is \$84.7 trillion with a 95% confidence interval of \$9.1 - \$290.6 trillion or a 10% loss in annual global income.

For grand coalition, the mean present value of socio-economic impacts in 2050 would be \$9 trillion with a confidence range of about \$1 to \$21 trillion. Under grand coalition, the estimate of socio-economic impacts in 2050 is 33% less than the impact estimated under the non-cooperation scenario and would have a mean socio-economic impact representing a 4% loss in global income. In 2100, the mean present value of socio-economic impacts is \$13.6 trillion or about a 1.6% loss of annual global income, with a confidence interval of \$2.1 - \$38.3 trillion. This impact is 84% less than the impact under non-cooperation.

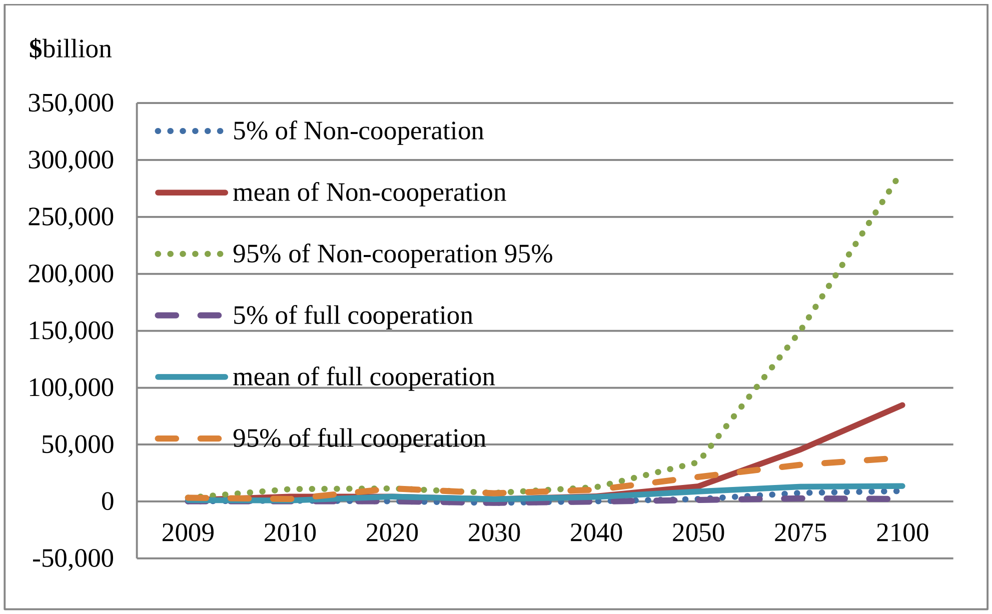

Figure 4-8: Socio-Economic Impacts: Non-cooperation and Grand Coalition (450 ppm)

Figure 4-8 shows the estimates of socio-economic impacts with a 5% - 95% range for the period of 2009 to 2100 under non-cooperation and grand coalition. Under non-cooperation there is a 5% chance that the costs of impacts would exceed $291 trillion in 2100. Furthermore, the socio-economic impacts at the 95th percentile under non-cooperation are expected to rise very slowly until 2050 and then increase precipitously for the rest of the century. In the PAGE09 model, the global impacts from climate change are a function of the increase in global mean temperature due to cumulative GHG emissions in the atmosphere. The model assumes that discontinuity in the climate impacts occurs when the rise in the global temperature exceeds 3℃ above the pre-industrial level and that climate change will be irreversible once discontinuity sets in. The simulation results shown in Figure 4-8 imply that under non-cooperation, discontinuity in climate impacts would occur after 2050.

The magnitude of climate change damages is subject to large uncertainty and is sensitive to assumptions underlying the estimation. Therefore we used an alternative damage function that yields higher damage estimates than the estimates derived from default damage function embedded in the PAGE09 model. We then examined how this change will affect the economic feasibility, i.e. the net benefit of coalitions. Figure 4-9 summarizes the socio-economic impacts associated with a high damage assumption.

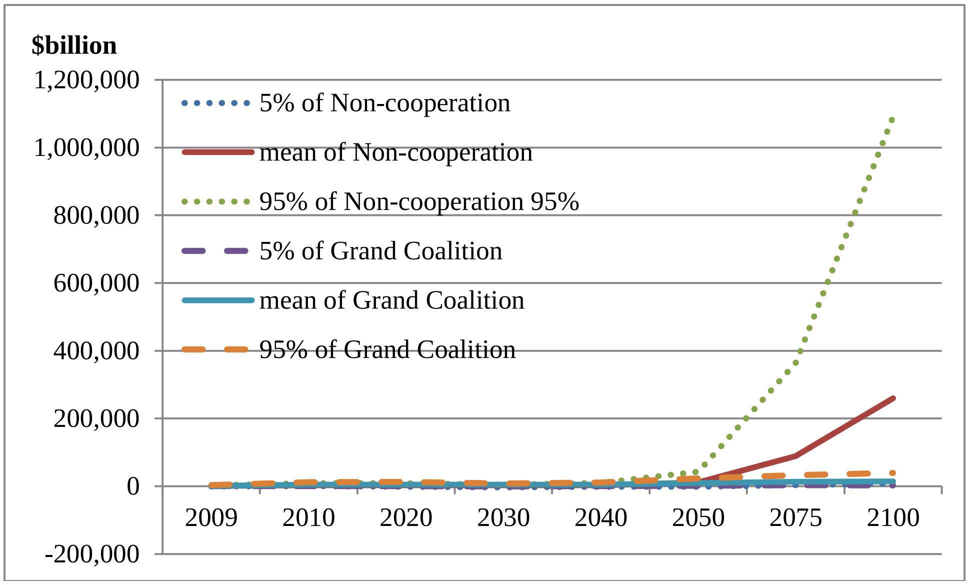

Figure 4-9: Socio-Economic Impacts: Non-cooperation and Grand Coalition (450 ppm under the high damage assumption)

Assuming there will be high damage, non-cooperation would result in global socio-economic impacts amounting to $260 trillion in 2100. There is a 5% chance that the impacts will exceed $1,090 trillion in 2100. Under grand coalition, the impacts are estimated to reach $9 trillion in 2050 and $14 trillion in 2100. There is a 5% chance that the impacts will exceed $39 trillion in 2100.

We will now consider the costs required to achieve 450 ppm CO_2eq. The climate mitigation cost depends on the quantity of emissions reductions, which is equal to the difference in emission levels associated with the climate stabilization goal and the BAU pathway. Given the stabilization of GHG concentration below 450 ppm CO_2eq, the higher the BAU emissions path, the higher the quantity of emissions reductions required, and thus the higher the cost of mitigation. The IPCC 5th Assessment Report provides an estimate of the cost needed to stabilize the GHG concentration at 430 - 480 ppm. If all regions immediately begin to participate in the global effort to reduce emissions to reach the concentration goal, the costs entail losses of 1 - 4% in global consumption in 2050 and losses of 2 - 12% in 2100 relative to BAU levels. The IPCC 4th Assessment Report shows that mitigation would cost a maximum 3% of GDP to stabilize GHG concentrations in the atmosphere between 445 - 710 ppm CO_2eq in 2030. In 2050, reaching the 445 - 535 ppm CO_2eq concentration requires mitigation costs of about 5.5% of GDP. The abatement costs to reach the goal of 450 ppm concentrations through grand coalition under the PAGE09 model simulation are 4% of GDP in 2050 and 2% of GDP in 2100.

The present value of the aggregated abatement costs under grand coalition to limit the concentration of GHGs to 450 ppm is estimated at $260.5 trillion under the simulation run by the PAGE09 model. The 95% confidence interval for the present value of the aggregated abatement cost is $76 - $539 trillion.

The abatement costs for developed regions are less than those for developing regions. BAU emissions are higher for developing regions due to their higher economic and population growth rates. Consequently, the required emissions reductions for the 450 ppm stabilization goal are also larger for developing regions.

The abatement costs in the IA region are the highest at $113.5 trillion (with a range of $27 - $249 trillion). The next highest costs are for the AF and CA regions. The abatement cost in the EU is $3 trillion with a range between -$0.26 and $8 trillion. The abatement costs can be negative if the cost of reducing one unit of CO_2 emissions is lower than the savings in energy costs expected. Energy efficiency improvements in the industrial and building sections can reduce CO_2 emissions as well as energy consumption and energy costs. The PAGE09 model assumes a time profile of technology deployment such that regions will rely mostly on low-cost options including energy efficiency improvements in the initial phase of implementing climate stabilization policy. The technology portfolio will shift gradually to accommodate more high-cost options including various low-carbon energy technologies as the implementation of climate policy deepens. Thus, the abatement cost consists of two stages of policy effects: the negative cost in the initial stage of policy implementation and the positive cost in the mature stage as the reduction requirement increases. To the extent that investments in energy efficiency improvement have been underway regardless of climate policy in the past, the BAU estimate also contains the negative cost of mitigation.

We have thus far evaluated the effects of grand coalition and non-cooperation on socio-economic impacts and abatement costs. This leads us to a discussion of the benefits that are anticipated from the grand coalition for climate stabilization. It is certain that the socio-economic impacts associated with scenarios of climate policy actions will be less than those associated with no policy action, as the monetary value of the reduced impacts reflects the benefits of climate policy actions. The amount of benefits needs to be compared with the cost of abatement to examine the rationale for climate policy actions.

In this dissertation, the difference in socio-economic impacts between non-cooperation and grand coalition reflects the benefits of the climate agreement to limit GHG concentration to 450 ppm. In Figure 4-10, the area between the two impact curves represents the benefits associated with achieving climate stabilization. Under non-cooperation, the present value of the aggregate socio-economic impacts from 2009 to 2100, in which the global mean temperature rises 3.87℃ relative to the pre-industrial level, is $160 trillion, with a 95% confidential interval of $29 - $481 trillion. Under grand coalition, the present value of the aggregate climate impacts is about $51 trillion with a 95% confidential interval of $11 - $117 trillion. Therefore, if all nations participate in a climate agreement to limit the atmospheric concentration of GHGs to 450 ppm, the aggregate climate impacts decrease from $160 trillion to $51 trillion.

On the other hand, under the assumption of high damage, non-cooperation results in the aggregate socio-economic impacts being valued at $309 trillion over 2009 - 2100, with a 95% confidential interval of $16 - $1,487 trillion. Under grand coalition, the present value of the aggregate impacts is $54 trillion with a 95% confidential interval of $13 - $126 trillion. Thus with the participation of all regions, the aggregate climate impacts decrease from $309 trillion to $54 trillion.

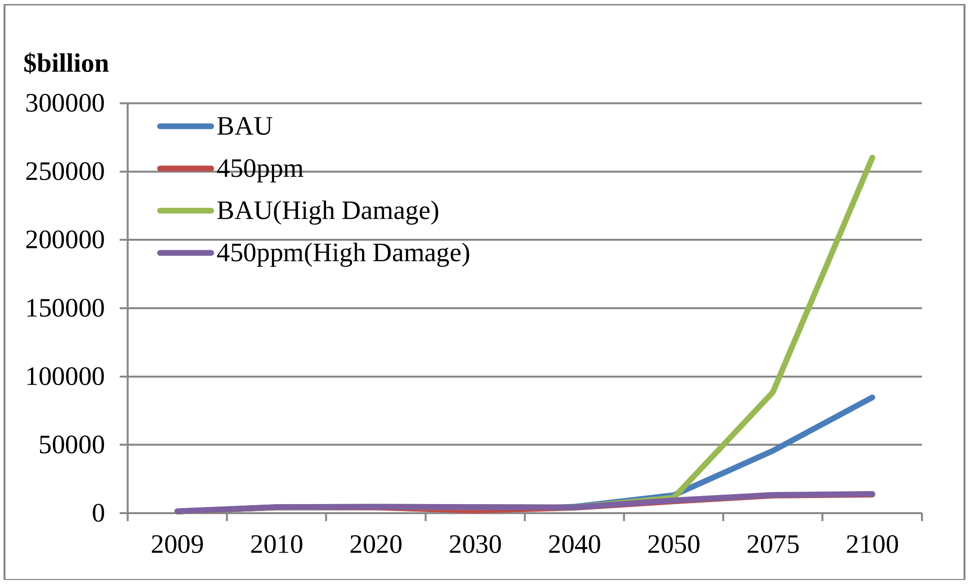

Figure 4-10: Global Socio-Economic Impacts: 450 ppm

The estimated net benefits from joining the grand coalition or partial coalitions equal the difference between the amount of climate benefits expected as a result of the coalition and the cost of emissions abatement required to achieve these benefits. The abatement cost estimates depend upon two factors: the availability and cost of low carbon energy technologies and the required quantities of emissions reductions relative to BAU trends for emissions levels. The present value of the aggregate abatement costs for the grand coalition is estimated at $261 trillion according to the model's simulation. Compared to the present value of climate benefits under grand coalition, the grand coalition produces net negative benefits, implying that coalition members as a whole suffer from welfare loss.

However, it should be noted that the benefit estimates from climate change stabilization are subject to large uncertainty due to the uncertainty associated with climate impacts and their valuation. The abatement costs are also subject to uncertainty but it has been established that the uncertainty in the estimates of benefits is larger than the uncertainty in the estimates of abatement costs[37]. If, for example, we considered the impacts estimate close to the upper limit (95th percentile) of the range, $116 trillion, as being more relevant, the mean value would become positive and rise to $104 trillion. Or, if climate change is assumed to be associated with a higher damage function than the default function provided by the model, the 450 ppm grand coalition results in positive net benefits estimated at $54 trillion.

Using the mean value of benefits, the grand coalition faces welfare loss. But using the benefits at the 95th percentile or a high damage assumption to consider the large uncertainty associated with climate impacts, the grand coalition is economically feasible with a positive welfare gain. As the viability of grand coalition is sensitive to the degree of uncertainty in estimating climate impacts, this research shows that developing regions suffer losses if they join the grand coalition to limit GHG concentrations to 450 ppm by 2100. When developing regions participate in the grand coalition, the model simulations show that their GHG emissions abatement costs are estimated to be higher than the climate benefits they receive from the global reduction in GHG emissions. In other words, these regions lose by participating in the grand coalition. India and South East Asia suffer the largest loss, followed by AF and CA.

Table 4-3 shows the emissions reductions required for 2009 - 2100 by member regions under grand coalition; the present value of aggregate abatement costs and climate benefits; the present value of average costs for reducing one ton of CO_2; and

[37] IPCC 5th Assessment Report indicates that climate impacts are likely to be underestimated and that the risks associated with the climate impacts are likely to be larger than those associated with abatement (IPCC. 2014a, 2014b).

the present value average benefits associated with reducing one ton of CO_2. In IA, the cost of reducing one ton of CO_2 is $1,839, while in the EU the abatement cost is estimated at $207 per ton. The abatement cost depends upon emissions reduction: the more emissions are reduced, the larger the costs of the reduction. By 2100, the EU needs to reduce 14,456 Mton CO_2 emissions, while IA needs to reduce 61,705 Mton, a much larger quantity. Consequently, IA's abatement costs are much higher.

Table 4-3: Comparison of Aggregated Abatement Cost and Climate Benefits across Participating regions under the Grand Coalition (Present Value)

	Abatement Cost ($trillion)	AC/ Capita ($/person)	Benefits ($trillion)	Benefits/ capita ($/person)	AC/ton ($/ton)	Benefits/ ton ($/ton)
EU	3.0	6,084	8.6	17,422	207	592
U.S.	3.9	7,970	7.4	14,894	183	343
OT	3.1	12,146	5.6	22,267	417	765
EE	2.7	11,000	2.6	10,903	284	281
Developed Total	12.7	37,200	24.2	65,486	1,091	1,987
CA	34.9	41,237	9.8	11,531	903	253
IA	113.5	53,676	40.9	19,373	1,839	664
AF	88.4	40,646	26.9	12,381	2,444	745
LA	11.1	17,819	7.3	11,751	341	225
Developing Total	247.9	153,378	84.9	55,036	5,527	1,887
Global Total	260.6	35,997	109.1	17,422	1,175	492

Assessing the economic feasibility of limiting GHG emissions concentration below 450 ppm CO_2eq reveals that grand coalition would not be appropriate. The grand coalition produces negative net benefits estimated at -$152 trillion over the period of 2009 to 2100 using the PAGE09 model-driven damage function. Only when the upper bound of the damage function is used can an economically feasible grand coalition achieve a 450 ppm atmosphere. In this latter scenario, positive net benefits are estimated at $54 trillion. The model simulation reveals that the abatement cost required for achieving the 450 ppm goal exceed the amount of reduced damages expected by limiting GHG concentrations to this level. These simulation results may reflect that (1) BAU emissions are set at a very high level so that the quantity of emissions reductions needed to meet the temperature goal is also high, and/or that (2) the damage function underestimates the full extent of climate impacts, which are subject to large uncertainty.

Table 4-4: Net Benefit of Grand Coalition ($trillion)

	Net benefit (with mean benefits)	Net benefit (with upper level benefits)	Net benefit (with high damage)	Global Mean Temperature (degree C)
EU	5.6	27.3	23.0	1.9
U.S.	3.4	21.4	21.1	
OT	2.5	14.8	21.2	
EE	-0.23	5.8	8.7	
CA	-25.2	0.8	-14.9	
IA	-72.5	18.8	1.5	
AF	-61.5	3.7	-17.2	
LA	-3.8	14.8	10.7	
Total	-151.7	107.4	54.1	

4.2.1.2 Partial Coalitions

If the necessary emissions reductions under grand coalition involve too great a cost to be feasible, what kind of coalition can feasibly achieve the global GHG emissions concentration target of 450 ppm by 2100? This section analyzes the economic feasibility of two coalitions, Coalitions 1 and 5, among the eight partial coalitions on the basis of three criteria used in the previous chapter, namely: socio-economic impacts, abatement costs, and net benefits[38].

We will first assess the environmental effectiveness of the two coalitions by evaluating the estimates in terms of reduced damages, global mean temperature, and GHG concentration. The socio-economic impacts of the two coalitions are shown in Figure 4-11 and Figure 4-12. From 2009 to the middle of this century, the socio-economic impact estimates for the two coalitions show similar trends. The difference in socio-economic impacts among the various coalitions begins to appear after 2050. The largest socio-economic impacts are expected from Coalition 1, which is a coalition consisting only of developed regions. The outcomes in 2050 and 2100 under the assumption of high damage are shown in Figure 4-13. The trend is similar to those under the base damage scenario, but the scale of global impacts is quite distinguishable especially for the case of non-cooperation.

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[38] The net benefits reported in tables and diagrams for partial coalitions include only the net benefits incurred by coalition members. Benefits and costs also exist for parties not participating in coalitions. It should be noted that the benefits or costs that impact non-members may cause them to pressure members to act beyond the net benefits they receive from being part of the coalition.

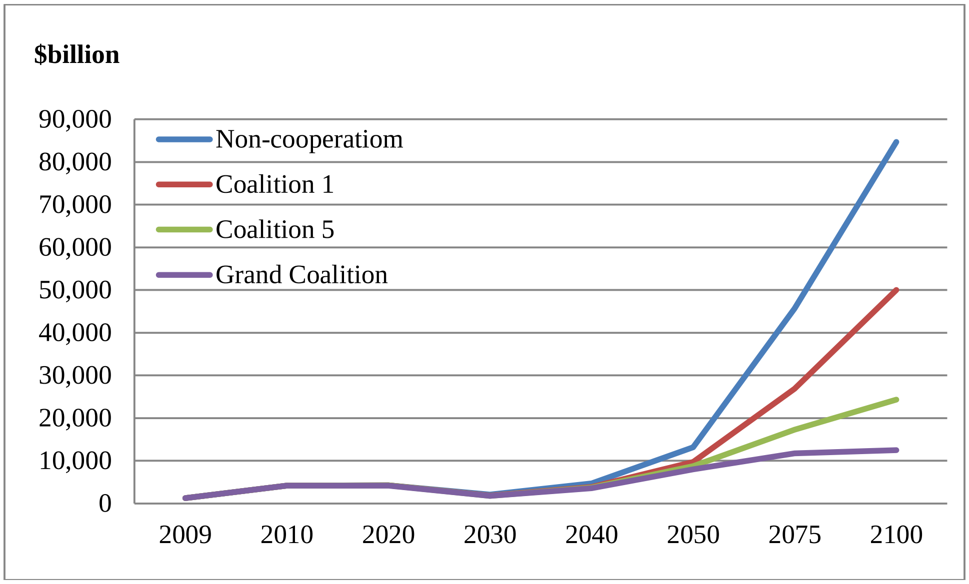

Figure 4-11: Socio-Economic Impacts of Coalition 1 and 5 with Non-cooperation and Grand Coalition

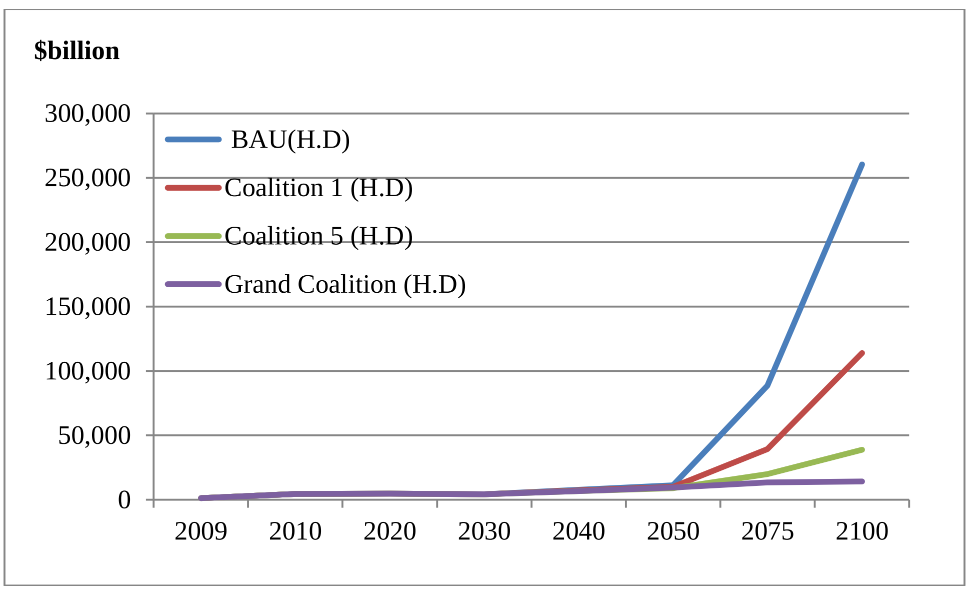

Figure 4-12: Socio-Economic Impacts of Coalition 1 and 5 with Non-cooperation and Grand Coalition (High Damage)

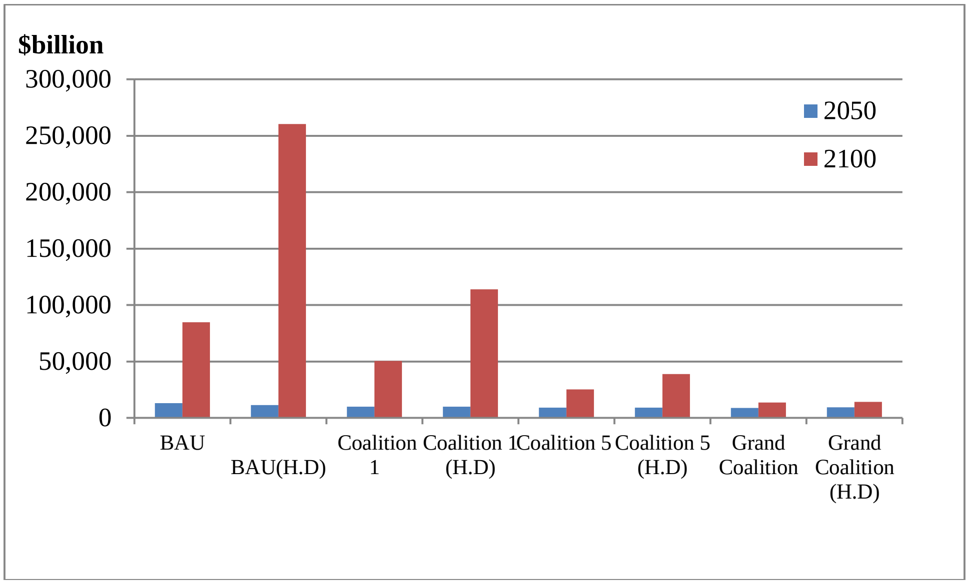

Figure 4-13: Socio-Economic Impacts of Coalition 1 and 5 with Non-cooperation and Grand Coalition (High Damage with Default Damage)

Coalition 1 was created to evaluate the role of developing regions in contributing to a global effort to stabilize atmospheric GHG concentration at 450 ppm. CA and IA's influence is observable in the estimates of socio-economic impacts under Coalition 5.

Figure 4-14 shows the estimates of socio-economic impacts with a 5 - 95% range for the period between 2009 to 2100 under Coalition 1 and Coalition 5. The mean present value of socio-economic impacts under Coalition 1 in 2050 is $9.9 trillion with a confidence range of about $1.5 - $25.3 trillion. In 2100, the mean present value of impacts is $50.3 trillion, or about a 5% loss of annual global income, with the confidence of $6.0 - $174.3 trillion. There is a 5% chance that the impacts will exceed $174.3 trillion. Compared to the impacts under grand coalition, the socio-economic impacts under Coalition 1 increase by $1.2 trillion in 2050 and $36.7 trillion in 2100. The global mean temperature rises by 3.21℃ under Coalition 1. This reveals that the goal of achieving a 2℃ temperature rise will not be possible without the participation of developing regions.

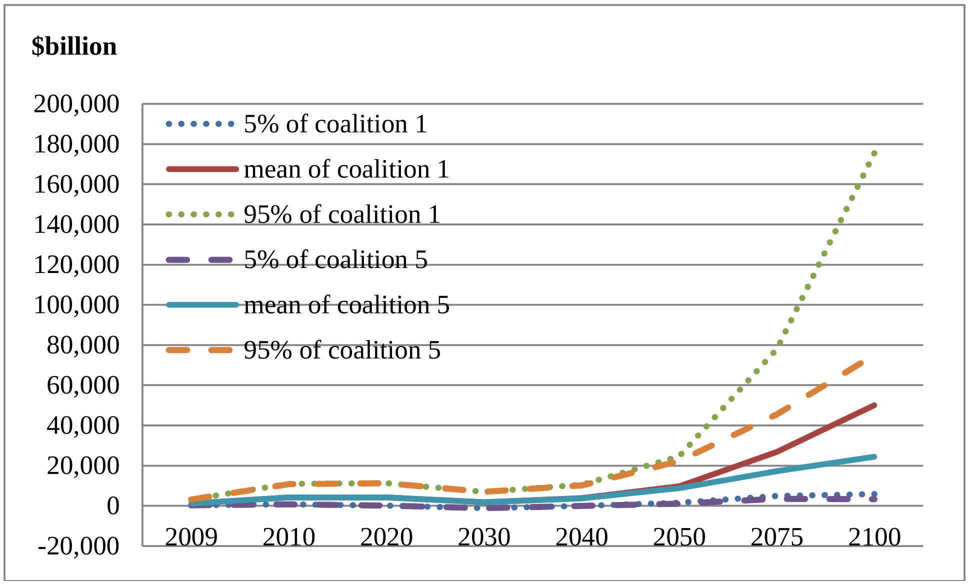

Figure 4-14: Socio-Economic Impacts of Coalition 1 and Coalition 5

If all developed regions and CA and IA participate in an effort to limit global warming, which is modeled in Coalition 5, the mean present value of socio-economic impacts in 2050 are \$9.0 trillion with a 95% confidence range of about \$1.3 - \$23.1 trillion. In 2100, the impacts are \$25.2 trillion and there is a 5% chance of the impacts exceeding \$77.2 trillion. The estimated impacts amount to a 4% loss in annual global income in 2050 and a 3% loss in 2100.

Table 4-5 compares the estimates in present value of abatement cost and the benefits of abatement under Coalition 1 in units of aggregate, per capita, and per ton of abatement. The aggregate abatement costs to Coalition 1 are estimated at $15 trillion, and the average abatement costs are estimated at $1,295 per ton of reduced CO_2 emissions. On the other hand, the participants of Coalition 1 obtain aggregate benefits estimated at $6.6 trillion, and the average benefit is estimated at $603 per ton of reduced CO_2 emissions. Comparing the costs and benefits of mitigation indicates that Coalition 1 is not economically viable.

Table 4-5: Comparison of Abatement Costs and Climate Benefits (Present Value): Coalition 1

	Abatement Cost ($trillion)	AC/ Capita ($/person)	Benefits ($billion)	Benefits/ capita ($/person)	AC/ton ($/ton)	Benefits/ ton ($/ton)
EU	3.6	7,310	1.5	3,001	248	102
U.S.	4.7	9,516	1.8	3,738	217	85
OT	3.6	7,380	2.3	4,652	495	312
EE	3.1	6,409	1.0	1,985	335	104
Total	15.0	44,156	6.6	19,821	1,295	603

Table 4-6 shows a similar comparison of costs and benefits for Coalition 5. The estimated aggregate abatement cost is $167 trillion, of which the developing region members CA and IA shoulder 91%. The estimated abatement costs per ton of reduced emissions are $935 for CA and $1,896 for IA, which are higher than the estimated costs for developed regions.

Table 4-6: Comparison of Abatement Costs and Climate Benefits (Present Value): Coalition 5

	Abatement Cost ($trillion)	AC/ Capita ($/person)	Benefits ($trillion)	Benefits/ Capita ($/person)	AC/ton ($/ton)	Benefits/ ton ($/ton)
EU	3.2	6,525	6.3	12,834	222	436
U.S.	4.2	8,499	5.6	11,297	196	260
OT	3.3	12,938	4.5	17,846	444	613
EE	2.8	11,735	2.1	8,555	302	221
CA	36.1	42,665	7.5	8,812	935	193
IA	117.0	55,333	33.3	15,750	1,896	540
Total	166.6	137,695	59.3	75,093	3,995	2,263

The aggregate benefits from Coalition 5 are estimated at $59 trillion, which are much less than the abatement costs. Thus, Coalition 5 lacks economic viability. The estimation results indicate that developed region members—EU and U.S.—would gain from Coalition 5, i.e., the benefits to them would be higher than the costs of abatement, while the other members—EE, CA, and IA—would lose from this coalition. Game theory suggests that these three members would thus decline to participate in Coalition 5, meaning that the coalition cannot support the 450 ppm goal. A more detailed breakdown on net benefits, i.e., economic feasibility, can be seen in Table 4-7 and Table 4-8.

Table 4-7 and 4-8 summarize the estimated net benefits expected of Coalitions 1 and 5. Coalition 1 produces a negative net benefit of $8.4 trillion using the PAGE09 model-driven damage function. When a higher damage function is used, it is revealed that Coalition 1's goal to achieve a 450 ppm atmosphere by 2100 is economically feasible. In this latter scenario, the positive net benefits are estimated at $14.9 trillion.

Table 4-7: Net Benefits of Coalition 1 ($trillion)

	Net benefit (with mean benefits)	Net benefit (with upper level benefits)	Net benefit (with high damage)	Global Mean Temperature (degree C)
EU	-2.1	3.4	0.9	3.21
U.S.	-2.8	2.5	2.8	
OT	-1.3	3.7	8.8	
EE	-2.2	-0.2	2.4	
Total	-8.4	9.4	14.9	

Table 4-8: Net Benefits of Coalition 5 ($trillion)

	Net benefit (with mean benefits)	Net benefit (with upper level benefits)	Net benefit (with high damage)	Global Mean Temperature (degree C)
EU	3.1	19.9	18.5	2.43
U.S.	1.4	15.3	17.1	
OT	1.2	11.2	18.1	
EE	-0.8	3.8	7.1	
CA	-28.7	-6.9	-18.3	
LA	-83.7	-8.9	-9.4	
Total	-107.4	34.4	33.1	

Coalition 5 consisting of CA, IA, and developed regions is expected to produce a negative net benefit of -$112 trillion using the model-driven damage function. A negative net benefit means that Coalition 5 is not economically feasible. However, if a high damage function is assumed, Coalition 5 becomes economic feasible due to a positive net benefit resulting from emissions reductions.

The evaluation of net benefits thus far is based upon the mean value of estimates derived from the Monte Carlo simulations. As previously pointed out, climate impacts are subject to large uncertainty with a possibility of extreme, non-linear events occurring at high temperatures. If this is the case, then the benefit that will be brought by abatement actions is likely to be higher than what the model shows. As the evaluation of benefits and abatement is sensitive to the estimates of climate impacts, it would thus be prudent to examine the robustness of estimated benefits against climate impacts exceeding the mean value, such those associated with the 95^{th} percentile in the distribution of potential impacts. As the second column in Table 4-7 and Table 4-8 shows, the estimates of net benefits become positive for Coalitions 1 and 5 when climate damages increase to the level associated with the 95^{th} percentile. The third column shows the estimates of net benefits for the two coalitions under the assumption of high damage. Under the assumption of high damage, the net benefits are higher than the existing estimates because the abatement costs for emissions reductions do not change while the reduced damage increases.

Each coalition produces positive benefits, but the model simulations show that these coalitions fail to achieve the temperature goal. Thus the next important task is to determine which coalition performs better than others in achieving the temperature target. Information on abatement costs and benefits will be useful in addressing the relative performance of various coalitions.

The model also shows the abatement cost, benefit, and net benefit that will accrue for each individual region if it chooses to become a member of coalition. Our research will evaluate the estimates of abatement costs and benefits. Although the 450 ppm CO_2eq goal will not be achievable, Coalition 5 produces the climate results that most closely reflect the temperature goal. The next chapter will examine if these coalitions are stable.

4.2.2 Stability

4.2.2.1 Non-cooperation and Grand Coalition

In this section we examine the stability of grand coalition, which in this case is designed to limit the atmospheric concentration of CO_2 at 450 ppm by 2100. The stability of the grand coalition depends upon the degree of incentives needed for participants to stay within this partnership. If the payoffs to individual participating regions, i.e., the net benefits, are greater than the payoffs gained from leaving the coalition, then each region has an incentive to remain in the grand coalition and full cooperation can be considered stable.

The grand coalition for 450 ppm is assessed as unstable. For each region, deciding not to join the cooperation (singleton) yields a higher payoff than the one expected from joining the coalition. Every region becomes better off by leaving the grand coalition than by participating in it. From this perspective, no region would join an agreement to limit the atmospheric concentration to 450 ppm by 2100.

The model estimates show that the benefits of singleton varies for developed and developing regions, as the additional payoff of singleton is estimated to be lower for developed regions than for developing regions. The increase in the payoff to developed regions for leaving the grand coalition amounts to \$2.2 - \$3.9 trillion, while the developing regions' decision to leave full cooperation generates an additional payoff of \$10.5 - \$98.9 trillion. Among the developing regions, IA and AF gain the largest increase in payoffs by choosing not to cooperate and lose the most by joining the grand coalition. The estimates of payoffs suggest that IA and AF are least likely to join full cooperation for the 450 ppm goal.

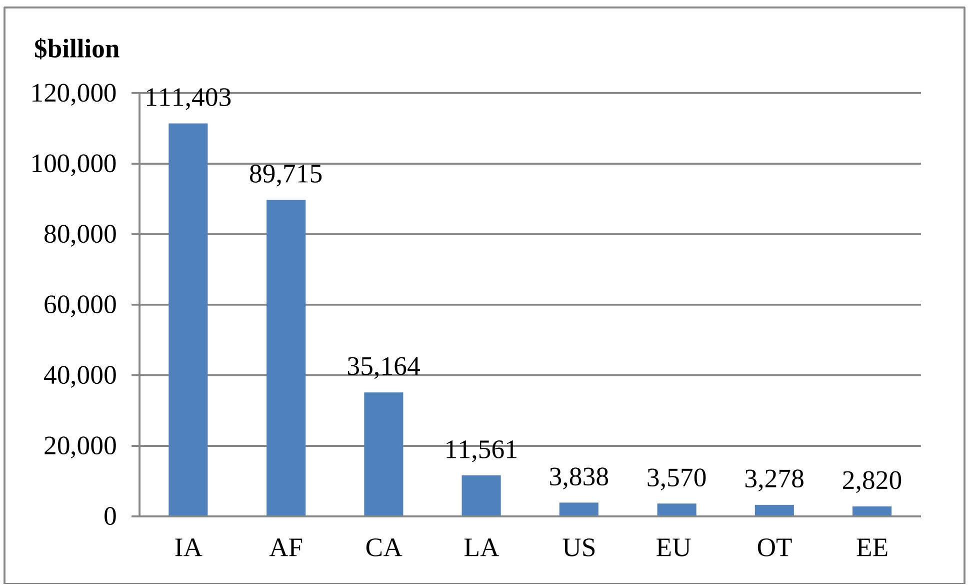

Figure 4-15: Free-rider Incentives from Grand Coalition

Figure 4-15 illustrates the free-rider incentives for the eight individual regions that would be members of the grand coalition. The free-rider incentives are calculated by comparing the net benefits from the grand coalition with the net benefits from leaving. India has the largest free-rider incentives at $111.4 trillion, followed by Africa at $89.7 trillion. Among developed regions, EE (FSU and rest of Europe) has the least incentive to free ride at an estimated $2.8 trillion. The US has the largest incentive to free ride among developed regions at $3.8 trillion.

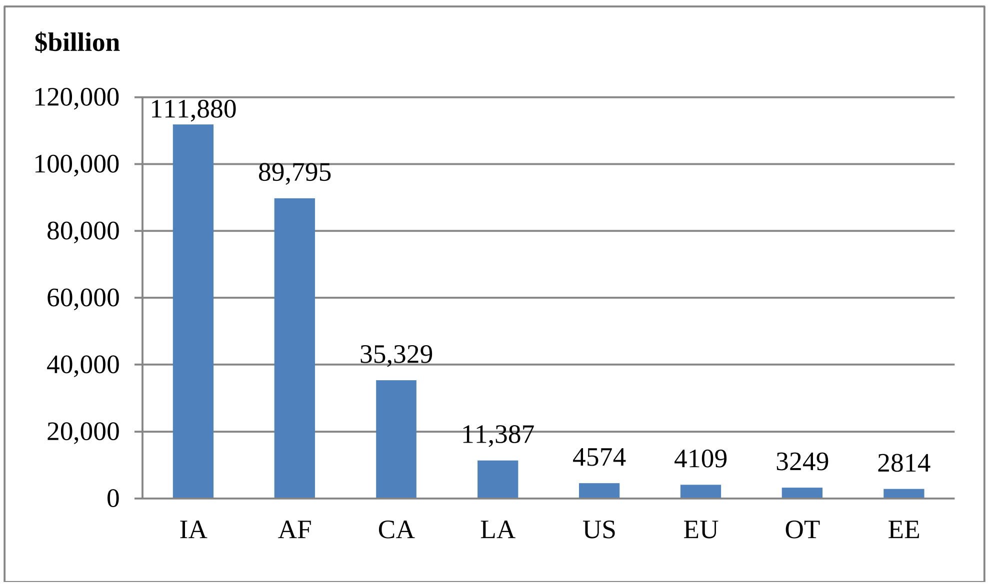

Figure 4-16: Free-rider Incentives from Grand Coalition (High Damage)

Figure 4-16 shows the estimates of free-rider incentives to participants in grand coalition under the assumption of high damage. The results are not much different from those estimated under the assumption of base damage. Consequently, grand coalition seems unstable regardless of the damage assumed.

What measures would need to be available to stabilize the grand coalition considering that each coalition member is subject to substantial free-rider incentives?

Carraro & Siniscalco (1998) suggest three ways to endogenously stabilize coalitions: transfer[39], issue-linkage[40], and threat[41]. Of these three measures, we first analyze transfer schemes. Compared to schemes of issue-linkage and threat, which are applicable across various coalition formations, transfer schemes can be designed to address challenges particular to specific coalitions.

A transfer scheme is an instrument that aims to restore stability to the coalition by offsetting free-rider incentives associated with singleton. Regions that stand to gain by participating in the grand coalition are to provide compensation to regions that stand to bear the greatest costs and thus have the strongest incentives to leave the coalition and free ride. We will discuss this financing issue later in combination with other measures aimed at improving coalition stability.

4.2.2.2 Partial Coalitions

Examining the stability of these eight coalitions includes evaluating their internal stability as mentioned in the grand coalition analysis. For example, testing the stability of Coalition 1 involves analyzing the case in which coalition members decide

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[39] These authors state "transfers are often proposed to tackle the profitability dimension of international negotiations, i.e. to compensate those countries which, because of their asymmetries, would lose from signing the agreement." (Carrraro & Siniscalco, 1998, p.565)

[40] Issue linkage is the way that "as for transfers, the linkage of environmental negotiations to other economic issues (e.g. trade, technological cooperation) may be useful." (Carrraro & Siniscalco, 1998, p.565)

[41] It means that "the number of signatories of an international environmental agreement could be increased were non-signatories threatened to be punished through adequate economic (e.g. trade) sanctions" (Carrraro & Siniscalco, 1998, p.566)

to leave the coalition. Coalition 5 will be analyzed here because it produces climate outcomes in which the global temperature increases will be nearer to the goal of the 2℃ temperature limit. The analysis of the six remaining coalitions will be presented in Appendix.

Coalition 1 is not internally stable. As shown in Figure 4-17, every developed region that participates in the coalition has an incentive to free ride, and thus stands to benefit by exiting the coalition. The incentives for developing regions to free ride range from $3.5 trillion to $6.8 trillion. The EU has the largest incentive to free ride of any region. Figure 4-18 illustrates the estimates of free-rider incentives under Coalition 1 assuming high damage. Every member of Coalition 1 has positive free-rider incentives similar to the outcomes observed under the model-driven damage function.

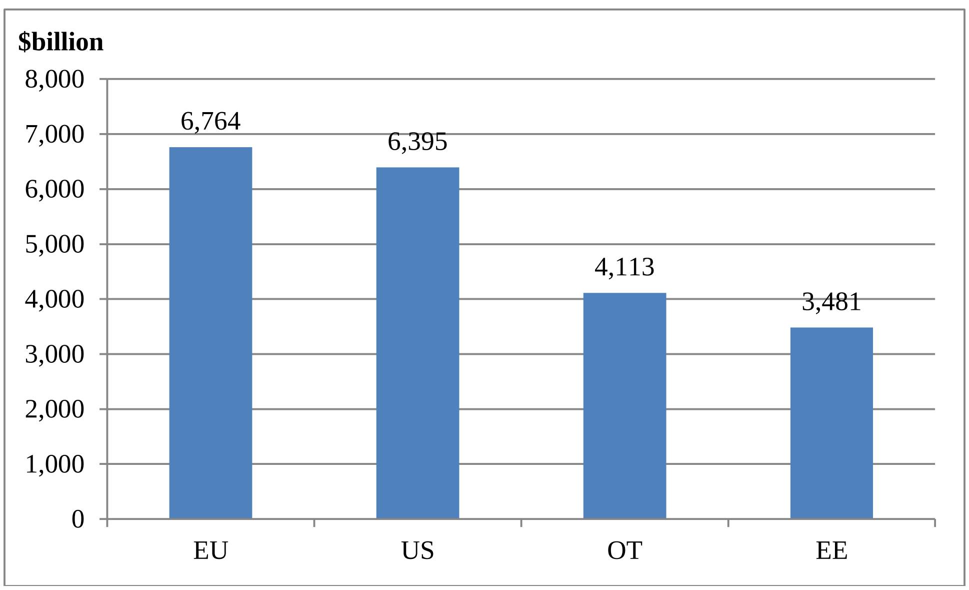

Figure 4-17: Free-rider Incentives for Coalition 1

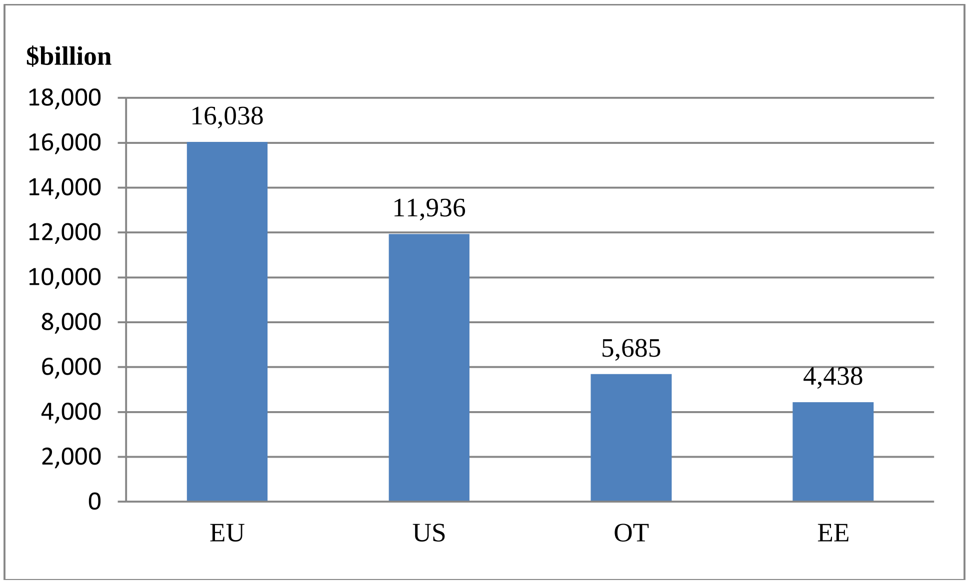

Figure 4-18: Free-rider Incentives for Coalition 1 (High Damage Assumption)

We note the relative contributions that could be expected from developed and developing regions in a global effort to limit the temperature increase to 2°C. The scenario for Coalition 1, which consists only of developed regions, results in a temperature increase of 3.21°C in 2100, indicating the crucial role developing regions must play in coalitions in order to achieve the global goal of 2°C. Not only is Coalition 1 unable to achieve the temperature goal, the coalition is also unable to maintain its stability because each participating region has a positive incentive to free ride. Chapter 6 will discuss in greater detail the issues surrounding the emissions reductions requirements of developed regions as well as those of developing regions.

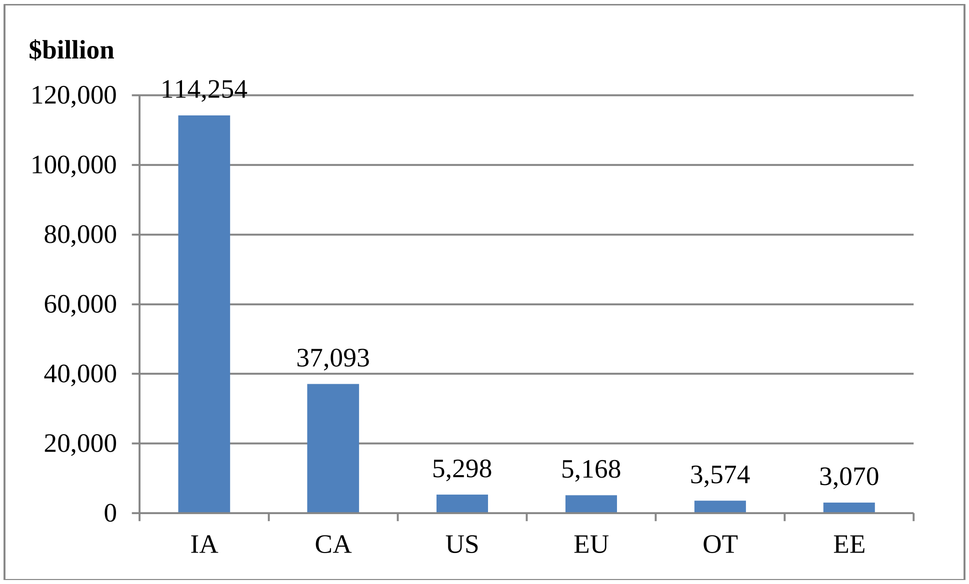

Figure 4-19: Free-rider Incentives for Coalition 5

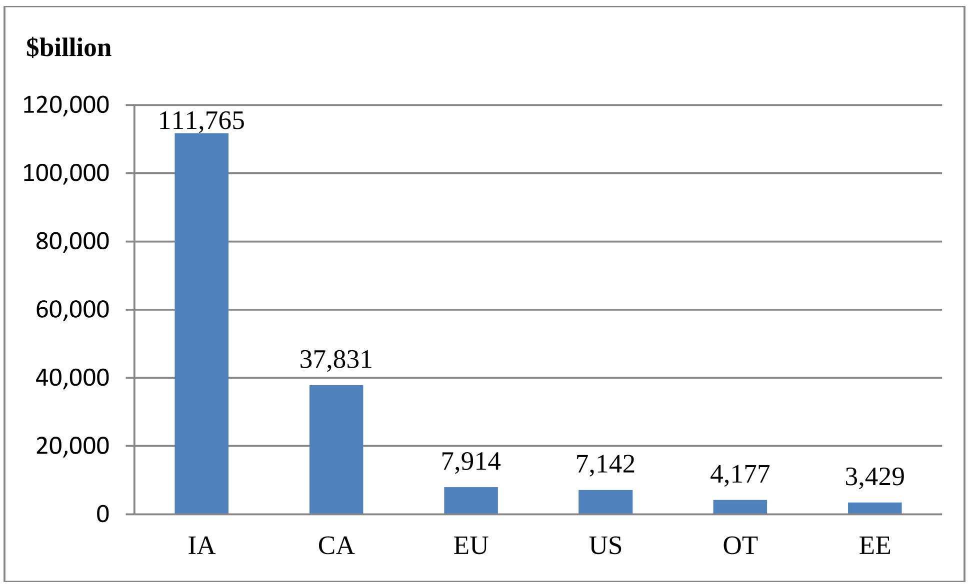

Figure 4-20: Free-rider Incentives for Coalition 5 (High Damage)

Estimated benefits expected from Coalition 5 indicate that every participant, i.e., the developed regions and the CA and IA regions, has incentives to leave the coalition. Figure 4-19 shows that the estimated net benefits of leaving the coalition range from \$3.1 trillion to \$114.3 trillion across the participating regions. Similar results are observed for Coalition 5 assuming high damage as illustrated in Figure 4-20. The magnitudes of net benefits expected from leaving the coalition are estimated to exceed those expected to be gained by membership. The participants have negative incentives to remain in the coalition, and thus Coalition 5 is internally unstable.

For both Coalitions 1 and 5, an evaluation of the net benefits indicates that every region can improve its welfare by leaving the coalition because each has a positive free-rider incentive. Are there ways to create an internally stable coalition and/or induce singleton regions to join a coalition? Chapter 6 will address this issue.

4.3 Summary

A total of ten coalition formations—non-cooperation, grand coalition, and eight partial coalitions—were analyzed using the PAGE09 model for the global goal of stabilizing the atmospheric concentration of GHGs at 450 ppm by 2100, which is in line with limiting the global temperature increase to 2℃ relative to pre-industrial levels. In the case of non-cooperation in which no region took action to limit CO_2 emissions, the global mean surface temperature was estimated to rise by 3.87℃. In the case of grand coalition in which every region agreed to participate in reducing CO_2 emissions, the resulting increase in the global mean surface temperature was estimated at 1.9℃. The recent IPCC AR5 that describes climate change scenarios provides a temperature range of 1.0℃ - 2.8℃ for the concentration range of 430 - 480 ppm CO_2eq by 2100 with a mean temperature of 1.5℃ - 1.7℃. The PAGE09 model's result of a 1.9°C increase under grand coalition is higher than the mean temperature presented in the IPCC assessment, but also within the range of estimates reported by the IPCC.

The eight partial coalitions reflect the assumption that some developing regions will participate in the reduction effort along with developed regions, the latter of which are all assumed to participate. In this analysis the African region is assumed not to participate in any coalition due to its immediate needs for poverty alleviation and economic growth. The developing regions were grouped into three: CA (China and Central Pacific Asia), IA (India and Southeast Asia), and LA (Latin America). Coalition 1 consists only of developed regions, as opposed to Coalition 8 that includes all developed and developing regions except Africa. Coalition 5 consists all developed regions and two developing regions: CA and IA.

The global mean temperature increase was estimated to be the highest under Coalition 1 at 3.21°C. Under Coalition 5, the global mean temperature increases from 1.60°C in 2050 to 2.40°C in 2100.

The socio-economic impacts in 2100, i.e., the damage expected from climate change under non-cooperation, was estimated at $84.7 trillion for the entire globe with a 95% confidence interval of $9.1 - $290.6 trillion. Grand coalition resulted in a much lower cost of climate impacts estimated at $13.6 trillion with a confidence interval of $2.1 - $38.3 trillion. Among the partial coalitions, Coalition 5 produced the least costly socio-economic impact estimate of $25.2 trillion with a confidence interval of $3.5 - $77.2 trillion. As expected, Coalition 1 produced the most costly climate impact estimate of $50.3 trillion, which is equivalent to a 6% loss of global income for the year[42].

Abatement costs are related to the quantity of emissions reductions required to meet the global temperature goal; hence, the greater the BAU emissions, the higher the abatement costs. The abatement costs under grand coalition were estimated at $260.5 trillion with India accounting for the largest abatement costs at $113.5 trillion because its BAU emissions were higher than other regions.

The benefit from emissions abatement is the reduction in climate impacts resulting from abatement actions, i.e., the difference in socio-economic impacts between non-cooperation and grand or partial coalitions. The net benefit, which is the benefit of having to pay fewer abatement costs, was closest to the temperature goal for the grand coalition. The net benefit for grand coalition was estimated negative, which indicates that grand coalition would not be economic feasible in this case[43]. But the net benefit to the developed regions participating in the grand coalition was estimated to be positive as the reduction in climate impacts was estimated to be greater than the abatement cost they have to incur. In contrast, the net benefit to developing regions aside from the Latin American region was estimated as negative because of the large

[42] On the other hand, the assumption of high damage would result in $369 trillion global welfare loss under non-cooperation and a much lower $54 trillion under grand coalition. Coalition 1 would involve impacts of $169 trillion and Coalition 5 involves $73 trillion. The estimates of impacts depend upon the assumptions underlying the damage function used.

[43] But under the assumption of high damage, grand coalition is able to produce a net gain in global welfare. Developed regions would increase their welfare while developing regions would suffer welfare loss. This is because developing regions face abatement costs than would be higher than developed regions when they join the coalition.

abatement costs these regions have to pay. It was the large abatement costs imposed on developing regions that made the net benefit of the grand coalition negative overall.

Estimating free-rider incentives reveals that every region has an incentive to free ride, even the developed regions under grand coalition despite their positive net benefit. These regions stand to gain even more from free riding because they could increase the benefit they would receive by cooperating by leaving the coalition. The internal stability test demonstrated that this was particularly true for developing regions whose free-rider incentives were estimated to be much larger than those of developed regions. India has the highest free-rider incentive, estimated at $111 trillion, followed by Africa at $89.7 trillion. Grand coalition as a whole failed to produce a positive net benefit. As indicated above, developed region participants were able to draw positive net benefits from grand coalition, however, the developed region participants would be able to acquire a higher net benefit by leaving the coalition, i.e., deciding to free ride, than by staying in the coalition. The grand coalition did not have internal stability as every participant had a positive free-rider incentive. The internal stability test for all partial coalitions also indicated that they were not internally stable. As a consequence, no coalition was possible for the case of 450 ppm stabilization[44].

[44] The assumption of high damage produces a similar result.

Chapter 5

ANALYSIS OF STATIC GAME OF STOCK EXTERNALITY UNDER THE CASE 2: 580 ppm

This chapter describes the climate and economic outcomes of ten coalitions—non-cooperation, grand coalition, and the eight partial coalitions—under the 580 ppm case. This chapter is structured the same as the 450 ppm case. First, we compare the climate outcomes under non-cooperation, grand coalition, and two partial coalitions (Coalition 1 and Coalition 5). Second, we examine the economic outcomes in terms of both economic feasibility and coalition stability. The economic feasibility section includes an analysis of the benefits, abatement costs, and net benefits of the chosen coalitions (non-cooperation, grand coalition and two partial coalitions) and the stability section examines the internal stability of the grand coalition and partial coalitions.

5.1 Climate Science Outcomes

5.1.1 Non-cooperation and Grand Coalition

This section shows the outcomes of non-cooperation and grand coalition under the 580 ppm by 2100 global emissions target. The non-cooperation scenario represents the BAU emission pathway assumed by PAGE09 model. Non-cooperation signifies that no region joins the coalition to achieve the global emissions reduction target. By contrast, grand coalition represents a case in which all eight regions defined in the PAGE09 model participate in an agreement to achieve the climate target.

Figure 5-1 shows the difference in the world's CO_2 emissions under non-cooperation and grand coalition. Under non-cooperation, the global CO_2 emission path grows until past the mid-21st century, then slightly decreases toward the end of the century because of increasing energy efficiency and declining energy intensity. Under grand coalition to achieve 580ppm CO_2eq in 2100, the global CO_2 emissions peak in 2030 then decline until the end of the century. In 2100, CO_2 emissions are 49,452 Mton under non-cooperation and 20,174 Mton under grand coalition.

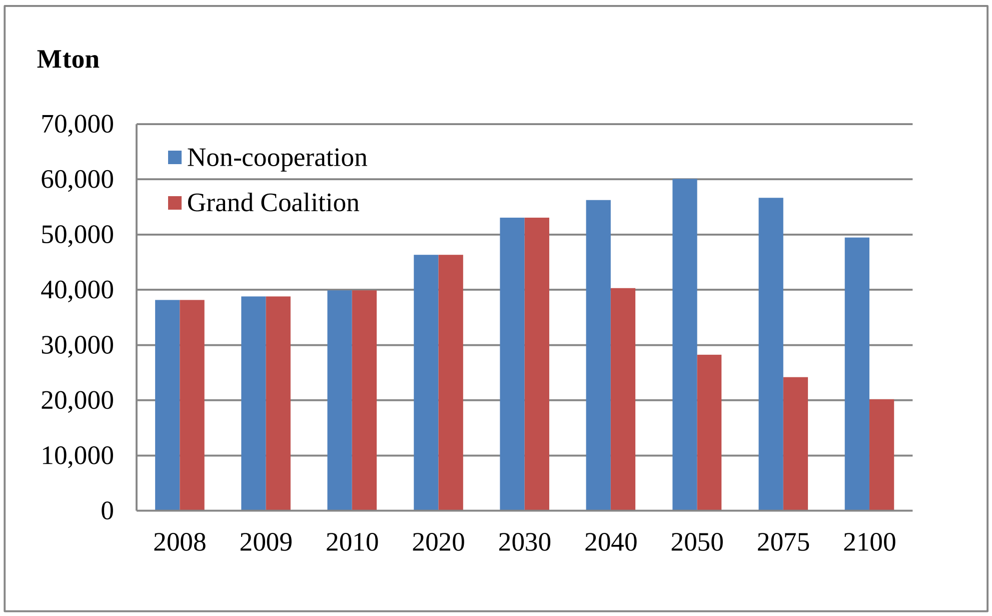

Figure 5-1: World CO_2 Emissions Under Non-Cooperation and Grand Coalition

Figure 5-2 shows the CO_2 concentration from 2008 to 2100 for non-cooperation and grand coalition with probabilistic calculations. In the figure, solid lines show the mean value of CO_2 concentrations and dotted lines show uncertainty ranges. After 2050, CO_2 concentrations under non-cooperation grow rapidly until the end of this century. The mean CO_2 concentration in 2100 is 704 ppm with a 95% confidence interval of 640 ppm - 779 ppm. The grand coalition designed to achieve the 580 ppm target shows that the CO_2 concentration increases in parallel with the CO_2 concentration under BAU until 2040 and thereafter increases at a lower rate than the CO_2 concentration under BAU until 2100. The mean CO_2 concentration reaches 508 ppm in 2050 and then gradually increases to about 552 ppm in 2100. The 95% confidence interval for the CO_2 concentration at the end of this century is 512 ppm - 598 ppm.

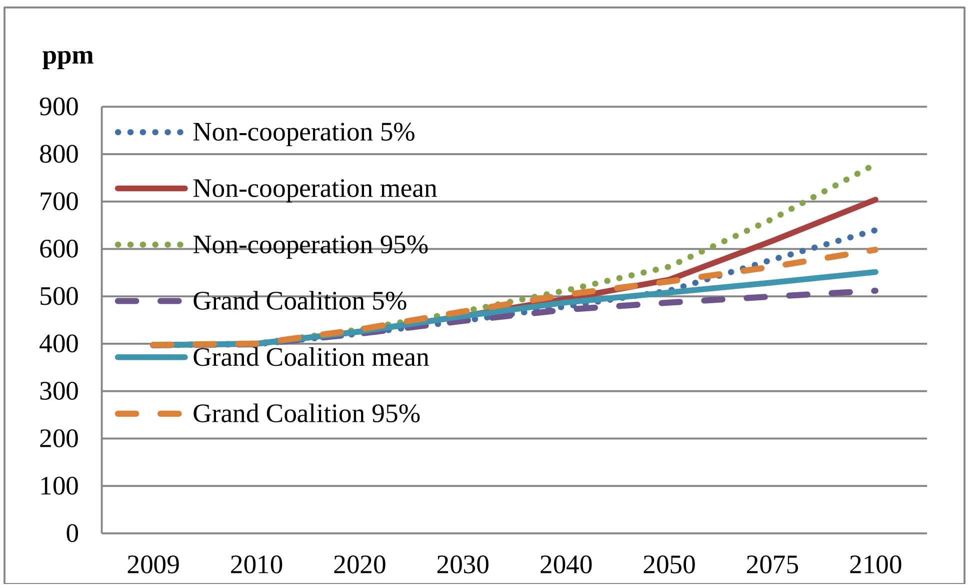

Figure 5-2: CO_2 Concentration

Figure 5-3 shows the mean value of the global mean temperature above the pre-industrial level is 3.87℃ in 2100 under non-cooperation. The 95% confidence interval for the temperature increase in 2100 is 2.41 - 5.90℃ relative to the pre-industrial level. Under grand coalition, the mean value of global mean temperature in 2100 rises 3.04℃ above the pre-industrial level. The 95% confidence interval for the temperature increase in 2100 is 1.91 - 4.61℃, which indicates a 5% chance that the global mean temperature under grand coalition exceeds 4.61℃ in 2100.

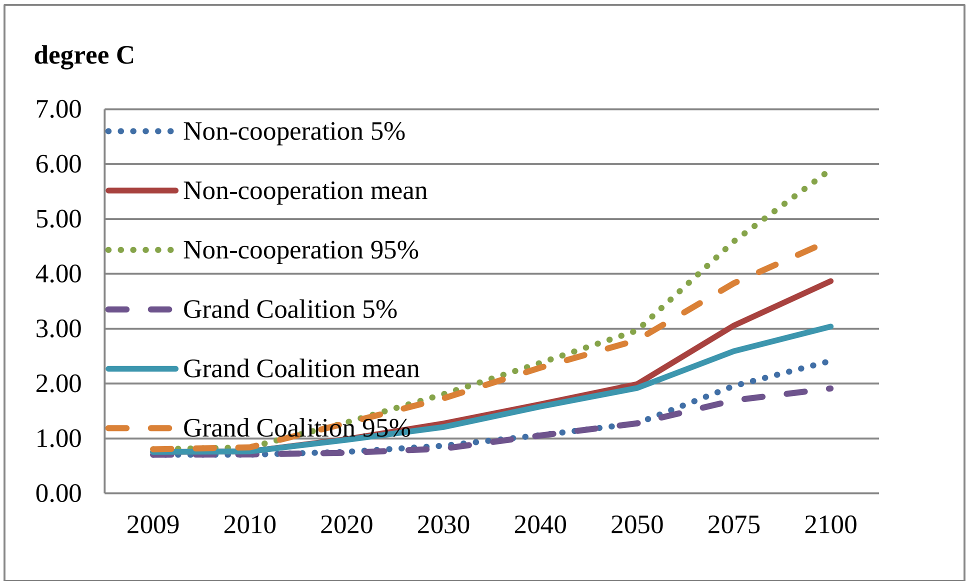

Figure 5-3: Global Mean Temperature

5.1.2 Partial Coalitions

This section presents the climate outcomes of the eight partial coalitions in terms of their CO_2 emissions and climate consequences for the period of 2008 - 2100. Specific comparisons of the outcomes are stated for Coalition 1 and Coalition 5. The outcomes of the other coalitions are shown in the Appendix B.

The Coalition 1 is designed to evaluate the outcomes if all developed regions were to participate in a climate stabilization agreement while Coalition 5 is designed to evaluate the outcomes if two major emitter regions (CA and IA) participate in an agreement with developed regions.

Figure 5-4 shows the CO_2 emission path of the eight coalitions for the period of 2008 - 2100 along with the emission path expected from non-cooperation and grand coalition. As mentioned, the participants of Coalition 1 consist only of developed regions; no developing regions would join the coalition. The CO_2 emissions under Coalition 1 are 51,831 Mton in 2050 and 43,190 Mton in 2100. These represent a 14% drop in emissions relative to the non-cooperation emission path in 2050 and a 13% drop relative to non-cooperation in 2100.

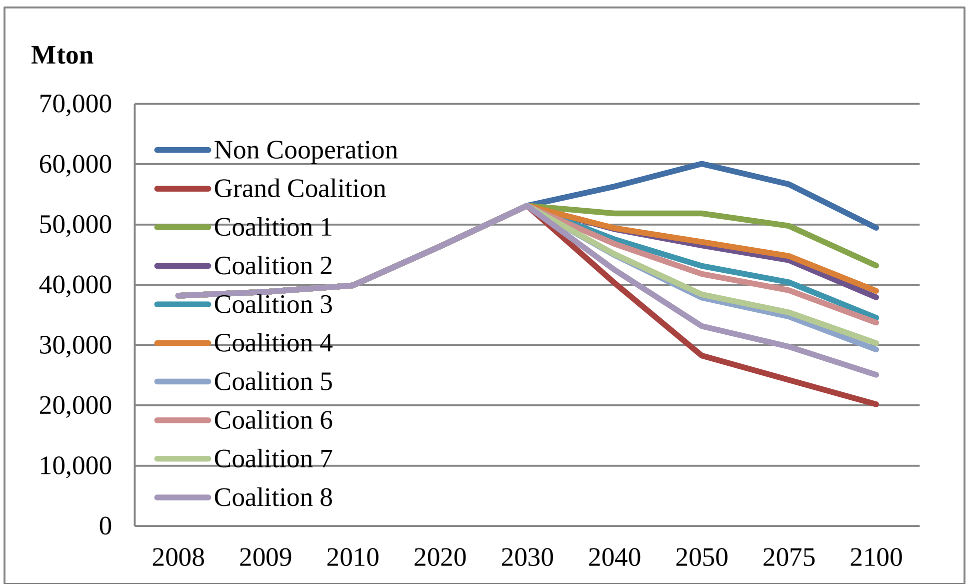

Figure 5-4: CO_2 Emissions under Coalitions

The CO_2 emissions of Coalition 8, which would comprise all developed and developing regions with the exception of the AF region, will be 33,125 Mton in 2050 and 25,084 Mton in 2100. The CO_2 emissions under Coalition 8 are less than those expected under non-cooperation by 45% by 2050 and 49% by 2100. CO_2 emissions under Coalition 5 will be 37,845 Mton in 2050 and 29,272 Mton in 2100, which is less than those expected under non-cooperation by 63% in 2050 and by 41% in 2100.

Figure 5-5 shows the CO_2 concentration from 2008 to 2100 for all eight coalitions, as well as for grand coalition and non-cooperation. When only developed regions join the climate agreement (Coalition 1), the CO_2 concentration are 526 ppm in 2050 and 662 ppm in 2100, which is 2% lower than the concentration under non-cooperation by 2050 and 6% lower by 2100. By contrast, the CO_2 concentration for Coalition 1 is 3.5% higher than that of the grand coalition by 2050 and 20% higher by 2100. Coalition 5 in which all developed regions and two developing regions (CA and IA) join the climate agreement result in a CO_2 concentration of 515 ppm in 2050 and 594 ppm in 2100, which is 4% lower than the concentration under non-cooperation by 2050 and 15.6% lower by 2100. The CO_2 concentration under Coalition 5 is 1.3% higher than the grand coalition's concentration by 2050 and 7.6% higher by 2100. Figure 5-5 shows that Coalition 5 cannot achieve the GHG emission stabilization target of 580 ppm in 2100. Therefore, achieving the climate target requires the participation of as many developing regions in the coalition as possible.

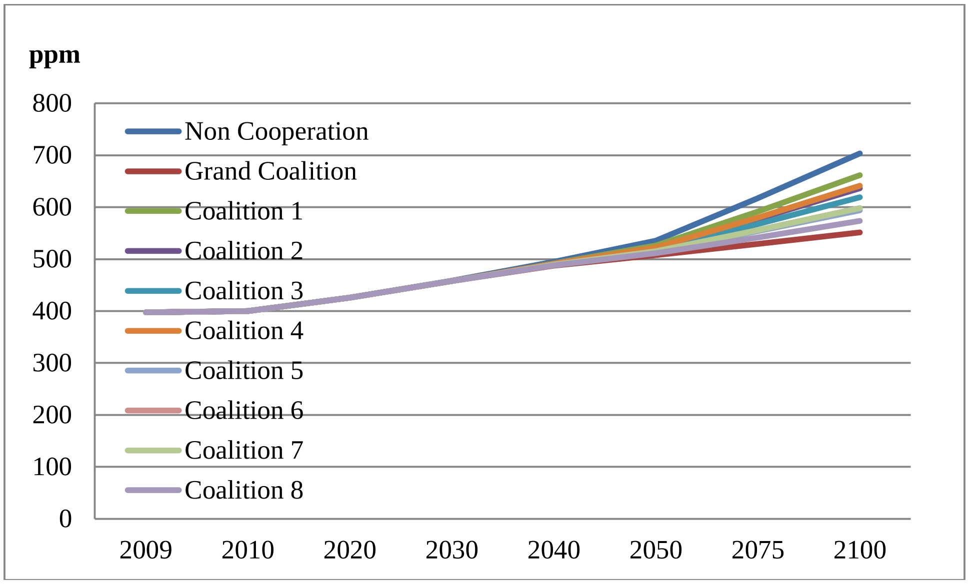

Figure 5-5: Concentration under Coalitions

Table 5-1 examines CO_2 concentrations and the global mean temperature of all eight coalitions in addition to grand coalition and non-cooperation. The range of uncertainty in CO_2 concentrations and global men temperature will be discussed next.

Table 5-1: CO_2 Concentration and Global Mean Temperature by all Coalitions

	2050	2100	
	CO_2 Concentration (ppm)	CO_2 Concentration (ppm)	Global Mean Temperature (degree C)
Non-Cooperation	535	704	3.87
Grand Coalition	508	552	3.04
Coalition 1	526	662	3.43
Coalition 2	522	636	3.32
Coalition 3	519	619	3.21
Coalition 4	523	641	3.41
Coalition 5	515	594	3.09
Coalition 6	518	616	3.29
Coalition 7	515	598	3.18
Coalition 8	511	574	3.05

Figure 5-6 shows the mean CO_2 concentrations under Coalitions 1 and 5, as well as the concentrations for non-cooperation and grand coalition for the period of 2008 - 2100. The CO_2 concentrations under Coalitions 1 and 5 reveal trends similar to those under BAU and the grand coalition until the mid-21st century. But after 2040, the CO_2 concentration path of each coalition shows marked differences. The mean value of CO_2 concentrations for Coalition 1 is 662 ppm in 2100 with a 95% confidence interval of 607 ppm - 728 ppm. There is a 5% chance that the GHG concentration of Coalition 1 exceeds 728 ppm by 2100. The CO_2 concentrations of Coalition 5 (that includes CA, IA, and all developed regions) also keeps increasing until the end of the century, but is less than the concentrations under Coalition 1, reaching 594 ppm in 2100. The 95% confidence interval for the CO_2 concentrations at the end of the century is 548 ppm - 648 ppm.

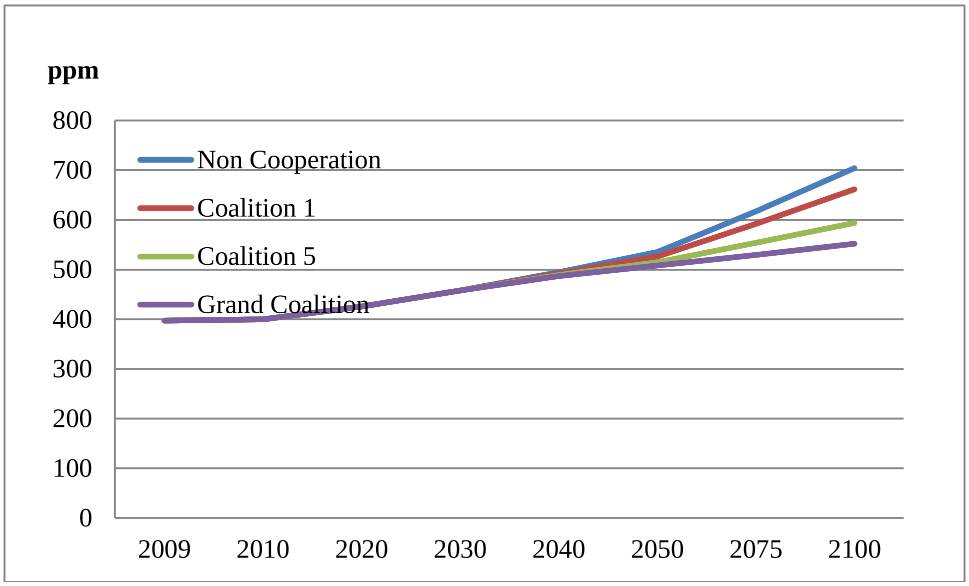

Figure 5-6: CO_2 Concentration of Coalition 1 and 5

Figure 5-7 compares the global mean temperature under Coalitions 1 and Coalition 5. Under Coalition 1, which includes only developed regions, the global mean temperature is 3.43℃ in 2100. The 95% confidence interval for the global mean temperature at the end of this century is 2.15 - 5.23℃. Coalition 5 leads to lower global mean temperatures than Coalition 1. If the developed regions join the coalition with CA and IA, the global mean temperature is 3.09℃ in 2100. The 95% confidence interval for the global mean temperature at the end of this century is 1.93 - 4.75℃, meaning that there is a 5% chance that global mean temperature will be above 4.75℃ in 2100.

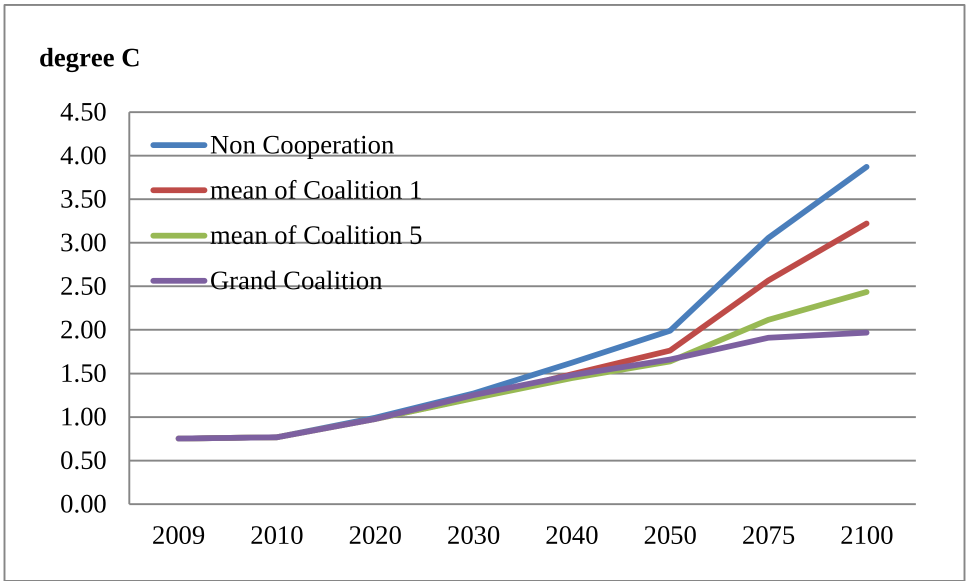

Figure 5-7: Global Mean Temperature of Coalition 1 and 5

5.2 Economic Outcomes

This section shows the results of the PAGE09 model simulations for coalition formations to achieve the goal of climate stabilization at 580 ppm. The structure is the same as 450 ppm case in the previous chapter. We assess the economic feasibility of the grand coalition and partial coalitions by analyzing three issues: socio-economic impacts, abatement costs, and net benefits. We then proceed to assess the stability of coalitions by analyzing the incentives for coalition formation.

5.2.1 Economic Feasibility

The main goal of this chapter is to find conditions under which grand coalition is economically feasible. First, we examine the benefits of grand and partial coalitions. For example, grand coalition would reduce socio-economic impacts by achieving the climate stabilization goal. Second, we assess the mitigation costs of achieving the climate stabilization goal under grand coalition and partial coalitions. An examination of net benefits will follow.

5.2.1.1 Non-cooperation and Grand Coalition

The socio-economic impacts are estimated using the PAGE09 model. If the grand coalition would achieve global GHG emission stabilization at 580 ppm by the end of this century, the grand coalition could reduce the socio-economic impacts from those expected under BAU. The simulation outcome of the socio-economic impacts will be stated in terms of mean present value accompanied by an uncertainty range. Under non-cooperation, the mean present value of socio-economic impacts is $13.2 trillion in 2050, which is equal to a 6% loss in annual global income. In 2100, the mean present value of the socio-economic impacts under non-cooperation is $84.7 billion with a 95% confidence interval of $9.1 - $290.6 trillion which is equal to a 10% loss in annual global income.

Under grand coalition, the mean present value of socio-economic impacts in 2100 is $43.2 trillion with 95% confidence interval of $5.4 - $149 trillion. The mean socio-economic impact is equal to a 5.3% loss in global income. This impact is about 51% less than the impact under non-cooperation.

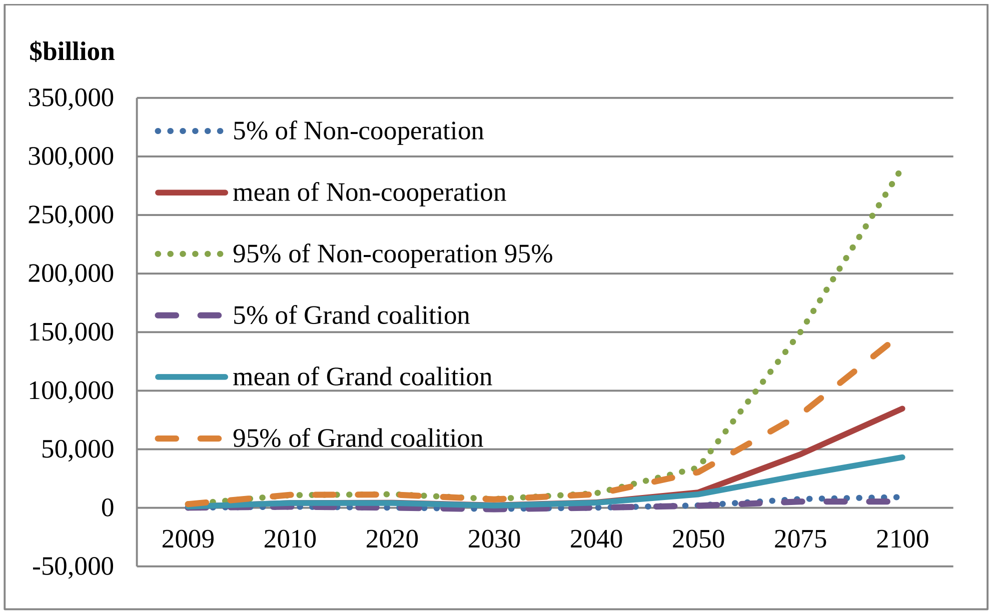

Figure 5-8: Socio-Economic Impacts: Non-cooperation and Grand Coalition (580 ppm)

Figure 5-8 shows the estimated socio-economic impacts with the uncertainty range for the period 2009 - 2100 under non-cooperation and grand coalition. Under non-cooperation, there is a 95% confidence interval of $9.1- $290.6 trillion, meaning there is a 5% chance that the impacts will exceed $290.6 trillion in 2100. The socio-economic impacts at the 95th percentile under non-cooperation increase steeply after 2050. The PAGE09 model assumes that discontinuity in the climate impacts occur when the global temperatures increases more than 3℃ above the pre-industrial level and continues to occur as the end of this century approaches. In Figure 5-8, we would find that the climate discontinuity occurs after 2050 under non-cooperation.

Next we will examine the costs of achieving the 580 ppm global GHG stabilization goal by 2100. As mentioned in Chapter 4, mitigation costs depend upon the difference in emission levels between BAU and the climate stabilization goal. The greater the difference, the higher the mitigation costs.

Under grand coalition, the present value of the aggregated abatement costs to stabilize the GHG concentration at 580 ppm is estimated at $11.1 trillion under the simulation run by the PAGE09 model. The 95% confidence interval for the present value of the aggregated abatement cost is -$46.1 - $76.3 trillion.

The estimated abatement costs for developing regions are higher than the costs for developed regions. Developing regions have higher BAU emissions than developed regions, and so their required emissions reductions for achieving the 580 ppm goal are larger. The IA region has the highest abatement costs at $7.2 trillion with an uncertainty range of -$20.4 - $39.3 trillion.

Based on the estimated socio-economic impacts and abatement costs under the grand coalition to limit global GHG concentration to 580 ppm in 2100, the benefits[45] and net benefits expected from grand coalition can be assessed. The expected benefit under the grand coalition for 580 ppm depends upon the difference between the socio-economic impacts of BAU and those of the 580 ppm grand coalition: the greater the difference is, the greater the benefit. Figure 5-9 shows the socio-economic impacts under BAU and grand coalition. The benefit is equal to the area between the two impact curves.

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[45] As pointed out in the 450 ppm case, the benefits of climate action or policy are the reductions in socio-economic impacts resulting from the climate action taken to achieve the climate stabilization goal.

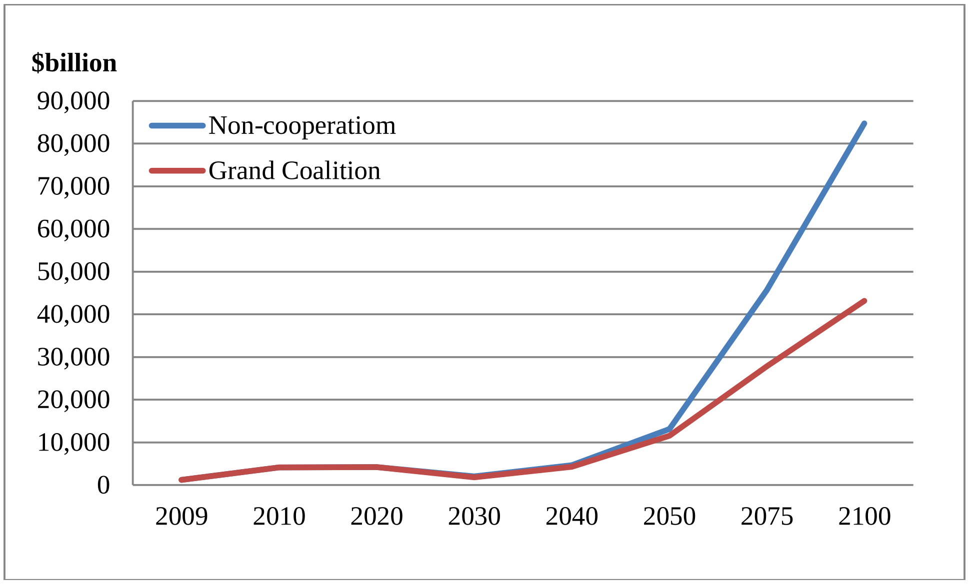

Figure 5-9: Global Socio-Economic Impacts: 580 ppm

In the 580 ppm case, the present value of benefits for the grand coalition is estimated at $61.6 trillion. The present value of the abatement costs for the grand coalition is estimated at $11.1 trillion. The grand coalition for 580 ppm produces the net benefit of $50.5 trillion, based upon the mean values of socio-economic impacts and abatement costs. Taking into account the large uncertainty accompanying the estimates of socio-economic impacts, as well as the likelihood of underestimating climate change impacts, replacing the mean value with the value at the 95th percentile in the distribution of impacts ($273.7 trillion) results in a net benefit of $196.4 trillion, much higher than the original value of $50.4 trillion.

Estimating the benefit of climate change mitigation is subject to large uncertainty due to the inherent uncertainty associated with estimating the socio-economic impacts of climate change. Table 5-2 illustrates the degree of uncertainty by showing how the benefits differ between the mean value and the 95th percentile value in the impacts distribution.

When we use the benefits at the 95th percentile, the resulting benefit to participating regions increases by \$3.4 trillion at least and \$54.1 trillion at most. Benefits to developing regions, especially in the IA and AF regions, would be much higher than the benefits to developed regions when higher impacts were assumed. The net benefits per ton of CO_2 reduced also increases substantially from \$429 to \$1,409 with an assumption of impacts at the 95th percentile.

Among the developed regions, OT has the highest benefit per ton of CO_2 reduced whether measured on the basis of the mean or the 95th percentile value. Developing regions, especially in the CA and IA regions, have the second highest benefit per ton of CO_2 reduced at \$1,218 and \$1,348 respectively.

The analysis so far indicates that a policy to limit global GHG concentration at 580 ppm would be rational. Assessing the economic feasibility of such a policy reveals that the grand coalition would be economically feasible. The model simulation reveals that positive net benefits in aggregate would be \$50,455 billion using the mean value, and \$196.4 trillion using the upper value (95th percentile). It also reveals that there would be positive net benefits to every individual region participating in the grand coalition. In particular, the IA and AF regions would receive the largest benefits by participating in the grand coalition. Notwithstanding the uncertainty of the benefit estimates, limiting global GHG concentration to 580 ppm would appear to be feasible and every region would stand to benefit from pursuing this goal.

Table 5-2: Comparison of Climate Benefits across Participating regions under the Grand coalition

	Mean value of benefits		Upper value (95th percentile) of benefits	
	Benefit ($trillion)	Benefit/ton ($/ton)	Benefit ($trillion)	Benefit/ton ($/ton)
EU	4.2	267	15.2	976
U.S.	3.9	172	13.3	582
OT	3.5	444	10.9	1,409
EE	1.6	164	4.9	512
CA	4.9	120	19.7	486
IA	24.6	380	78.6	1,218
AF	14.9	393	51.0	1,348
LA	4.1	120	14.7	429
Total	61.7	264	208.3	890

5.2.1.2 Partial Coalitions

This section answers the following question: What kind of coalition is economically feasible for achieving a global GHG emissions concentration of 580 ppm by 2100? This section analyzes the economic feasibility of two coalitions (Coalitions 1 and 5) among the eight partial coalitions on the basis of the same three criteria that were used in the previous chapter, i.e., socio-economic impacts, abatement costs, and net benefits.

The socio-economic impacts from the simulation results of these two coalitions are shown in the Figure 5-10. From 2009 to 2040, the estimates of socio-economic impacts follow a similar trend. Differences in socio-economic impacts begin to appear after 2040. The largest socio-economic impacts are expected from Coalition 1, which is a coalition consisting only of developed regions. Coalition 1's results would illustrate the necessity of developing regions participating in a global effort to stabilize atmospheric GHG concentrations at 580 ppm. CA and IA's influence on the estimates of socio-economic impacts would be observed under Coalition 5.

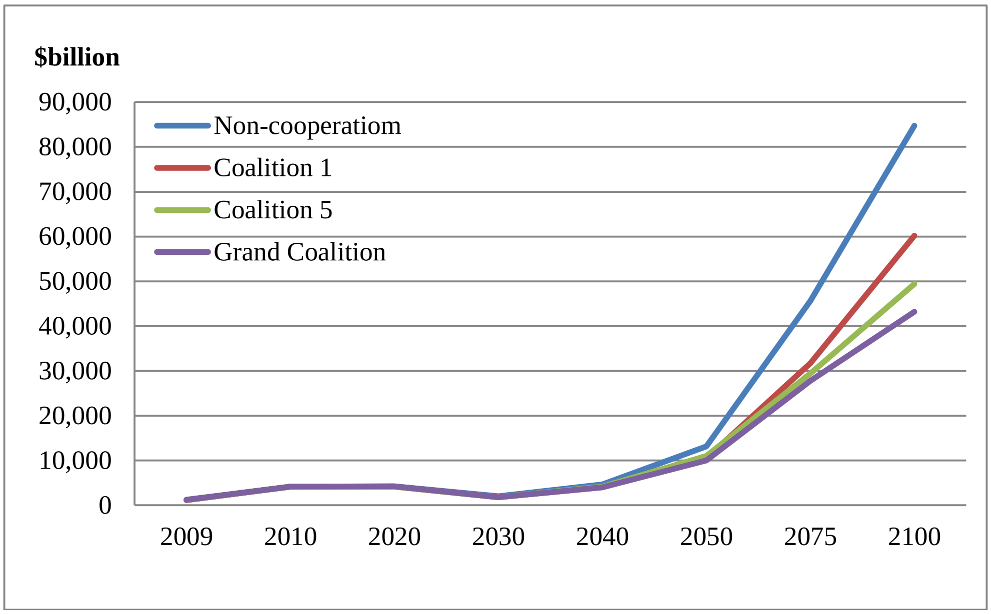

Figure 5-10: Socio-Economic Impacts of Coalition 1 and 5 with Non-cooperation and Grand Coalition

Figure 5-11 represents the estimates of socio-economic impacts with a 5% - 95% uncertainty range for the period of 2009 - 2100 under Coalitions 1 and 5. The mean present value of socio-economic impacts under Coalition 1 in 2050 is $10.5 trillion with a confidence range of about $1.6 to $27.1 trillion. In 2100, the mean present value of impacts is $60.2 trillion, or about a 7% loss of annual global income, within the confidence of $7.0 to $210.8 trillion. Compared to the impacts under grand coalition, the impacts under Coalition 1 are about 39% higher. The global mean temperature rises by 3.43℃ under Coalition 1. According to IPCC AR5, the 580 ppm target or RCP 4.5 corresponds to a 2100 temperature increase of 2.3 - 2.9℃, which is lower than the expected temperature increase that would result from a coalition of only developed regions (Coalition 1). This implies that the participation of developing regions is necessary to meet the goal of a 580 ppm GHG concentration.

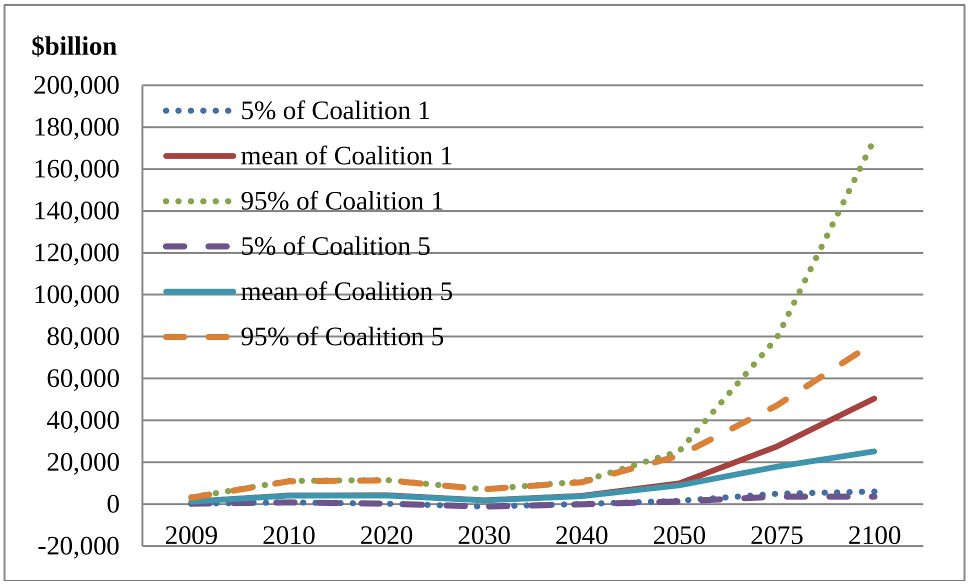

Figure 5-11: Socio-Economic Impacts of Coalition 1 and Coalition 5

Coalition 5 shows the effects of CA and IA participating along with developed regions in limiting global GHG concentrations at 580 ppm. The mean value of socio-economic impacts in 2050 would be $11.0 trillion with a 95% confidence range of about $1.6 trillion - $28.3 trillion. In 2100, the impacts would be $49.4 trillion and there is a 5% chance that the impacts would exceed $169.1 trillion. The estimated impacts amount to a 6% loss of annual global income in 2100.

Table 5-3 and Table 5-4 show the present value of aggregate abatement cost, the climate benefits, present value average cost of reducing one ton of CO_2, and the present value of average benefits associated with reducing one ton of CO_2 under Coalitions 1 and 5. Under Coalition 1, the aggregate abatement cost would be -$0.79 trillion and -$116 to reduce one ton of CO_2 emissions[46]. Coalition 1 leads to benefits estimated at $3.06 trillion. OT has the potential to gain more benefits than other members.

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[46] Abatement Costs in the PAGE09 represent “a continuous curve, with an optimal possibility of negative costs for small cutbacks, with marginal costs becoming positive for larger cutbacks.” (Hope, 2011b. p.5). Negative costs mean that abatement action is profitable: for example, investment in energy efficiency improvement reduces both carbon emissions and energy use which may result in savings in energy costs exceeding the cost of investment. Under these circumstances, abatement action can increase profitably until the negative costs reduce to zero. The negative costs of abatement in developed regions will be examined further in Chapter 6 while discussing key arguments and issues.

Table 5-3: Comparison of Abatement Costs and Climate Benefits (Present Value): Coalition 1

	Abatement Cost ($trillion)	AC/ Capita ($/person)	Benefits ($trillion)	Benefits/ capita ($/person)	AC/ton ($/ton)	Benefits/ ton ($/ton)
EU	-0.2	-452	0.06	129	-31	9
U.S.	-0.3	-585	0.7	1,368	-29	68
OT	0.05	184	1.6	6,358	12	405
EE	-0.3	-1,336	0.7	2,712	-68	138
Total	-0.75	-2,189	3.06	10,569	-116	620

Coalition 5, in which CA and IA regions participate with developed regions, would have abatement costs at $7.3 trillion and CO_2 emissions reductions costs at $131 per ton. The benefits from Coalition 5 would be $31.5 trillion. It would cost $2,373 to obtain benefits from one ton of CO_2 emissions reductions.

Table 5-4: Comparison of Abatement Costs and Climate Benefits (Present Value): Coalition 5

	Abatement Cost ($trillion)	AC/ Capita ($/person)	Benefits ($trillion)	Benefits/ Capita ($/person)	AC/ton ($/ton)	Benefits/ ton ($/ton)
EU	-0.3	-584	2.6	5,347	-40	369
U.S.	-0.4	-748	2.7	5,480	-37	271
OT	-0.01	-48	2.7	10,917	-3	696
EE	-0.4	-1,558	1.2	5,031	-79	255
CA	0.8	1,022	3.1	3,642	46	164
IA	7.6	3,591	19.2	9,057	245	618
Total	7.29	1,675	31.5	39,473	131	2,373

We summarize the estimated net benefits expected of Coalition 1 and 5 in Table 5-5. Coalition 1 produces net benefits of $42.9 trillion. Coalition 5 in which CA and IA join the agreement with developed regions is expected to produce benefits of $47.1 trillion.

The benefits indicated above for Coalitions 1 and 5 are the mean values estimated from the Monte Carlo simulations. As pointed out when discussing the benefit estimates of the grand coalition, climate change includes the possibility of generating extreme events of uncertain intensity and frequency. Assuming that the impacts at the 95th percentile might incorporate higher risks of extreme events, the net benefits evaluated at the 95th percentile are larger than those evaluated at the mean level. Table 5-5 summarizes the result.

Table 5-5: Net Benefits of Coalitions ($trillion)

	Net benefit (with mean benefits)	Net benefit (with upper level benefits)	Global Mean Temperature (degree C)
Coalition 1	3.81	131.2	3.43
Coalition 5	24.1	120.1	3.09

Coalitions 1 and 5 produce positive net benefits, which implies that participation in these coalitions is rational. In terms of environmental effectiveness, Coalition 1, which results in a higher temperature than grand coalition, performs poorly and underscores the importance of developing region participation. This point is also illustrated by Coalition 5 in which the climate stabilization goal is within reach assuming that the CA and IA regions participate along with developed regions.

5.2.2 Stability

5.2.2.1 Non-cooperation and Grand Coalition

We assess the stability of the grand coalition whose aim is to achieve a GHG concentration of 580 ppm by 2100. A coalition is stable if the payoff a region receives from participating in the coalition[47] is greater than the payoff that could be gained from leaving the coalition. Stability analysis provides information on free-rider incentives that may be available to regions that consider deviating from the coalition. The information on the magnitude of free-rider incentives helps to transform unstable

[47] In this research, we consider the payoff to a participant region to be the net benefit of emissions reductions.

coalitions to stable coalitions. The stability of a coalition would be restored if the benefits participating regions receive were transferred to offset the free-rider incentives regions could potential gain by leaving.

The stability analysis using the PAGE09 model indicates that grand coalition for 580 ppm is not stable, i.e., leaving the coalition is more beneficial to the parties than staying with the coalition.

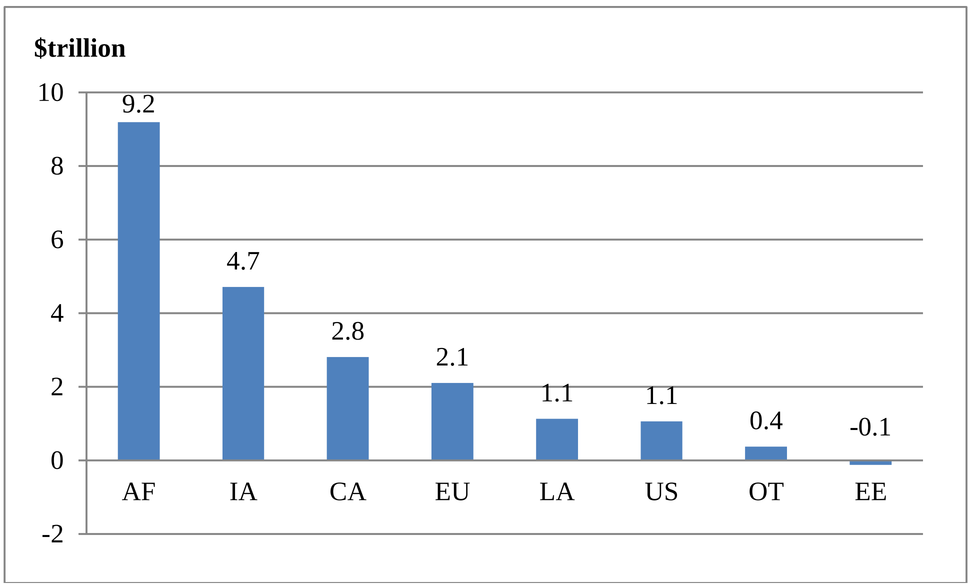

Figure 5-12: Free-rider Incentives from Grand Coalition

Figure 5-12 shows the estimates of free-rider incentives for all participating regions in grand coalition. The free-rider incentives are estimated as the difference between net benefits resulting from grand coalition and the net benefits that would result from leaving the grand coalition. The AF region among the eight individual regions has the largest free-rider incentives accounting for $9.2 trillion, followed by

IA at $4.7 trillion. Among the developed regions, the EU has the largest free-rider incentives at about $2.1 trillion, followed by the US at $1.1 trillion. Only EE region has a negative free-rider incentive, implying that EE would benefit more by staying in the coalition. The net benefits to EE from its participation in the grand coalition are $2.0 trillion and the net benefits from leaving the grand coalition are $1.8 trillion.

As shown in the Figure 5-12, every region except EE has a positive incentive to free ride, i.e., it is in their interest to leave the coalition rather than stay. As a result, a grand coalition designed to limit the global GHG concentration to 580 ppm by 2100 is unstable. However, the net benefit resulting from the grand coalition's actions is large enough to offset the total amount of free-rider incentives. The global net benefits from the grand coalition are estimated at $50.5 trillion, while the estimate of the total free-rider incentive is $21.3 trillion. Are there other measures that could offset the free-rider incentive so as to make the grand coalition more stable? This question will be addressed in the discussion chapter.

5.2.2.2 Partial Coalitions

In this section, we examine the internal stability of partial coalitions. Specifically, we focus on Coalitions 1 and 5. The PAGE09 model simulation indicates that Coalition 1 is internally unstable. As shown in Figure 5-13, every developed region except the U.S. has a free-rider incentive, meaning that all but one participating region in Coalition 1 can increase its welfare by leaving the coalition. The free-rider incentives for developed regions range from $3.9 trillion to -$0.3 trillion. The EU has the largest free-rider incentives at $3.8 billion, followed by OT at $0.6 trillion. In contrast to other developed regions, the US has a negative incentive to free ride. Coalition 1 provides the U.S. a net benefit estimated at $1.0 trillion. If the US decided to leave Coalition 1, the net benefit would decline to $0.7 trillion. This result exemplifies the importance of the U.S. in the global effort to stabilize the climate. By leaving the coalition, the U.S. would save on abatement costs, but the savings would be wiped out by increased impacts from climate change as shown by the decline in net benefit that would result from the region leaving the coalition. This implies that it is in the interest of the U.S. to participate in the coalition. This decision would involve the U.S. incurring some abatement costs, but the potential benefit it would gain in terms of lowering the cost of climate impacts exceeds the abatement costs as shown by the increase in net benefit.

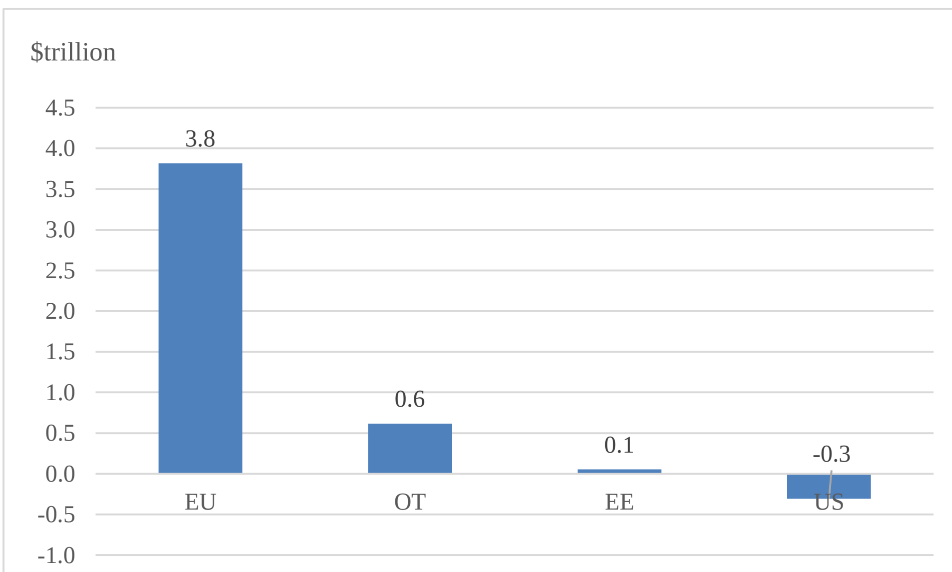

Figure 5-13: Free-rider Incentives for Coalition 1

The results of the model simulation indicate that Coalition 1 would not be successful in achieving the goal of 580 ppm, which corresponds to a 3°C temperature increase, and that the coalition is also internally unstable. The temperature increase under Coalition 1 is 3.43℃, indicating that developing region participation is crucial to limiting temperature increase. This issue is addressed by Coalition 5 that includes the participation of two of the major emitter regions among the developing regions, CA and IA. Coalition 5's stability test results are shown in Figure 5-14.

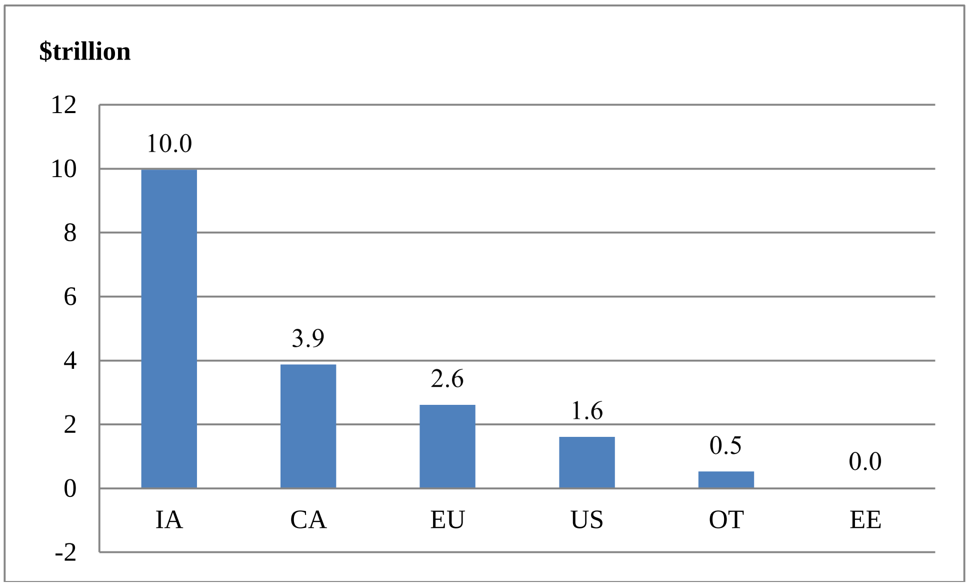

Figure 5-14: Free-rider Incentives for Coalition 5

Except for the EE region, the participant regions in Coalition 5 all have incentives for leaving the coalition. The estimated net benefits of leaving the coalition range from $10 to -$0.02 trillion across all the participating regions. In contrast to Coalition 1, the net benefits of leaving the coalition, i.e., the total amount of free-rider incentives, are estimated not to exceed the net benefits expected from participating in Coalition 5.

The IA region has the largest free-rider incentive in Coalition 5 at $10 trillion, followed by CA at $3.9 trillion. By contrast, only EE does not have a positive free-rider incentive. Rather, EE has a negative free-rider incentive of 0.02 trillion.

Coalition 5 leads to a global mean temperature increase of 3.09℃ in 2100, which is fairly close to the 3℃ goal. But the coalition was also assessed to be unstable according to the stability test. Are there measures to compensate for the free-rider incentives so as to make Coalition 5 stable? This question will be addressed in the discussion chapter.

5.3 Summary

In this chapter, the 580 ppm scenario was analyzed as an alternative to the 450 ppm goal. The climate and socio-economic impacts of the alternative scenario were assessed for the grand coalition and eight partial coalitions on the basis of the PAGE09 model's simulations.

Of the total eight partial coalitions, the outcomes of Coalitions 1 and 5 are presented in this chapter and those of the remaining coalitions are summarized in the Appendix B. These two coalitions are distinct as Coalition 1 highlights the possible effects of developed regions' unilateral abatement actions and Coalition 5 highlights the effects of collaboration between developed regions and a couple of major developing regions.

Under non-cooperation, which represents BAU, the global mean temperature was estimated to rise by 3.87 ℃. Under grand coalition, the increase in the global mean temperature was estimated at 3.04 ℃ in 2100. The recent IPCC AR5 provides a mean temperature range of 2.3℃ - 2.6℃ for the GHG concentration range of 580 - 650 ppm CO_2eq by 2100 with the 5^{th} to 95^{th} percentile of the scenario estimated at

1.5℃ - 4.2℃ [48]. The model simulation's result of 3.04℃ for grand coalition is higher than the mean temperature increase presented in the IPCC AR5, but is within the range of estimates reported by the IPCC.

Under Coalition 1, the global mean temperature rise was estimated at 3.21℃, the highest among partial coalitions. In contrast, Coalition 5 produces a global mean temperature increase of 3.09℃ in 2100, which is very close to the temperature increase produced under grand coalition.

Regarding the socio-economic impacts associated with reduced GHG emissions and corresponding changes in global temperature, non-cooperation shows impact estimates of $84.7 trillion with a 95% confidence interval of $9.1 trillion - $290.6 trillion, while grand coalition resulted in a much less costly $43.2 trillion with a confidence interval of $5.4 trillion - $149 trillion. As expected, Coalition 1 produced the largest socio-economic impacts from climate change among the partial coalitions at $60.2 trillion in 2100, which is equivalent to a 7% loss of global income for the year. Under Coalition 5, the socio-economic impacts would be $49.4 trillion with a confidence interval of $6 trillion - $169 trillion.

As mentioned above, abatement costs depend on the quantity of emissions reductions required relative to BAU. The abatement costs under grand coalition were estimated at $11.1 trillion. Among the partial coalitions, the abatement cost associated with Coalition 1 was estimated to be negative. This implies that the savings in energy costs resulting from investing in energy efficiency improvements to reduce carbon

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[48] IPCC states it is "likely" that the 580ppm concentration will produce a temperature increase below 3℃ (IPCC. 2014d. p.26).

emissions exceed the costs that the regions in Coalition 1 would bear for mitigation. The abatement cost for Coalition 5 was estimated at $7.4 trillion.

The net benefits from emissions reductions were estimated to be positive for not only grand coalition, but also for all partial coalitions. The positive net benefit implies that collective action by the coalition would increase the welfare of all coalition members because the aggregate cost of mitigation action would be less than the reduced damage, i.e., the socio-economic impacts of climate change.

However, a positive net benefit does not imply that the coalition is stable. The test of coalition stability found positive free-rider incentives for all coalitions including the grand coalition, meaning that all coalitions are unstable. In the stability test for the grand coalition, the AF region has the highest free-rider incentives, estimated at $9.2 trillion, followed by IA at $4.7 trillion. The only exception is EE, which has a negative free-rider incentive. Under Coalition 1, the U.S. is the only country with a negative free-rider incentive, which implies that the U.S. would benefit more from joining the coalition than remaining outside it. The EU has the largest free-rider incentive at $3.8 trillion, followed by OT at $0.6 billion. Hence Coalition 5 is not stable because all participating regions except EE have positive free-rider incentives. IA has the largest incentives to leave the coalition at $10 trillion, followed by CA at $3.8 trillion.

Chapter 5 addressed the potential performance of coalitions, both grand and partial, in terms of their climate and socio-economic outcomes under an alternative goal of 580 ppm. The next chapter will compare the 580ppm target with the 450ppm case and also discuss potential measures to make coalitions stable by neutralizing free-rider incentives.

Chapter 6

DISCUSSION

The last two chapters analyzed the climate and economic implications of the 450 ppm and 580 ppm scenarios. Climate outcomes we examined included CO_2 concentration, CO_2 emissions, and temperature. Economic outcomes included impacts, abatement costs, net benefits, and coalition stability. On the basis of the data and the information generated from these analyses, we will assess five cross-cutting issues over these two scenarios: (i) the relationship between temperature increases and changes in socio-economic impacts; (ii) the socio-economic impacts characterizing BAU emissions as well as the 450 ppm and 580 ppm stabilization targets; (iii) the social cost of climate stabilization; (iv) the identification of feasible coalitions; (v) the limitations of Integrated Assessment Models (IAMs).

6.1 A Relation between Temperature and Socio-economic Impacts

Model simulations show that even a slight decline in the global temperature resulting from cooperative action to reduce GHG emissions can lead to a substantial decrease in the socio-economic impacts of climate change. Figure 6-1 illustrates how coalitions fare in terms of their effect on the environment and the economy under the GHG concentration stabilization goal of 450 ppm. Here the environmental factor is represented by the degree of global warming, measured as an increase in global temperature from the pre-industrial level. The economy factor is represented by the changes in the cost of the socio-economic impacts of climate change. The comparison between non-cooperation and Coalition 1 (the weakest coalition due to its consisting only of developed regions) indicates that the reduction of global warming by 0.7°C (3.9°C- 3.2°C) would be accompanied by a 38% decrease in the socio-economic impacts of climate change. Achieving the stabilization goal of 450 ppm through grand coalition would entail a reduction in temperature increase from 3.9°C to 2°C and be accompanied by an 84% reduction in the socio-economic impacts of climate change[49].

The comparison between Coalitions 1 and 5 indicates that a 0.78°C temperature difference would be associated with a $25 trillion difference in the socio-economic impacts of climate change. These findings imply that it would be desirable to encourage more regions to participate in a coalition for climate change mitigation. An estimated $25 trillion income loss could be avoided by the combined mitigation effort of developed and developing regions as compared to a unilateral effort by developed regions, though the temperature difference would be small.

If impacts from climate change are assumed to be greater than modeled, i.e. if the damage function is higher, then the estimated impacts associated with temperature increase would be higher than those derived from the model based on the assumption of a lower damage function. Figure 6-2 illustrates this difference.

The difference in estimated impacts from a global temperature increase between the high damage function and base damage function—the damage function imbedded in the model—is not distinguishable until the temperature increase approaches 2.5°C. The estimated impacts associated with a high damage function

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[49] A similar conclusion was reported by the IPCC AR5 which noted that limiting temperature increase to 2℃ would eliminate most of the risks expected from climate change.

increase rapidly once the temperature passes the 2.5°C mark. For instance, a 1.9°C temperature increase under the grand coalition leads to an impact estimate of $14 trillion using a high damage function, but an estimate of $13 trillion using a base damage function. On the other hand, a 3.9°C temperature increase under non-cooperation leads to an estimate of $260 trillion using a high damage function. This estimate is 67% higher than the one associated with the base damage function. The global welfare loss associated with a high damage function is estimated at $114 trillion, or double the loss associated with the base damage function under Coalition 1 (the coalition of developed regions only).

Thus, the difference in the global mean temperature increase may not be large, but the resulting global socio-economic impacts can be discernably large, depending upon which damage function is assumed for analysis. Thus it seems advisable that the process of climate change coalition formation would involve encouraging a greater number of regions to participate in abatement efforts in order to avoid the impacts from high global temperature increases.

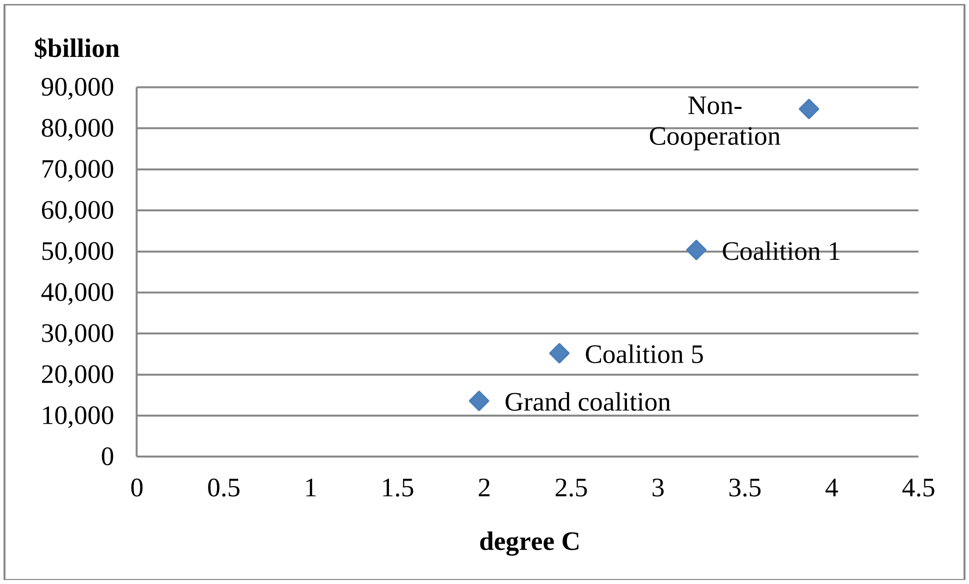

Figure 6-1: The Economy and Environment: 450 ppm Case

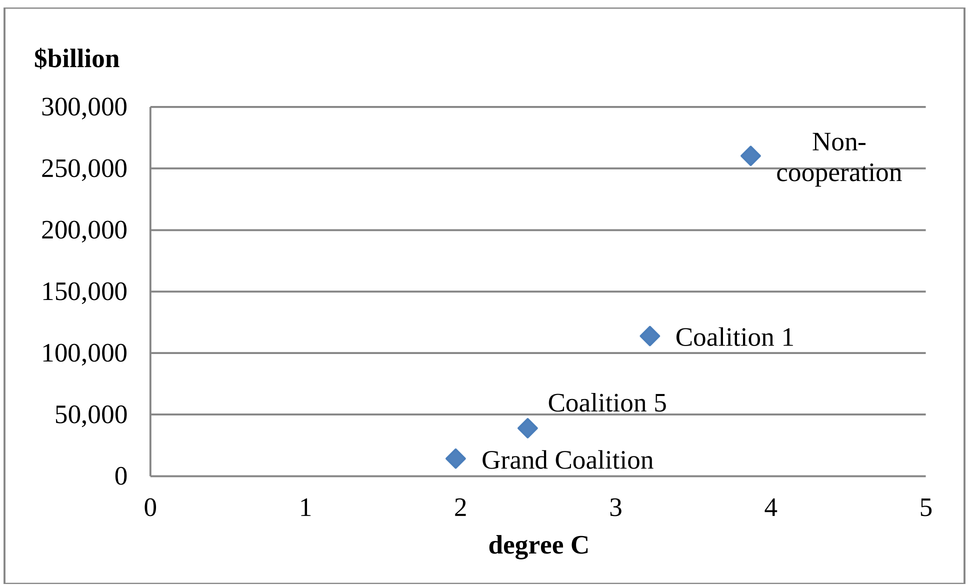

Figure 6-2: The Economy and Environment: 450 ppm Case (High Damage)

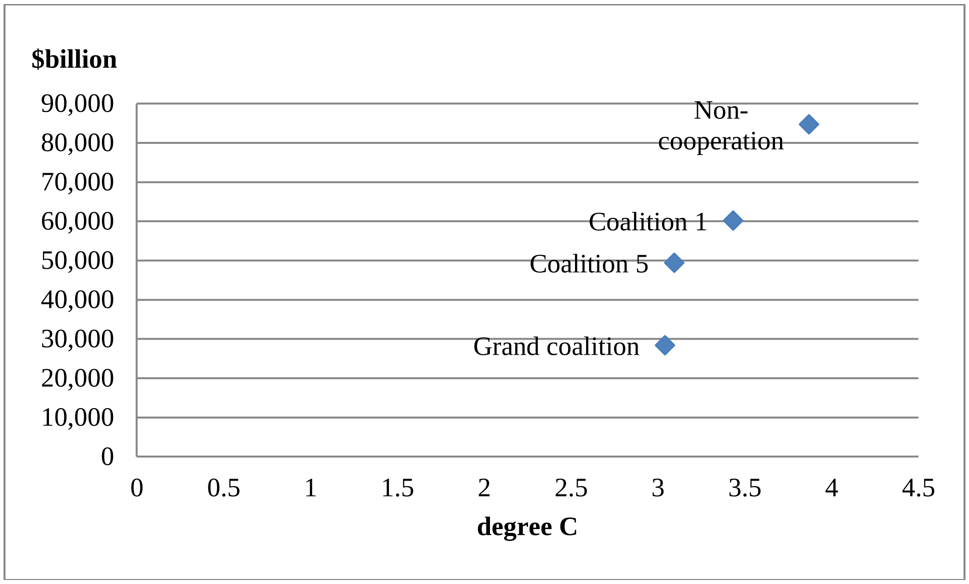

Figure 6-3: The Economy and Environment: 580 ppm Case

In the alternative case of a 580 ppm goal as illustrated in the Figure 6-3, the reduction in the socio-economic impacts of climate change associated with reduced global warming is much more than the reductions estimated for the 450 ppm goal. This is due to larger impacts that are expected to accompany higher concentrations of GHGs. Grand coalition for 580 ppm would reduce the warming by 0.9°C (3.9°C - 3°C), which would be accompanied by a 66% reduction in the socio-economic impacts. Even Coalition 1, the weakest among partial coalitions, would reduce the socio-economic impacts of climate change by 30% with the warming reduced by only 0.4°C. Comparing non-cooperation to Coalition 5 indicates that a 0.78°C temperature difference would be associated with a $35 trillion difference in the socio-economic impacts of climate change.

The relationship between changes in global mean temperature and socio-economic impacts across coalitions is particularly noticeable in the 580 ppm case. As shown in Figure 6-3, Coalition 1's temperature is higher than Coalition 5's by 0.33°C and the consequent increase in socio-economic impacts is estimated at about $10 trillion. Coalition 5's temperature is higher than the grand coalition's by 0.04°C and the consequent increase in socio-economic impacts is estimated at about $21 trillion. This implies that the reduction in socio-economic impacts can be more significant as more regions participate in the mitigation effort.

Next, we examine the characteristics of BAU and stabilization goals in the context of socio-economic impacts. Figure 6-4 illustrates the estimated socio-economic impacts of climate change associated with the stabilization goals of 450 ppm and 580 ppm.

6.2 Characteristics of BAU, 450 ppm and 580 ppm

The socio-economic impacts of climate change under BAU would accelerate in the second half of the century. The trajectory of the socio-economic impacts of climate change under the 580 ppm goal would be non-differentiable from the BAU's until 2050. After that the impacts under the two scenarios would begin to diverge, with the impacts under the 580 ppm goal increasing at a much slower rate than the impacts expected under BAU. The timing of differentiation from the BAU trajectory would be much earlier for the 450 ppm stabilization goal—as early as 2040. The socio-economic impacts under the 450 ppm goal would rise at a much slower rate than the impacts under the alternative goal of 580 ppm, and would reach a plateau in 2075. The aggregate socio-economic impacts under the 450 ppm goal (2°C goal) would be one-third of those estimated for the BAU and one half of those estimated for the alternative goal of 580 ppm. On the other hand, under the high damage assumption, the socio-economic impacts associated with BAU would rise rapidly after 2050. However, the socio-economic impacts associated with grand coalition are not much different from the impact trend of the existing 450 ppm grand coalition. As discussed in Figure 6-2, the difference in impacts begins to appear after the temperature increase of 2.5°C for the high damage function. The magnitude of impacts is marginally higher than in the existing grand coalition but there is little difference in trend between the two.

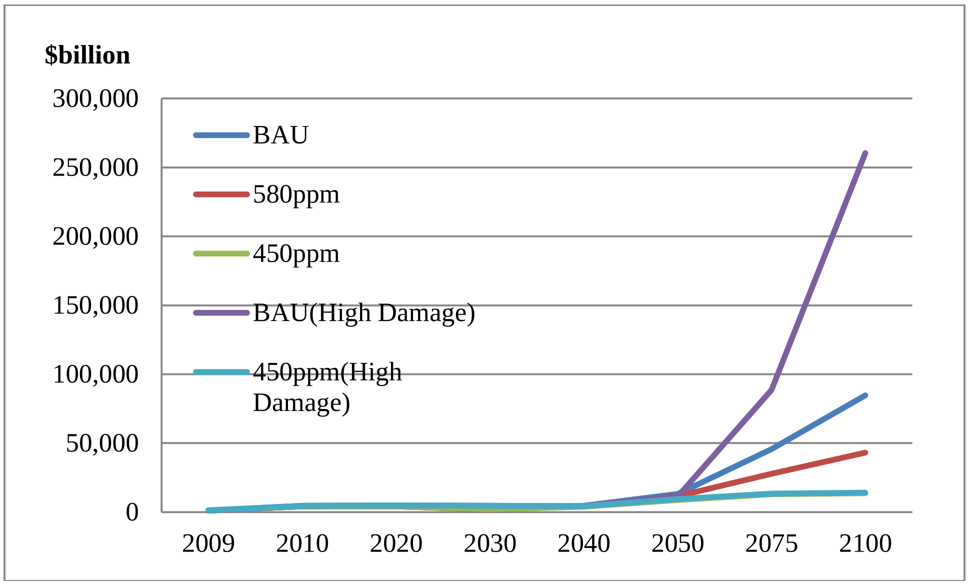

Figure 6-4: Socio-Economic Impacts: BAU, 450 ppm and 580 ppm

6.3 Social Cost of Climate Change

The socio-economic impact of climate change is just one part of the cost that society would have to bear. The other element is the cost of abatement that society would have to pay to mitigate climate change. The cost of climate action for society, i.e., the social cost of climate stabilization, is the sum of these two costs associated with a particular level of global warming; in other words, it is the climate damage expected from the chosen level of global warming to be stabilized plus the cost of reducing emissions relative to BAU to achieve the particular level of climate stabilization required.

Table 6-1 summarizes the results of the PAGE09 model simulation of the social cost of climate stabilization at two different levels of CO_2 concentrations: 450 ppm and 580 ppm. A striking feature is the tremendous difference in abatement cost between 450 ppm, i.e., the 2°C goal, and 580 ppm: $260 trillion vs. $11 trillion. The cost related to BAU is given as a reference as it involves only the climate damage costs, i.e., the socio-economic costs of climate change when no mitigation action is taken. We can assess the degree of appropriateness for the climate stabilization goals by evaluating the social costs of climate stabilization across various climate goals.

Table 6-1: Social Cost of Climate Stabilization ($trillion)

	450 ppm		580 ppm	BAU		
	Base	High Damage		Mean	Mean (High Damage)	95%
Present Value of Damage Cost	51	54	98	160	369	481
Present Value of Abatement Cost	261	261	11	0	0	0
Social Cost of Climate Stabilization	311	315	109	160	369	481

Estimating the social cost of climate stabilization indicates that the 450 ppm goal would involve a higher cost to society than staying with the BAU. This is due to the abatement cost associated with achieving the 450 ppm stabilization target increasing more than the climate damage cost would decrease as a result of this target being achieved. A study similarly showed that stabilizing the temperature at a lower concentration of GHGs would involve a higher social cost than continuing with BAU

(Nordhaus, 2008). The result is however subject to the magnitude of climate damage expected from the BAU emissions trajectory. The climate damage estimates are subject to large uncertainty and the model estimates are in general understood to reflect conservative estimates of climate damage, as most of them are unable to incorporate the possibility of irreversible, non-linear climate damage from unmitigated climate change. If, for instance, the climate damage under BAU doubled in Table 6-1 above, the 450 ppm goal would be an appropriate stabilization target, as its social cost is less than BAU. A similar result is observed if a high damage function is assumed for analysis. Under this assumption, the social cost of climate change is estimated at $369 trillion, more than double the estimate associated with the base damage function. Assuming a high damage function, the grand coalition results in the social costs of climate stabilization being estimated at $315 trillion, which is lower than the social cost of climate change under BAU, indicating that the 450 ppm goal is appropriate. Which damage function is assumed for analysis is critical in assessing the appropriateness of climate goals such as the 450 ppm target.

6.4 Identification of Feasible Coalitions

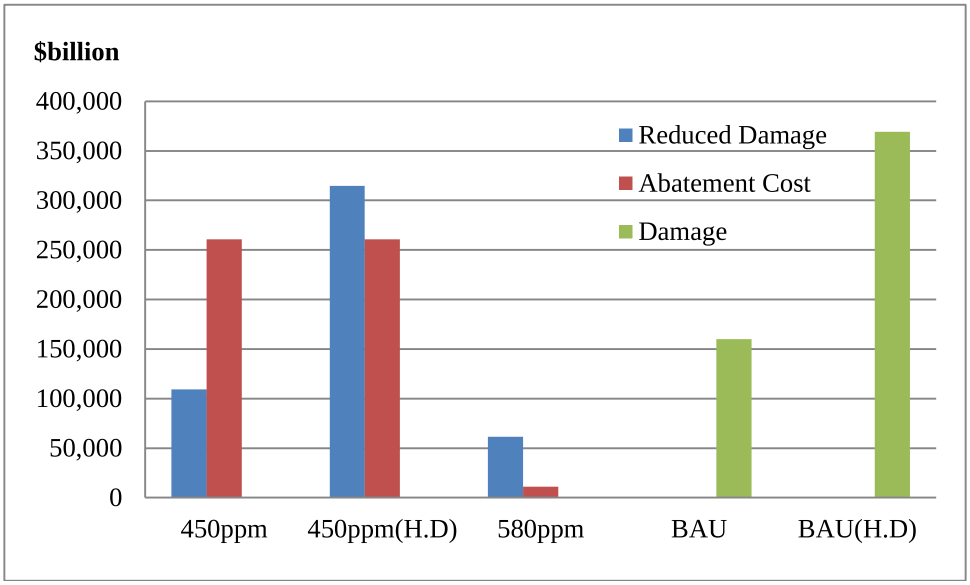

Figure 6-5: Reduced Damage and Abatement Costs: 450 ppm and 580 ppm

Estimated social costs of climate stabilization also indicate that obtaining the 450 ppm goal would involve much higher social costs than obtaining the 580 ppm goal. As shown in Figure 6-5, a 23-fold increase in abatement costs that would result from tightening the concentration target from 580 ppm to 450 ppm would bring in only a two-fold increase in reduced damage from climate change. This implies that the 580 ppm goal is more appropriate than the 450 ppm goal from the perspective of minimizing the social cost of climate stabilization. But, as indicated earlier, the 450 ppm goal can be an appropriate target if we assume a high damage function because the potential damage may exceed abatement costs.

At the 2009 UNFCCC Conference of Parties in Copenhagen, world leaders agreed to limit global warming to 2°C relative to the pre-industrial level of global atmospheric temperature. This was a political decision that had nothing to do with the formal analysis of the social cost of climate stabilization. In the context of the social cost of climate stabilization, the 2°C target may imply either that, given the emissions path, the risks of climate damage perceived by the world political leaders were higher than those presented by models such as PAGE09, or that, given the climate damage associated with the 2°C goal, the abatement costs envisaged by the world political leaders were lower than those estimated by models.

As indicated earlier, the aggregate abatement cost depends upon the emissions reductions required to meet the 2°C target relative to the BAU emissions path. This means that the aggregate abatement cost is equal to the product of the cost penalty per unit of low carbon technology and the scale of low carbon technology required to meet the target. If we assume that the cost penalty per unit of low carbon technology is uniform throughout the world, i.e., that there is no difference between developing and developed regions and that all would have full access to low carbon technologies, the aggregate abatement cost would be roughly proportional to the scale of low carbon technology required to meet the target.

Figure 6-6 and Figure 6-7 illustrate the aggregate abatement costs and damage costs estimated for developing and developed regions for the climate targets of 450 ppm, 450 ppm (high damage), and 580 ppm. For both targets, developing regions incur higher aggregate abatement costs than developed regions. This is due to the assumption in the PAGE09 model that the BAU emissions would be much higher for developing regions than for developed regions due to higher levels of economic growth: 3.4% per year expected for developing regions compared to 1.9% per year expected for developed regions. Consequently, developing regions would have more carbon emissions to avoid than developed regions, i.e., the scale of low carbon energy technology deployment and diffusion would be higher for developing regions[50].

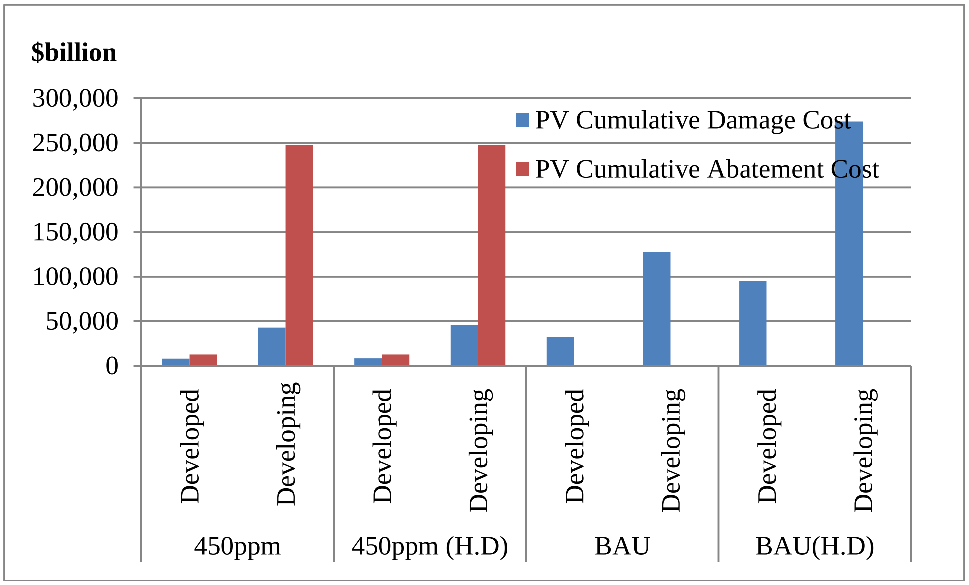

Figure 6-6: Damage Costs and Abatement Costs (450 ppm case): Developed Regions vs. Developing Regions

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50 The latest IPCC Working Group III Reports provide similar results on the basis of assessing 1200 scenarios.

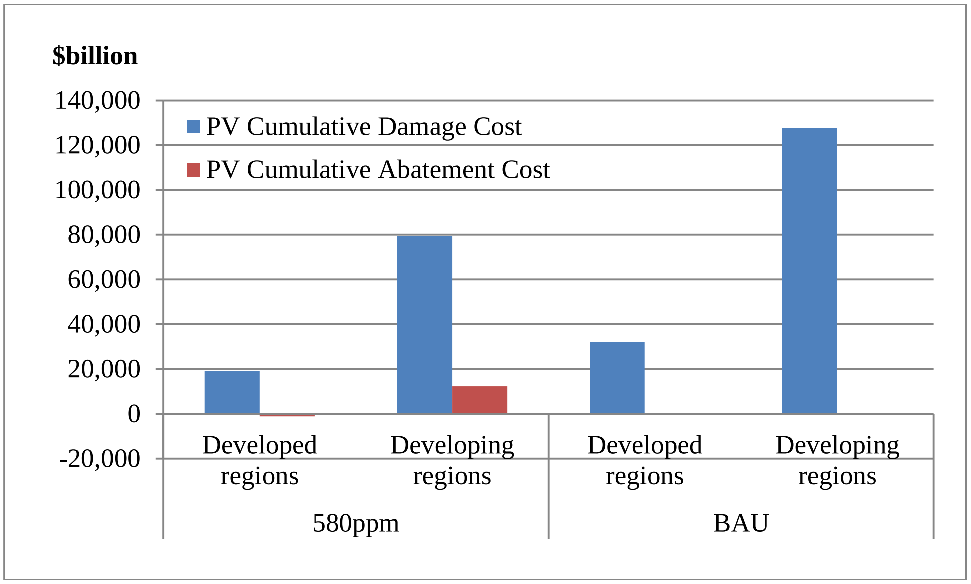

Figure 6-7: Damage Costs and Abatement Costs (580 ppm case): Developed Regions vs. Developing Regions

The issues of free-rider incentives and stability associated with coalitions for the goals of 450 ppm and 580 ppm were analyzed in Chapters 2 and 3. We found that many coalitions were unstable and noted that we need to identify measures that could stabilize coalitions which were evaluated to have the capacity to achieve the goals of 450 ppm and 580 ppm, i.e., the grand coalitions and Coalition 5 for the 580 ppm goal. In this section, we analyze the measures that will provide stability to these coalitions by comparing the net benefit accruing to coalitions with free-rider incentives potentially available to coalition members.

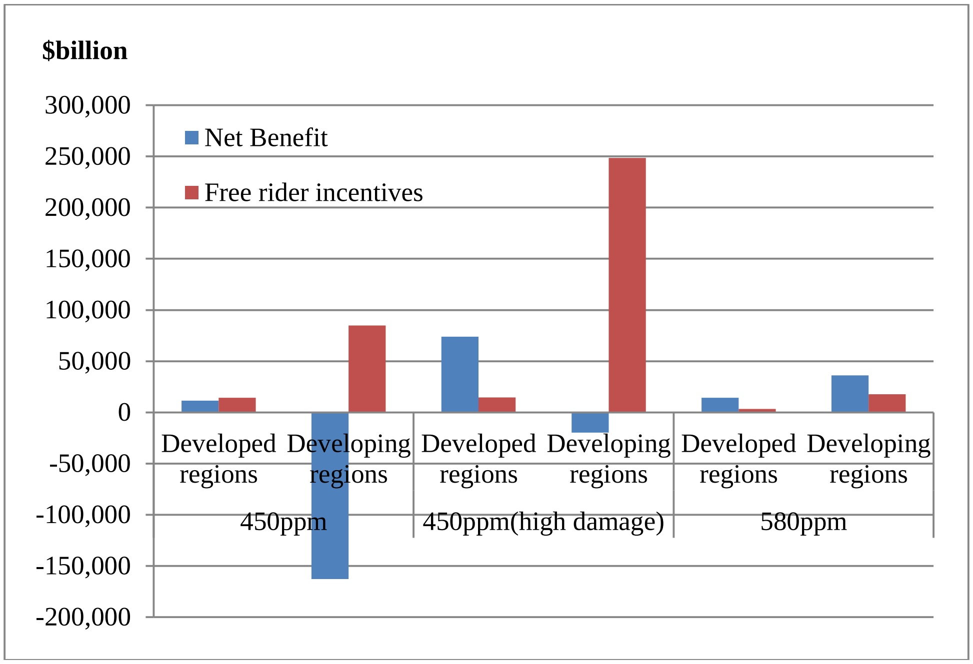

Figure 6-8: Analysis of stability of Grand Coalitions

For ease of analysis, coalition members are grouped into the two blocs of developed and developing regions to compare the net benefits and free-rider incentives. Figure 6-8 shows the results.

The grand coalition scenario under 450 ppm provides net benefits of $11.5 trillion to developed regions. Aggregate free-rider incentives to developed regions are estimated at $14.8 trillion. Developed regions should be prepared to spend as much as $3.3 trillion among themselves in order to eliminate the possibility of singleton. For developing regions the net benefit of participating in grand coalition is negative at $162 trillion, while the estimate of free-rider incentives amounts to $84.9 trillion. This means that a total of $247.9 trillion is required to incentivize developing regions to join the grand coalition for 450 ppm. This is equivalent to an annuity of $3 trillion assuming a zero discount rate and 80-year payoff period. This amount was 4% of the world's GDP in 2014, or $77.6 trillion. Globally, i.e., the aggregate of developed and developing regions, a total of $251 trillion is required to make the grand coalition stable for a goal of 450 ppm.

It is up to policy makers to determine whether the world is willing to allocate about 4% of the global GDP to make this coalition stable. One way of gauging the world's willingness is to examine the level of current commitment or ambition. The world established the Green Climate Fund (GCF) in 2010 under the UNFCCC to support developing regions' efforts to address climate change problems. The goal was to raise $100 billion for the fund by 2020. If this target had been reached today, it would represent about 0.12% of the global GDP[51]. Given the large gap between 4% and 0.12%, the possibility of transferring 4% of global GDP to developing regions for the purpose of 2℃ climate stabilization goal seems remote.

However, a high damage function would yield a net benefit different from the outcome estimated for the 450 ppm grand coalition based on the base damage function. The net benefit for developed regions participating in the 450 ppm grand coalition increases 84% compared to the base damage function estimate and is large enough to offset free-rider incentives. The net benefit for developing regions in the grand coalition under the high damage function increases by eight-fold relative to the one estimated with the base damage function, but even this is not large enough to offset free-rider incentives.

This leads us to consider the 580 ppm case as an alternative. Figure 6-8 shows that the grand coalition's net benefit estimates exceed those of free-rider incentives for

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[51] In 2014 the GCF had just $10 billion, or 10% of the goal.

both developed and developing regions and thus would indicate that the grand coalition is stable. For developed regions the net benefit of grand coalition is $14.3 trillion, while the free-rider incentives are $3.4 trillion. For developing regions, the net benefit of grand coalition is $36.1 trillion, while the free-rider incentives are $17.9 trillion. We can conclude that the alternative goal of 580 ppm climate stabilization is feasible through grand coalition because it proved to be stable.

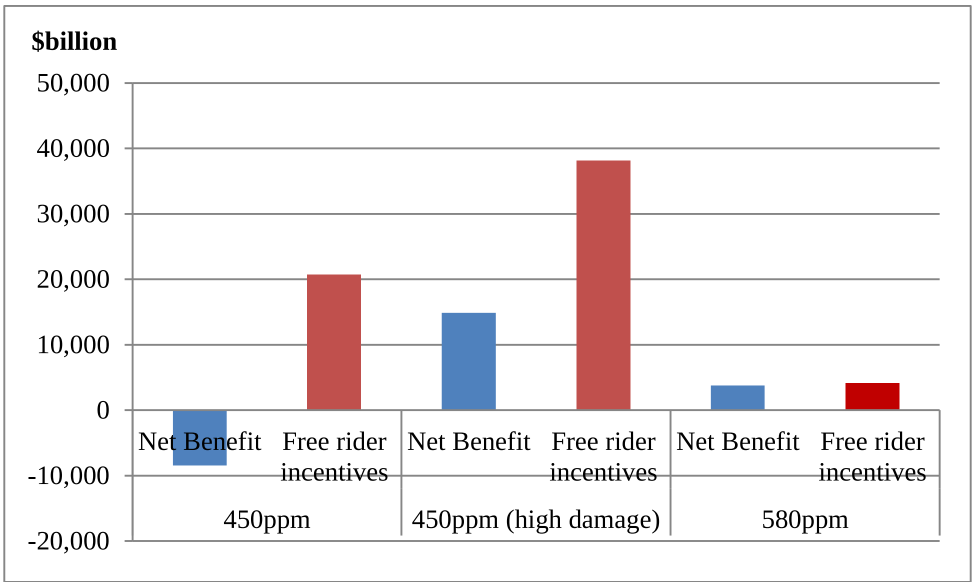

Figure 6-9: Analysis of stability of Coalition 1

This analysis finds that a 580 ppm target might be able to attract a stable coalition—at least on economic grounds. However, there are several potential dangers if countries were to adopt an "easy" solution, like the 580 ppm target, without considering the possibility of high damage risk scenarios that could arise from allowing the atmospheric temperature to rise to this level. In the case of other target-based environmental policies at the nation-state level, e.g., standards for air and water quality, it has been observed that it becomes politically difficult to revise a certain standard once it has been adopted, even if the underlying science recommends change (Glicksman & Batzel, 2009). This tendency may have particular relevance for climate policy decisions because high levels of uncertainty remain about the damage risks of climate change. If the IPCC process continues to find that peer-reviewed research is reporting higher damage risk by category and magnitude overtime, then this dissertation's analysis would caution that a stable coalition currently able to overcome free-rider incentives and find positive net benefits around a 580 ppm target might later become a source of political resistance to later revising the standard, for example, to 450 ppm.

Next we extend the analysis to partial coalitions in order to assess their capacity of maintaining coalition stability. Figure 6-9 illustrates the outcomes of the analysis for Coalition 1 for both cases of 450 ppm and 580 ppm.

For a 450 ppm goal, Coalition 1—the developed region coalition—suffers a net welfare loss of $8.5 trillion while the free-rider incentives to its members reach $20.8 trillion. This coalition is unstable and the financial resources that would be necessary to make the coalition stable amount to $29.3 trillion. It is up to policy makers in developed regions to determine whether they are willing to spend that much for the purpose of supporting a coalition that would be able to limit the global temperature increase to 3.2℃.

However, using a high damage function results in a net benefit estimate that is positive for the coalition members. Although the net benefit amounts to $14 trillion, the free-rider incentives also increase to $38 trillion. Coalition 1 is unstable even under the assumption of a high damage function due to free-rider incentives exceeding the net benefit of participation. The gap is $24 trillion and the coalition can be made stable if coalition members are willing to come up with measures to fill this gap.

Coalition 1 under 580 ppm produces a positive net benefit and much fewer free-rider incentives compared to the 450 ppm case. And yet the free-rider incentives still exceed the net benefit by $0.39 trillion. The financial resources required for making Coalition 1 stable are much smaller than those under the 450 ppm case, but the global temperature under this coalition would rise by 3.4℃, which is higher than the temperature increase expected under the grand coalition for 580 ppm (3.09℃).

Increasing the number of participants would produce better outcomes in limiting global warming. We examine how stability management would change when major emitter regions such as CA and IA join a coalition along with developed regions (Coalition 5).

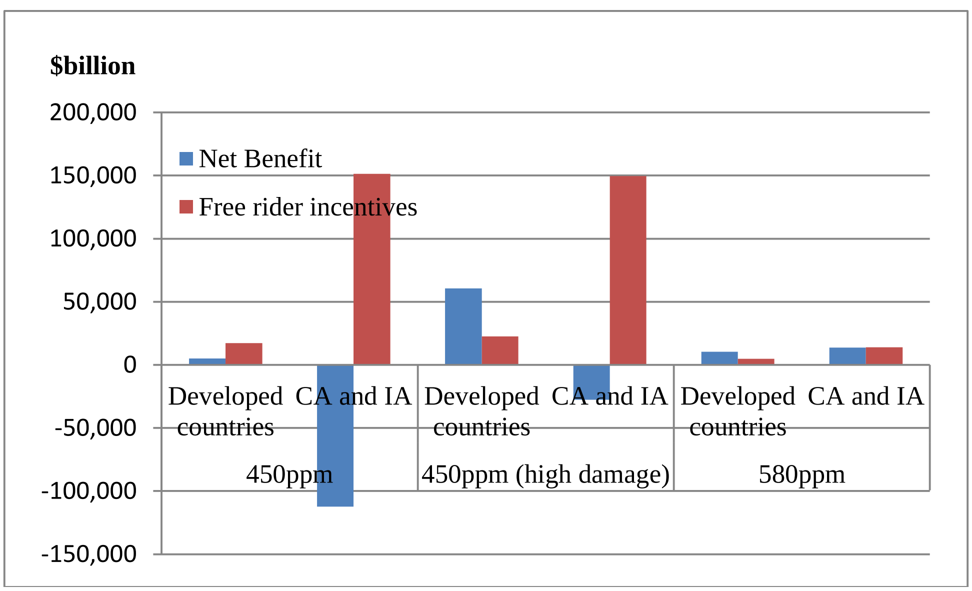

Figure 6-10: Analysis of stability of Coalition 5

Figure 6-10 illustrates the outcomes for Coalition 5 under both cases of 450 ppm and 580 ppm. When the climate goal tightens from 580 ppm to 450 ppm, it is developing regions that would be subject to a large incentive rise from \$13.7 trillion to \$151.3 trillion. The net benefit becomes negative for developing regions, amounting to \$112.4 trillion. Thus \$263.7 trillion is required to ensure the participation of developing regions in the 450 ppm Coalition 5. The outcome for developed regions is the same in that the free-rider incentives exceed the net benefit of joining the coalition, although the scale is much smaller. Globally, a total of \$275.9 trillion is required to make Coalition 5 stable.

Assuming a high damage function would yield a net benefit different from the existing estimates. The developed regions under the 450 ppm Coalition 5 have a reason to remain in the coalition because the potential net benefit for them exceeds free-rider incentives. In contrast, the developing regions under Coalition 5 have a reason to leave the coalition—even assuming a high damage function—because of the welfare loss resulting from participating. \$14 trillion of additional transfer would be needed to convince the developing regions to remain in the coalition even after the developed regions transferred \$33 trillion—the surplus of net benefits to them after offsetting their free-rider incentives—to reduce the free-rider incentives for developing regions.

With the 580 ppm goal, Coalition 5 is able to maintain its stability with a much smaller financial burden. Developed regions would have net benefits exceeding free-rider incentives by \$5.6 trillion. Developing regions would have free-rider incentives exceeding net benefits by \$65 billion. This amounts to less than a \$1 billion per year financial transfer on an annuity basis, which can be funded by the developed regions' surplus benefit of $5.6 trillion. Coalition 5 is stable and feasible.

The analysis thus far indicates that the 450 ppm goal is an unrealistic target due to the large amount of emissions reduction required. But if a high damage function is assumed, the 450 ppm goal becomes a realistic target because coalitions—grand as well as partial—would be able to reduce the socio-economic impacts associated with non-cooperation. Under a high damage function, coalitions for the 450 ppm case are unstable and thus infeasible. The alternative goal of 580 ppm is a feasible target although the global temperature rises beyond 2℃ and approaches 3.02℃. The grand coalition produces the net benefit of $50 trillion. The amount required to offset free-rider incentives would be $21 trillion, which is within the budget of net benefit.

If grand coalition is considered unrealistic due to its requiring a number of least developing regions to participate, the analysis indicates that Coalition 5 in which the members consist of developed regions and two large emitting developing regions—CA and IA—could be considered a viable alternative. The resulting temperature increase would be 3.09℃, slightly higher than the 3.02℃ under grand coalition. The surplus benefit after neutralizing free-rider incentives is $5 trillion, lower than $29 trillion expected under grand coalition.

If the realities of world politics and the pressure of immediate domestic imperatives such as job creation and economic growth preclude large emitting developing regions such as CA and IA from joining the global emission reduction effort, then we are left with Coalition 1. Although the parties to the UNFCCC decided to establish a new agreement requiring universal participation for climate stabilization, there are many ways to interpret the CBDR (Common but Differentiated

Responsibilities) principle and it may be that emissions reductions are realizable only for developed regions (IISD, 2014).

Coalition 1 then becomes a realistic representation. The analysis thus far indicates that Coalition 1 under the 450 ppm goal produces a temperature increase of 3.22℃, which is 0.2℃ higher than the temperature increase estimated for the grand coalition targeting 580 ppm. If we assume that developed regions accept the burden of historical responsibility for climate change, then their free-rider incentives are assumed to be zero. The negative net benefit of $8.5 trillion estimated for Coalition 1 is equivalent to a loss of $106 billion per year in annuity, which is equal to about a 0.3% loss in the developed regions' GDP in 2014.

If developed regions take the lead in reducing their emissions, it would be reasonable to expect that other regions would soon follow and that the global temperature increase would eventually be less than 3.22℃. This would make Coalition 1 an important point of departure on the journey towards climate stabilization.

6.5 Limitation of the Integrated Assessment Models (IAMs)

Analyzing climate change through the use of IAMs has fundamental problems associated with accurately estimating climate damages and accounting for uncertainty. IAMs use systems of simple equations to capture the process of climate and economic systems and analyze the socio-economic aspects of climate change. This type of model has drawbacks because it is impossible to correctly predict global damages resulting from climate change. First of all, there is a lack of data with which to link climate change with its impacts at the scale and speed expected for the remainder of this century simply because natural and human systems have never experienced such rapid changes ever before. No one knows for sure what damages will occur as a result of severe and pervasive climate change, but we know that there will be damage and that it will take place within the complex earth system. This implies that there are fundamental limits to the predictive capacity of the IAM approach that attempts to capture the complex impacts of climate changes solely on the basis of abstract equations. It is known that IAMs reflect only best guesses about likely outcomes (Kelly & Kostad 1999; Tol 2002; Nordhaus 2008).

In addition to data and information problems, the IAM approach is subject to three other fundamental limitations (Ackerman et al., 2009; DeCanio, 2003). The first concerns the difficulty inherent in the valuation of non-market activities and functions provided by natural capital, such as ecosystem services, life support function of the earth system, etc. The difficulty arises from the absence of market prices for these ecosystem services and other forms of natural capital, of which the stock and flow have the potential to be greatly impacted by climate change. The inability to monetize the damage to natural capital leads to underestimating the damages of climate change (IPCC, 2014b). The second limitation involves the discount rate used for calculating benefits and costs occurring far in the future. Having to choose among many possible rates of discount is a problem when using this type of model. Damage estimates are very sensitive to the choice of discount rate, especially because the climate damage is aggravated by the continuous increase in temperatures far into this century (Ackerman et al., 2009). The third limitation is technology outlook, which is characterized by a fundamental uncertainty. The emissions scenarios run by the model are associated with a specific set of technology scenarios based upon assumptions about technical progress and technology deployment (Ackerman et al., 2009). No amount of increase in R&D will be able to reduce the uncertainty associated with the type of technology that will be available in the future. Would it have been possible to forecast the current technologies we have in 2015 if we lived in 1915?

The issues of uncertainty associated with estimating climate change damage greatly influence the decisions regarding climate change actions or negotiations because each individual region cannot know for certain what the climate outcomes of its mitigation action will be. The payoff, i.e., the improvement in climate outcomes from the stabilization strategy, is uncertain and the individual decisions of countries must made based on uncertain knowledge about payoff. When information on payoff is uncertain, the game theory literature defines it as a game of incomplete information. Likewise, a game with uncertain payoff is defined as an incomplete or Bayesian game (Gibbons, 1992). The climate change game fits the definition of a typical incomplete game due to the uncertainty surrounding the payoff function.

When information is incomplete, what knowledge is available determines the outcomes of the game (Rasmusen, 1989; Carraro et al., 2006). In decisions involving climate change coalitions, new knowledge on the damages of climate change (for example, information which suggests climate-related damage will be at the high end of estimates) can change the course of the game. Indeed, the IAM results are highly sensitive to assumptions about information, risk and discount rate. As an integrated model, the IAM faces the challenge of predicting how human and natural systems will co-evolve and change in an unknowable future. The model does not have the capability to adequately capture the unpredictable effects that social, political, economic, and other inequalities can have on coalition decision-making processes. The outcomes of these model simulations are thus the product of a particular set of assumptions embedded in a given analytic structure, and should be interpreted as such. Comparing the PAGE09 model to other widely used IAMs (e.g. IPCC AR4 and AR5, DICE/RICE and WITCH) reveals that this program chooses to address risk by expressing a higher damage cost than its counterparts (see Table 3-10), and additionally values long term environmental viability more highly than the others by using a lower discount rate (Table 3-3). On the other hand, because the PAGE09 model structure is generally simpler in comparison with other models, it is also less affected by new information.

In recognition of climate damage uncertainty, we assume that there are two climate damage functions. These are the model-driven damage function and the information-driven damage function, which yields damage estimates higher than those of the former. To illustrate the effect of damage uncertainty on a climate coalition decision, we take EE to demonstrate the influence uncertainty associated with damage estimates has on coalition decisions. Under non-cooperation, EE climate damages by the end of this century with the model driven-damage function would be $3.6 trillion, and $12.4 trillion with the information-driven high damage function[52]. Under grand coalition, EE would have its damage reduced by $2.6 trillion with the default model-driven damage function and $11.4 trillion with the information-driven high damage function. Under grand coalition with the information-driven high damage function,

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[52] The value of damage estimated by the PAGE09 model is the model-driven damage function, which is the average value of the Monte Carlo simulations; the high damage estimate is the damage value at the 95th percentile of the damage distribution. Knowledge and information that are relevant but extraneous to the model equations system may require the use of high damage estimates such as the one valued at the high end of the damage distribution.

abatement action would produce benefits, measured as the value of avoided damages, which are an almost fivefold increase over the benefits associated with the model-driven damage function. The payoff, which is the net benefit, as a result changes from a negative \$23 billion to a positive \$8.7 trillion and EE would thus have a reason to join the grand coalition. Coalition 5 shows similar results. The reduced damage cost for India under this coalition would be \$2.1 trillion with the default model-driven damage function and \$9.9 trillion with the information-driven high damage function. Assuming a high damage function, the payoff turns from a negative \$0.78 trillion to a positive \$7.1 trillion and EE would have a reason for joining Coalition 5.

The decision-making related to climate change mitigation faces a suite of problems mostly originating from the unique character of climate change. As the recent IPCC report indicated (IPCC 2014b. p.216):

> Climate change includes longer time horizons and affects a broader range of human and Earth systems as compared to many other sources of risk. In many situations, climate change may lead to non-marginal and irreversible outcomes, which pose challenges to conventional tools of economic and environmental policy.

The uncertainty of climate damages is aggravated due to these long time horizons, the broad range of systems that are exposed to climate change, as well as non-marginal and irreversible outcomes. This leads inevitably to an uncertainty about payoffs that affects players contemplating mitigation action. Countries would be more inclined to undertake collective efforts for climate stabilization, for example, if there was a broad understanding among policy makers, consumers, investors, tax payers, manufacturers, financiers, researchers and civil society members that climate change would certainly lead to an irreversible reduction of natural capital resulting in a permanent loss of welfare; that the damages to life-support ecosystems would be unprecedented (though we cannot be precise about their magnitude); and that delaying abatement action would cost more to society than acting immediately. Enhanced understanding about the seriousness of climate-related damages and the socio-economic mandate to engage in immediate abatement would have the effect of increasing the potential payoffs to prospective members of climate coalitions. This dissertation found that payoffs are highly sensitive to the level of climate damage anticipated from inaction. The challenge for sparking effective action then lies in broadening and deepening the information and knowledge related to assessing the potential damages of climate change. This requires multi-dimensional evaluations especially because climate change is subject to large amounts of uncertainty. Every stakeholder, whether they are in the public, private, academia, or civil society sectors, has something to contributive in enhancing our understanding of the continuous and worsening threat of climate damages. The findings of this dissertation can provide useful input for such multi-dimensional approaches.

Chapter 7

CONCLUSION

7.1 An Interpretation of the COP Process

The nations participating in the climate negotiation process through the UNFCCC have been very slow in forming the necessary stable coalitions that could reduce GHG emissions to a “safe” level. Even the coalition formed around the Kyoto Protocol, arguably the largest and most promising to date, has not resulted in a significant reduction in emissions. Several factors have been offered to account for the delays in forming stable climate coalitions that can be found for example, in the work of Victor (2004), Helm (2012) and Haya (2012). Helm (2012), for instance, maintains that the Kyoto coalition has stalled due to its failure to properly address carbon consumption, Eurocentric focus, and openness for free riding. Alternatively, the analysis in this dissertation would support two economic explanations for the ‘sluggish’ coalition formation process to date. First, in many cases—particularly a grand coalition but even for partial coalitions—the net benefits might not have been sufficient for regions to act on their self-interest and organize a coalition. Second, even if net benefits were present for partial coalitions, if not a grand coalition, to form, there could have been free-rider incentives for regions to decline membership. These economic explanations would be consistent with the results of the game theory analysis presented in Chapters 4 and 5.

A notable recent development in climate negotiations has been the UNFCCC decision that member countries must submit their Post-2020 mitigation action plans—

known as the Intended Nationally Determined Contributions (INDC)—for deliberation at the Paris Convention in December 2015[53]. This shift in attention away from the Conference of the Parties to the INDCs might reflect the growing realization that building a coalition based on a climate stabilization target is too problematic—partly as a result of the economic factors discussed in this dissertation, i.e., high free-rider incentives.

7.2 Summary

The common ownership of resources is at the root of the problem for both climate change and conventional environmental challenges. The difference between the two problems lies in the level of challenges facing the decision makers tasked with addressing the process of internalizing the ownership externalities. The characteristics of climate change pose more difficult problems with diverse dimensions and broad scales that are incomparable with most environmental problems. The climate change solution requires an agreement at the global level to phase out GHG emissions and a global transformation of the energy system with a speed and scope unprecedented in history. The agreement has to be made among 197 countries, each with their own socio-economic circumstances and perspectives on the costs and benefits of emissions reductions.

[53] The submission of INDCs was agreed upon in the 2013 UNFCCC Conference of the Parties held in Warsaw, Poland. INDCs represent the GHG mitigation contributions that the member countries of the UNFCCC agreed to present Post-2020. UNFCCC (2013). Decision 9/CP.19. http://unfccc.int/meetings/warsaw_nov_2013/meeting/7649/php/view/decisions.php

Game theory provides a useful approach for analyzing strategic decisions in the context of climate policy games. This approach is used in many disciplines including international relations and politics, economics, and finance. It also has been applied to the study of climate change, particularly to issues relating to the negotiation of self-enforcing strategies for international agreements and/or coalitions. This dissertation used a game theoretic approach to analyze several possible coalitions for achieving two alternative climate stability goals, i.e., the 450 ppm and 580 ppm GHG concentrations targets, by evaluating their environmental effectiveness, economic feasibility, and stability. The PAGE09 model was used to numerically assess the effects of coalition games through model-based estimates of abatement decisions, climate consequences, and their socio-economic impacts.

The analysis indicates that coalitions aimed at achieving the 450 ppm target are economically unfeasible. Although grand coalition is able to limit global temperature increase to 1.97℃, this approach is economically unfeasible because the net benefit of the coalition, or payoff, is estimated as negative; i.e., the abatement cost far exceeds the expected value of benefits for the coalition as a whole. Model estimations point to a difference in payoffs between developed and developing regions in grand coalition, with a positive net benefit estimated for developed regions but the opposite for developing regions. This result is due to a larger burden of the collective abatement cost being placed on the developing regions.

In the case of Coalition 1 in which only developed regions participate and the temperature outcome is estimated at 3.22℃, the net benefit is also negative and the coalition is again judged unfeasible. In the case of Coalition 5 in which large emitting developing regions participate along with developed regions and the temperature outcome is 2.43°C, the net benefit is also negative. As in grand coalition, the developing regions' burden of carrying more of the abatement costs exceeds the benefits expected from the coalition. A coalition stability test indicates that all coalitions are unstable as free-rider incentives dominate the coalition games for the 450 ppm goal.

The benefits of responding to climate change are subject to large uncertainty due to the inherent lack of precise information about the severity of damages to human and natural systems that can be expected from this phenomenon. The model-based damage functions are based solely on variables that are quantifiable, and as a result are likely to underestimate climate damages.

It is important to put the benefit results obtained from the model-based damage estimates in perspective by assessing the outcomes associated with alternative damage functions. Anchoring the benefit calculations with a higher than average value of the damage function produces a different picture of the economic feasibility of the coalitions. For example, Coalition 1 yields a positive net benefit when assuming higher damage. In the cases of grand coalition and Coalition 5, the benefits increase but are not sufficient to yield a positive net benefit.

For an alternative target of 580 ppm, grand coalition and the two partial coalitions were found to be economically feasible as the estimation of costs and benefits show a positive net benefit. Parallel to the results of the stability test for the 450 ppm case, the 580 ppm case also reveals that coalitions pursuing this easier target are unstable as free-rider incentives dominate the grand and two partial coalitions.

Five key issues were assessed through the analysis of the 450 and 580 ppm cases. First, the environmental effectiveness and economic impacts were evaluated by estimating temperature increases and the socio-economic impacts associated with climate change. Small reductions in temperature levels led to substantial increases in avoided damages. This relation is particularly visible in the case of the grand coalitions for both GHG stabilization targets and Coalition 5 under the 580 ppm goal.

Second, issues related to socio-economic impacts, the social cost of stabilization, and coalition feasibility were assessed. The analysis of the social cost of stabilization indicates that the estimated social cost of climate change under BAU is lower than the estimated social cost of stabilization at 450 ppm. The model estimation reveals that the residual damage at 450 ppm is much lower than the damage under BAU, but the abatement cost for 450 ppm is greater than the reduced damage. As a result, the total social cost of stabilization is higher for the 450 ppm goal than for BAU. The model estimation indicates that the 450 ppm goal is too ambitious a target to achieve. On the other hand, a substantial reduction in the social cost of stabilization is estimated for the less ambitious target of 580 ppm. While the residual damage increases at 580 ppm, the savings in abatement cost compared to the 450 ppm target more than offset the damage increase leading to an overall reduction in the social cost of stabilization at 580 ppm relative to both the 450 ppm goal and BAU.

Third, financial measures to achieve coalition stability were assessed by comparing the net benefit of coalitions with the amount of free-rider incentives. In the case of the 450 ppm target, the net benefit to coalition participants is insufficient to offset the free-rider incentives available to coalition deserters. But the outcome is reversed in the case of the 580 ppm grand coalition, as the net benefit to participants exceeds the free-rider incentives. If appropriate financial transfer mechanisms are made available, the coalitions for 580 ppm can be made stable. For the case of the 580 ppm Coalition 5, the net benefit is insufficient to offset free-rider incentives available to developing regions. The stability of Coalition 5 depends upon the availability of additional financial resources that can be used to supplement the shortage of net benefits needed to offset the free-rider incentives to developing regions. Coalition 5 can be considered to more closely reflect realistic constraints on emissions reduction than the grand coalition, which assumes the participation of all regions. Thus Coalition 5 deserves more attention than the grand coalition.

Coalition 1 that seeks to achieve the 450 ppm target has the potential to build momentum for a successful global abatement agreement. When compared to the temperature increase resulting from the grand coalition for 580 ppm, Coalition 1's increase is only about 0.2℃ higher. This temperature gap may decline even further if the developed region abatement initiative under Coalition 1 has a spill-over effect of narrowing the trust gap that currently exists between developed and developing regions despite their common goal of climate stabilization. If developed regions lead by example in the way envisaged by Coalition 1, there would be fewer barriers for developing regions to participate in the global emissions reduction effort. If the grand coalition is difficult to realize, Coalition 1 may be a good starting point for the long journey towards eventual climate stabilization.

Lastly, this dissertation considered the impact of high damage estimates could have on coalition performance to account for the uncertainty of climate impacts. This uncertainty limits the appropriateness of the approaches taken by Integrated Assessment Models, including the PAGE09. Uncertainties about damage are directly related to uncertainties about payoffs, under which the climate change decision game can be classed as an incomplete or a Bayesian game (Gibbons, 1992). Information determines the outcome of games under the incomplete game (Rasmusen, 1989).

Applied to climate change decision games, this dissertation confirms that the presence of incomplete information about the damages expected from climate change can significantly influence the games' outcomes. As information on climate damage improves, the motivation for and effectiveness of abatement action is likely to also improve, potentially leading to an increase in coalition participation as well as to an increase in the ambitiousness of global targets to reduce GHG emissions. Efforts to improve the quality and scope of information on anticipated climate damage requires input from multi-dimensional elements and perspectives, and we hope this encourages researchers to evaluate the findings of this study multi-dimensionally and through an interdisciplinary framework.

In addition, as indicated in the methodology chapter, this dissertation is about game-theoretic modeling of coalition formation under top-down target-setting conditions. The research on coalition formation to address climate change needs to include bottom-up approaches to coalition formation. One useful area for future research would be game-theoretic analysis of bottom-up coalition formation on low/zero carbon energy technology transfer.

7.3 Concluding Thought

The quantitative outcomes of this dissertation are meant to be indicative, but not in any way definitive, findings that can improve our understanding of climate coalition decision making. The outcomes of climate coalition games are very sensitive to the amount of possible net benefits, which are in turn highly sensitive to the large uncertainties inherent in both natural and human systems. The fact that the presence of incomplete information can significantly influence the outcomes of games, as shown throughout Chapters 4 and 5, represents an important limitation of game theoretic analysis and deserves serious attention. As information on climate damage improves, the motivation for and effectiveness of abatement actions are also likely to improve, potentially leading to an increase in coalition participation as well as to an increase in the ambitiousness of global GHG emission reductions targets. In light of these limitations and uncertainties, the value of the net benefits estimated from the knowledge available at the time of the analysis can help researchers and policy makers to consider action as political conditions shift or more information becomes available. Moreover, when attempting to solve a problem as serious as climate change, it is always worthwhile to be reminded of Joergen Norgaard's rather appropriate remark: "Even if it isn't cost effective, saving the world could still be a good idea"[54].

[54] The quoted remark was given to the author by Dr. Lars Nilsson, a member of the dissertation committee.

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Appendix A

OUTCOMES OF PARTIAL COALITIONS UNDER THE CASE 1: 450 ppm

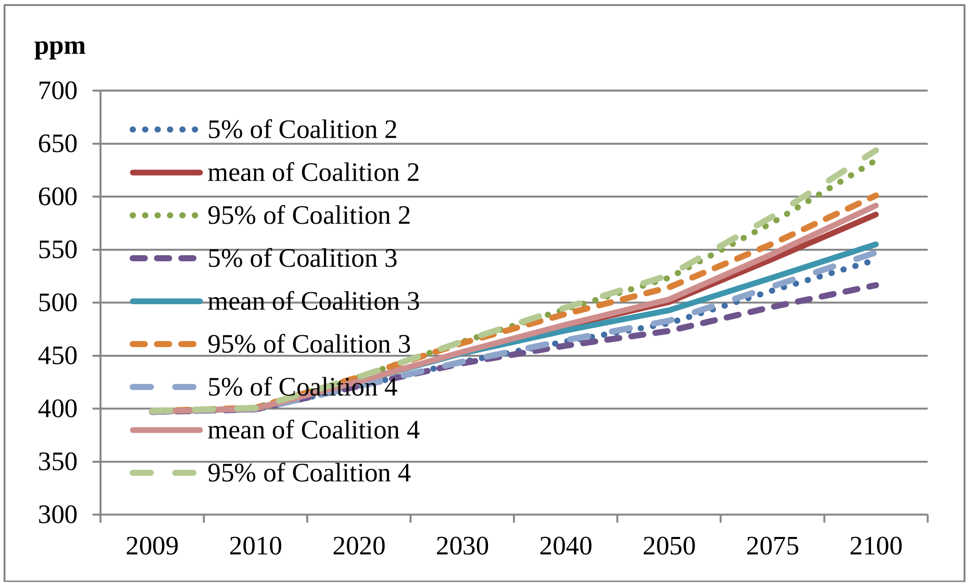

Figure A-1: CO_2 Concentration of Coalition 2, 3 and 4

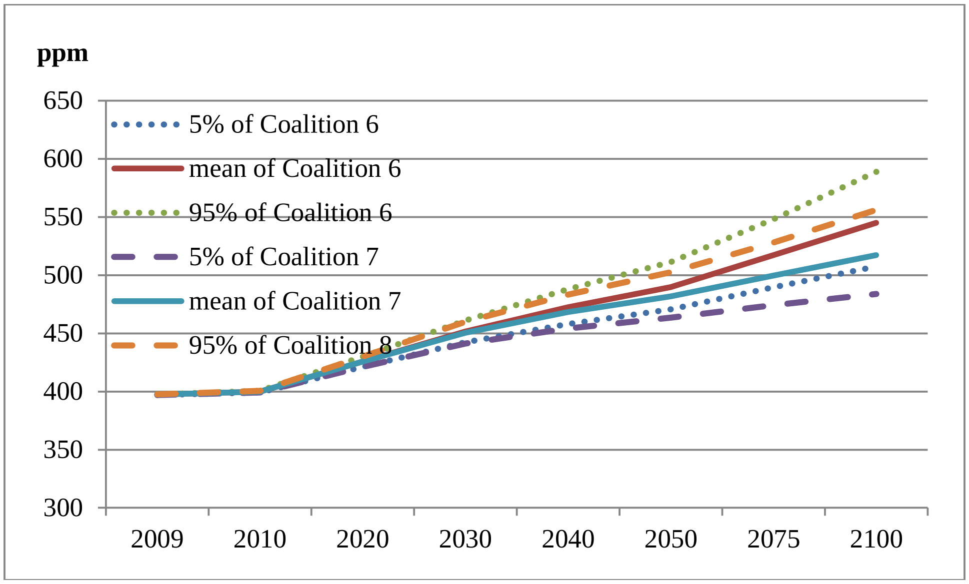

Figure A-2: CO_2 Concentration of Coalition 6 and 7

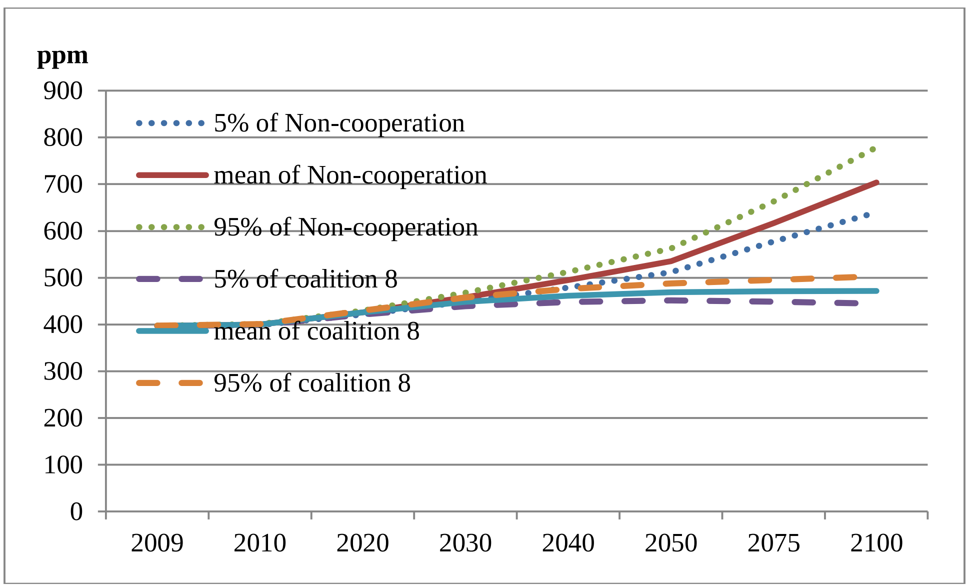

Figure A-3: CO_2 Concentration of Coalition 8 with Non-cooperation

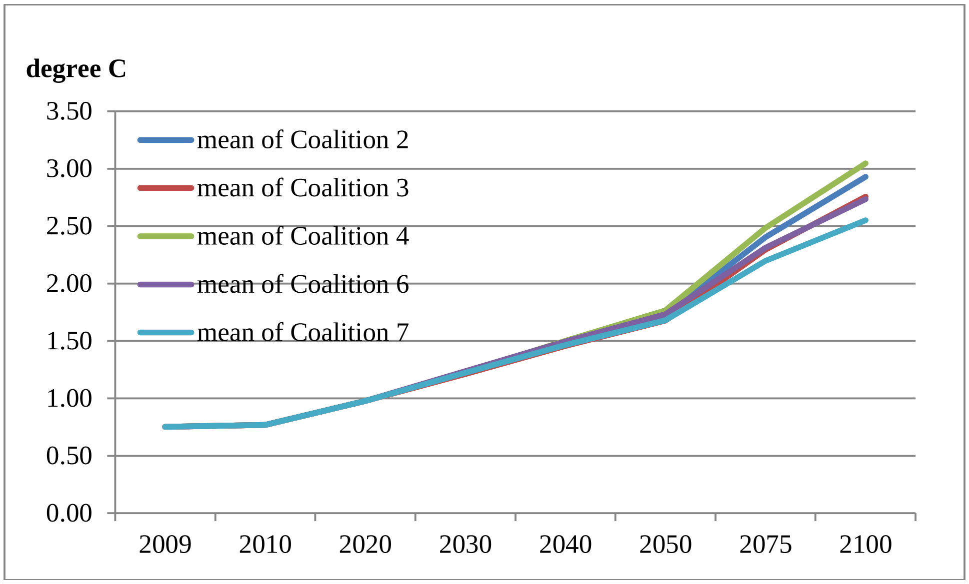

Figure A-4: Global Mean Temperature of Partial Coalitions

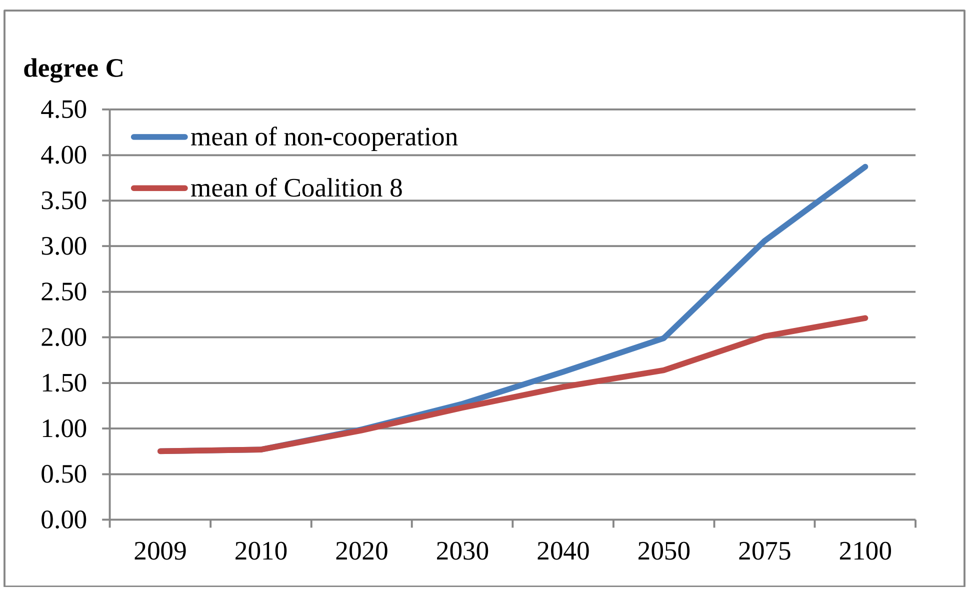

Figure A-5: Global Mean Temperature of Coalition 8 with Non-cooperation

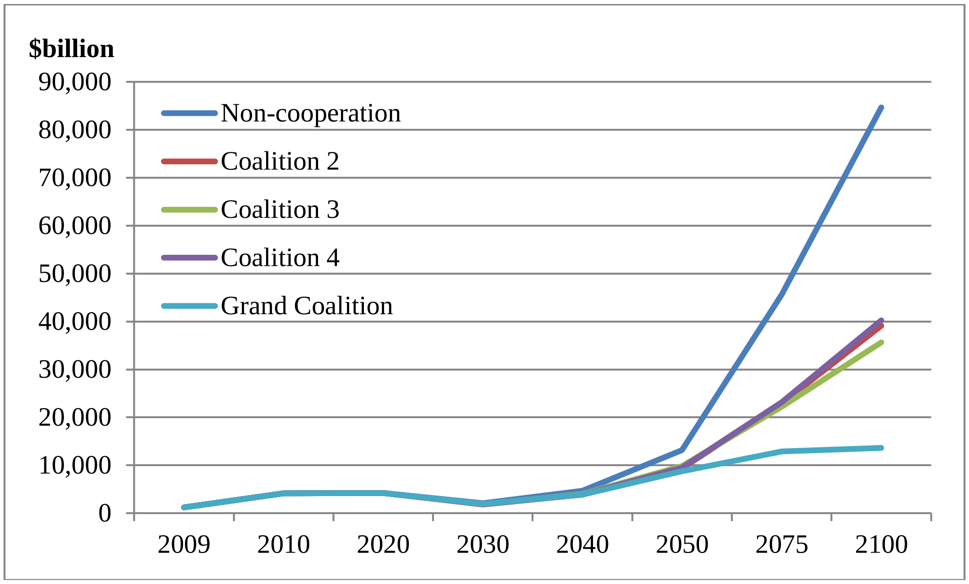

Figure A-6: Socio-Economic Impacts of Coalition 2, 3 and 4 with Non-cooperation and Grand Coalition

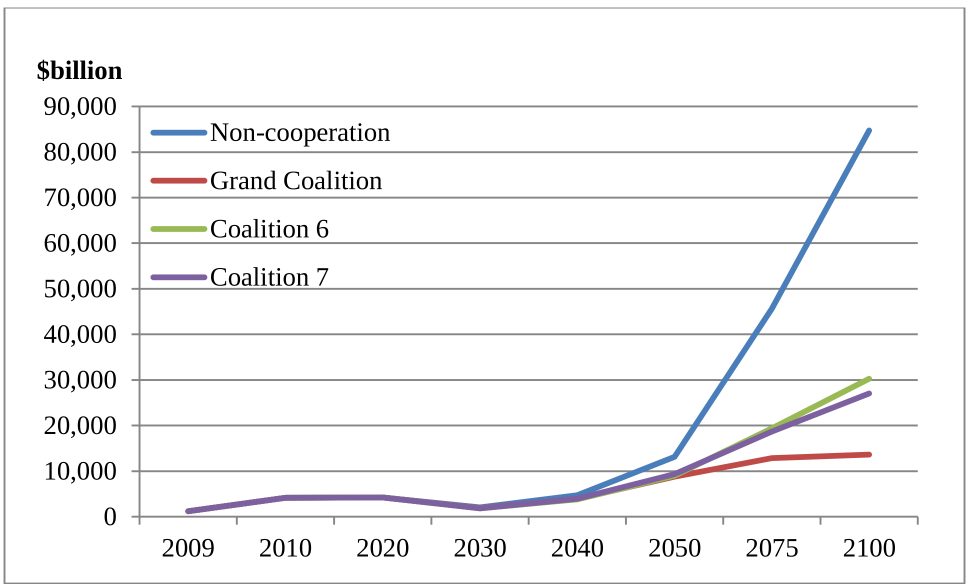

Figure A-7: Socio-Economic Impacts of Coalition 6 and 7 with Non-cooperation and Grand Coalition

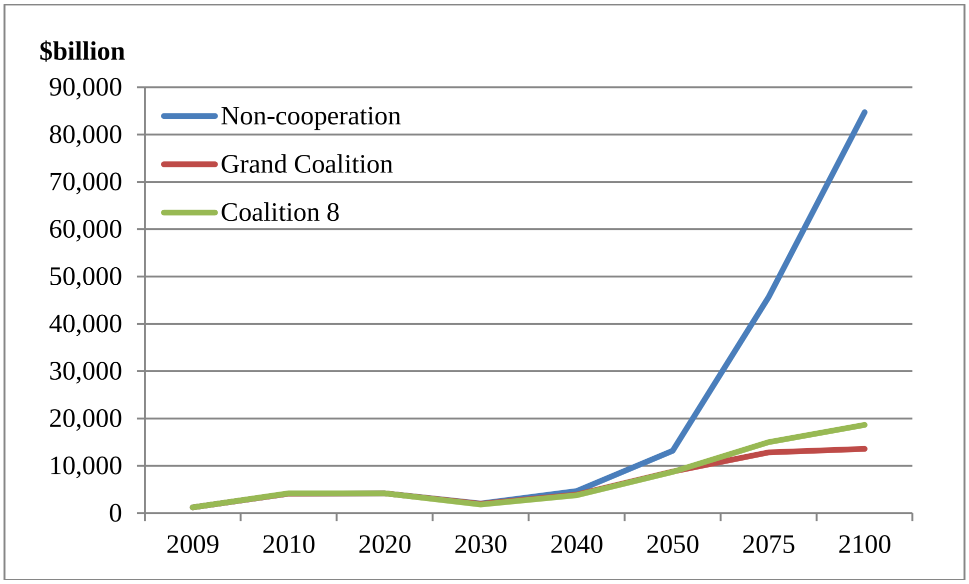

Figure A-8: Socio-Economic Impacts of Coalition 8 with Non-cooperation and Grand Coalition

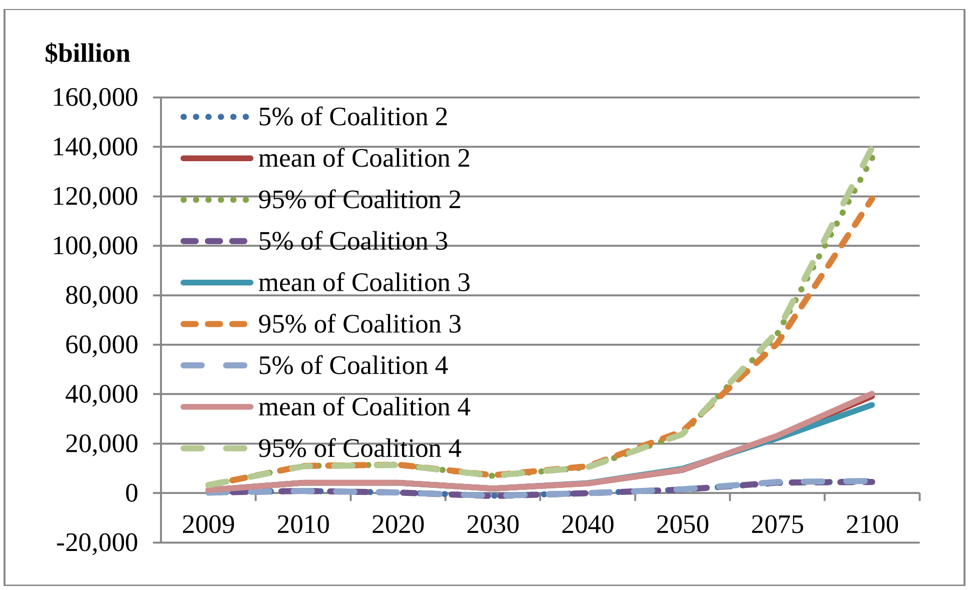

Figure A-9: Socio-Economic Impacts of Coalition 2, 3 and 4

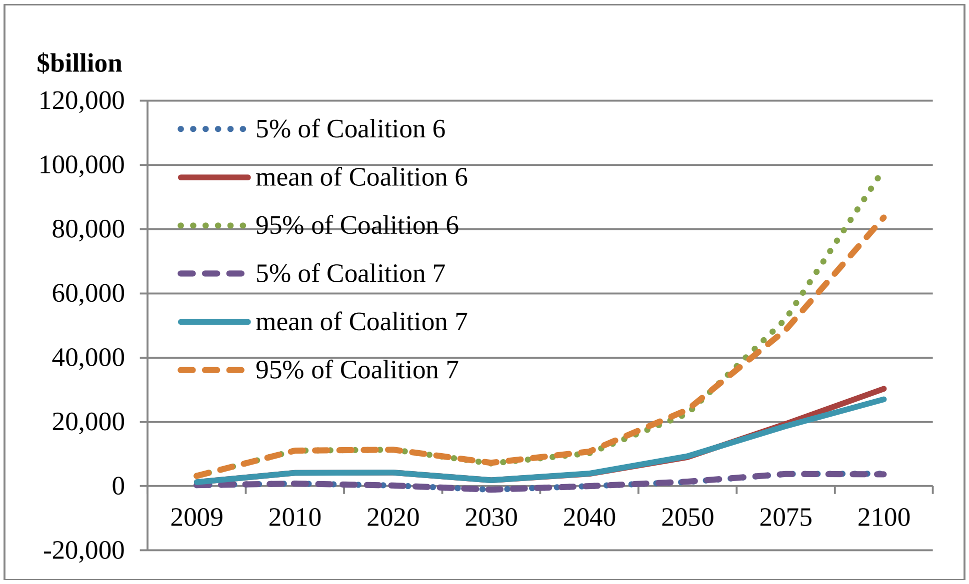

Figure A-10: Socio-Economic Impacts of Coalition 6 and 7

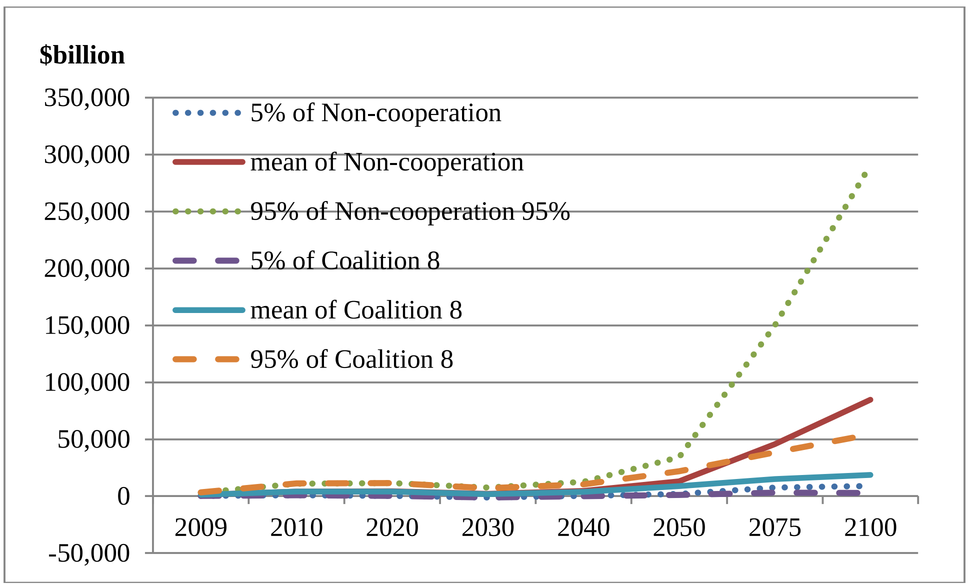

Figure A-11: Socio-Economic Impacts of Coalition 8 with Non-cooperation

Table A-1: Net Benefits of Coalitions ($billion)

	Net Benefits (with mean value)	Net Benefits (with upper level benefits)	Temperature (degree C)
Coalition 2	21,768	183,986	2.93
Coalition 3	-56,166	120,488	2.76
Coalition 4	45,307	207,074	3.05
Coalition 6	24,331	227,147	2.73
Coalition 7	-52,439	160,389	2.55
Coalition 8	-72,186	168,035	2.21

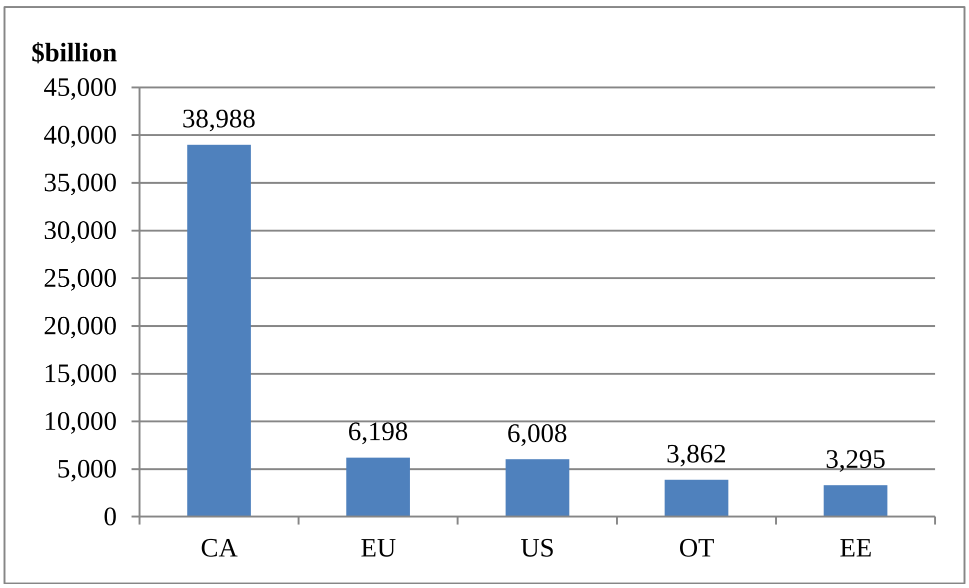

Figure A-12: Free-rider Incentives from Coalition 2 ($billion)

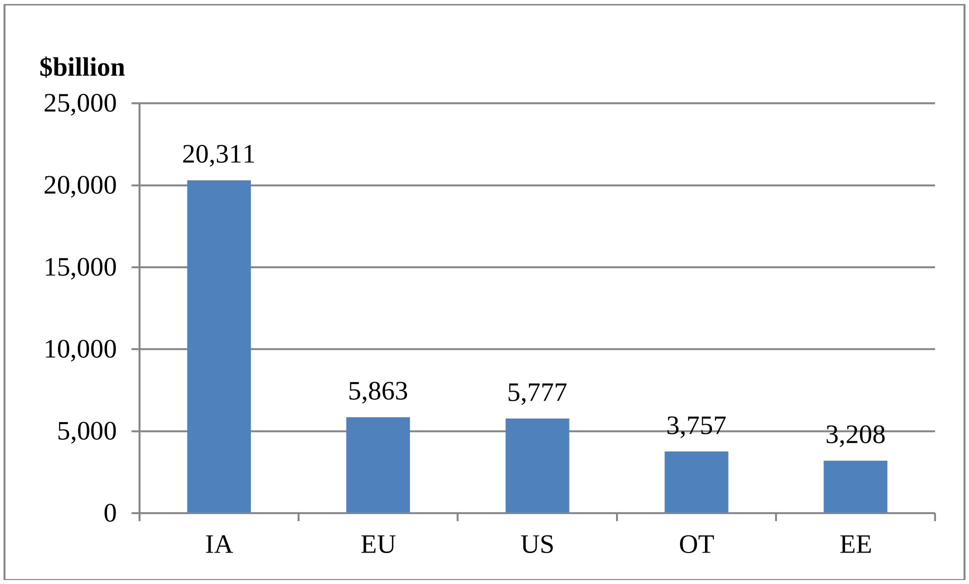

Figure A-13: Free-rider Incentives from Coalition 3 ($billion)

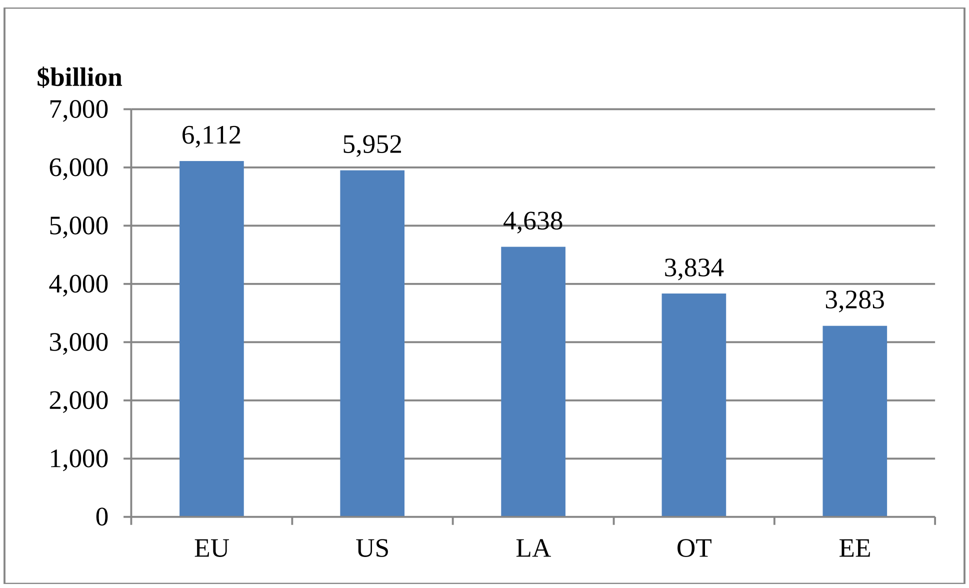

Figure A-14: Free-rider Incentives from Coalition 4 ($billion)

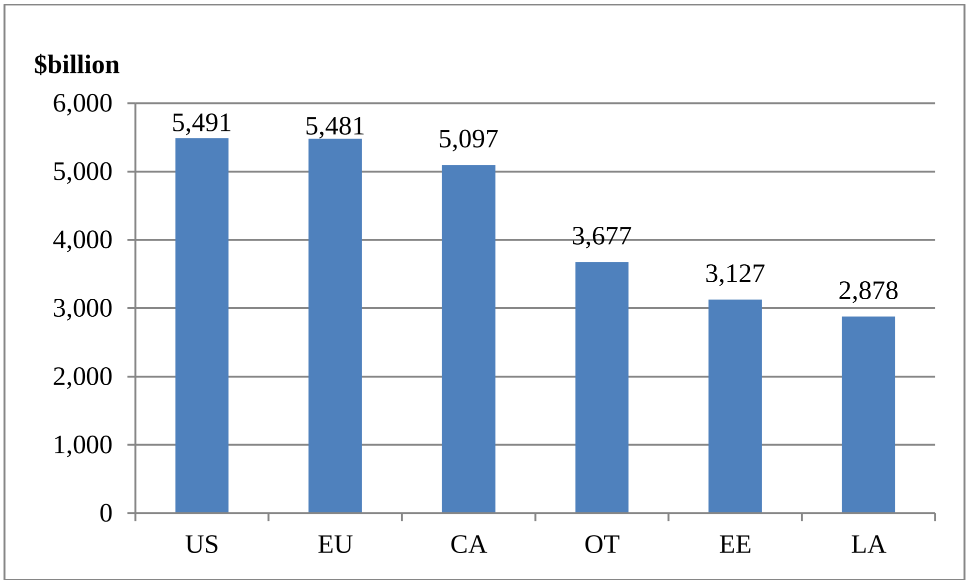

Figure A-15: Free-rider Incentives from Coalition 6 ($billion)

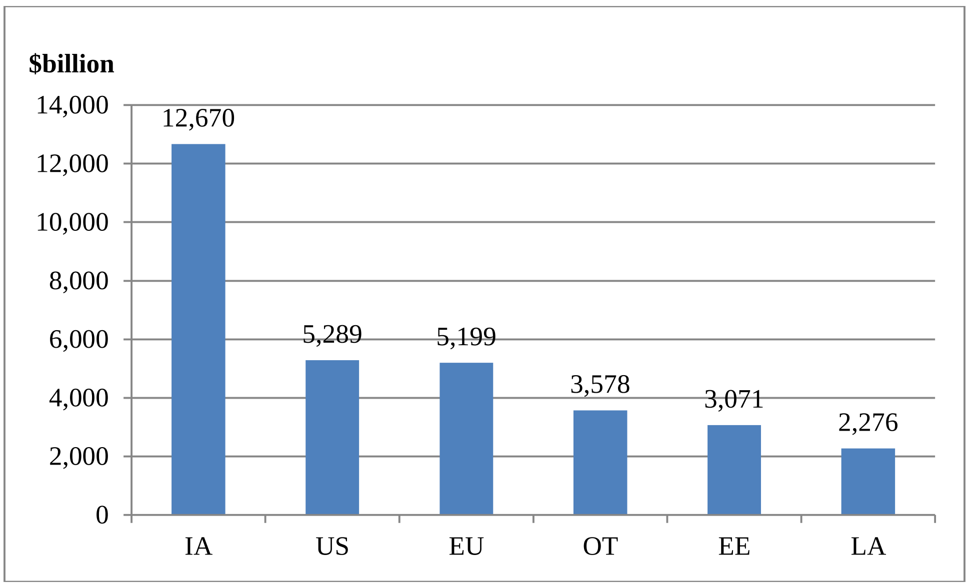

Figure A-16: Free-rider Incentives from Coalition 7 ($billion)

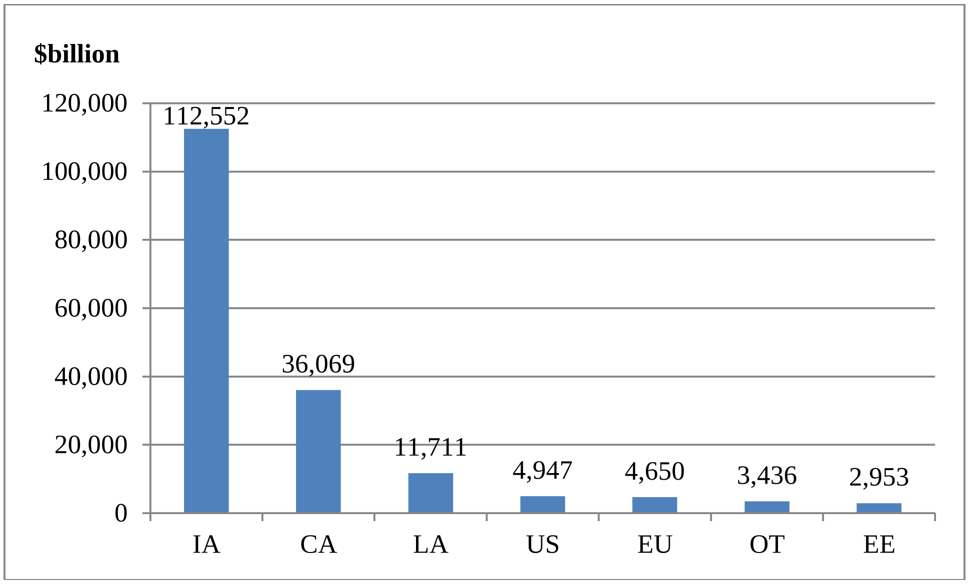

Figure A-17: Free-rider Incentives from Coalition 8 ($billion)

Appendix B

OUTCOMES OF PARTIAL COALITIONS UNDER THE CASE 2: 580 ppm

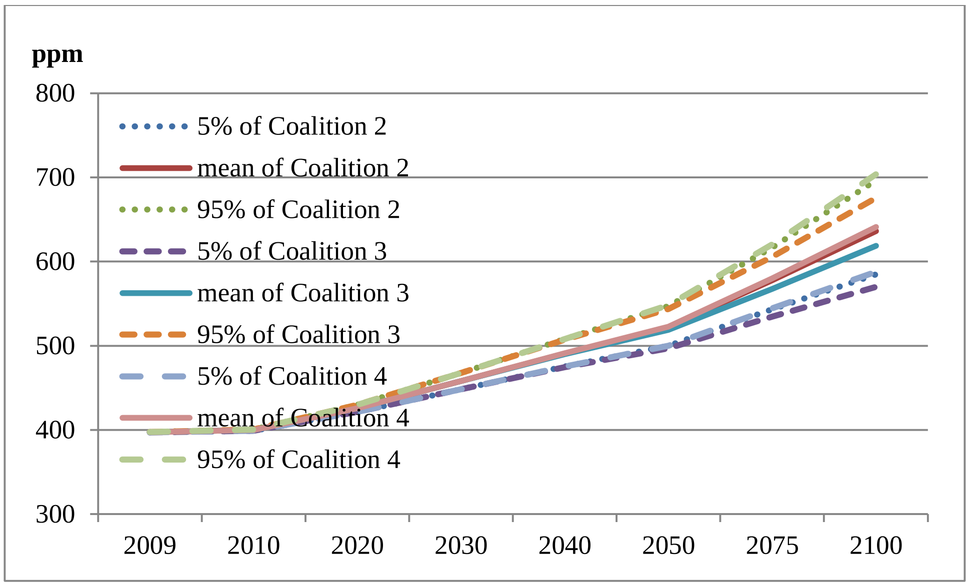

Figure B-1: CO_2 Concentration of the Coalition 2, 3 and 4

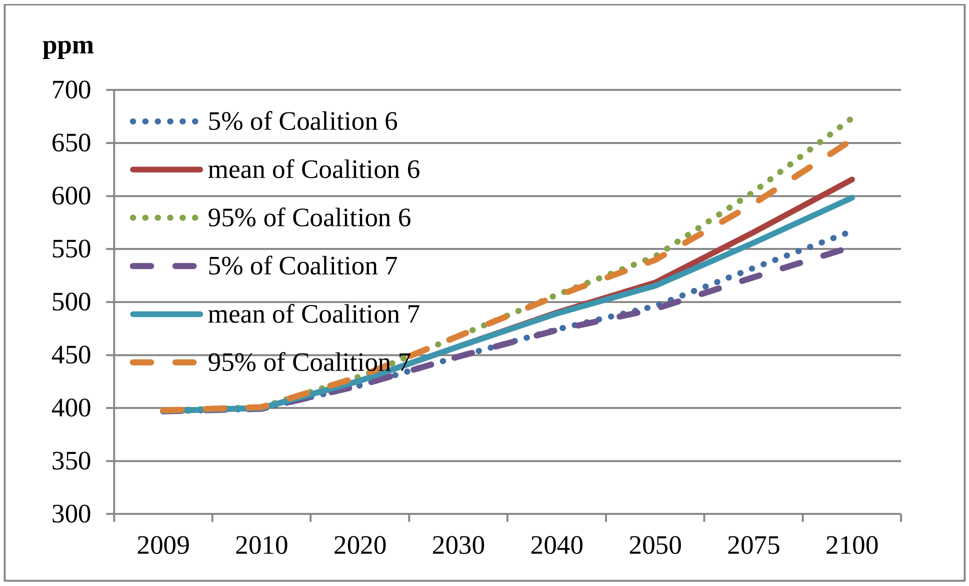

Figure B-2: CO_2 Concentration of the Coalition 6 and 7

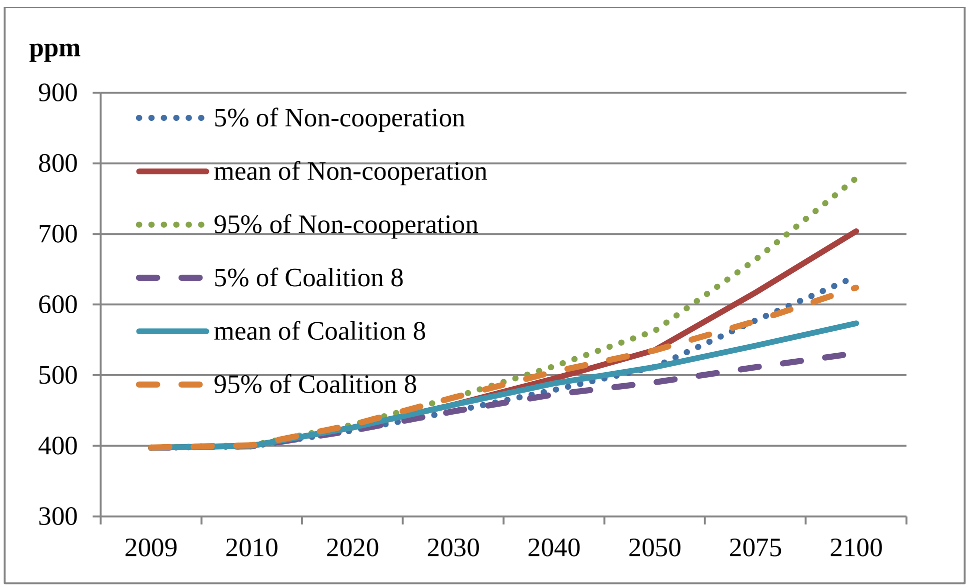

Figure B-3: CO_2 Concentration of the Coalition 8 with Non-cooperation

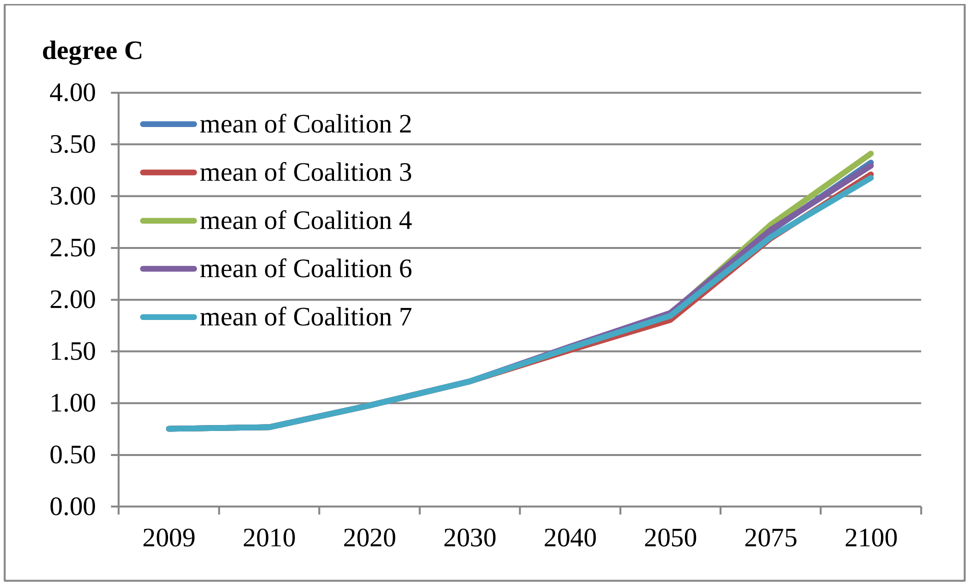

Figure B-4: Global Mean Temperature of Partial Coalitions

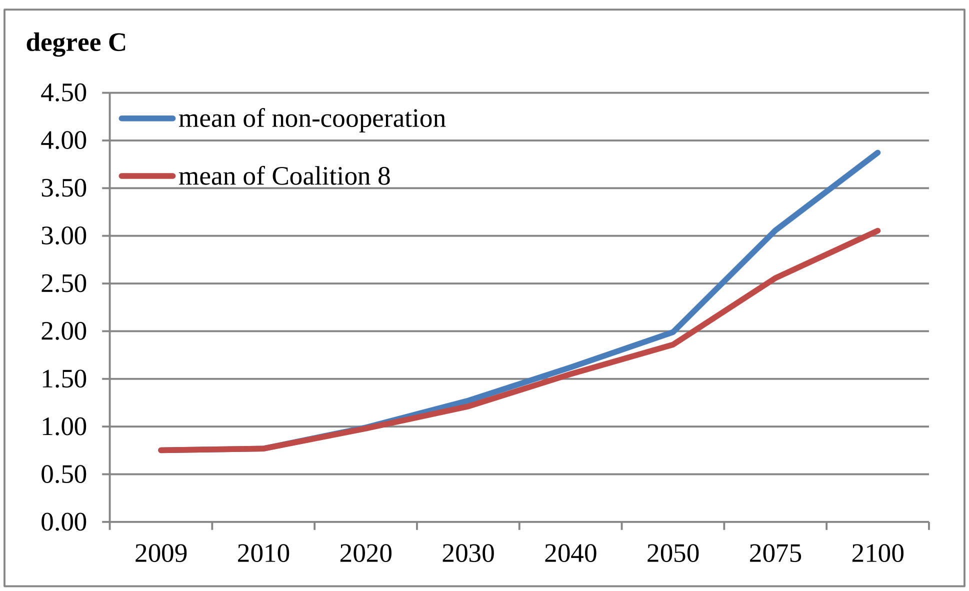

Figure B-5: Global Mean Temperature of Coalition 8 with Non-cooperation

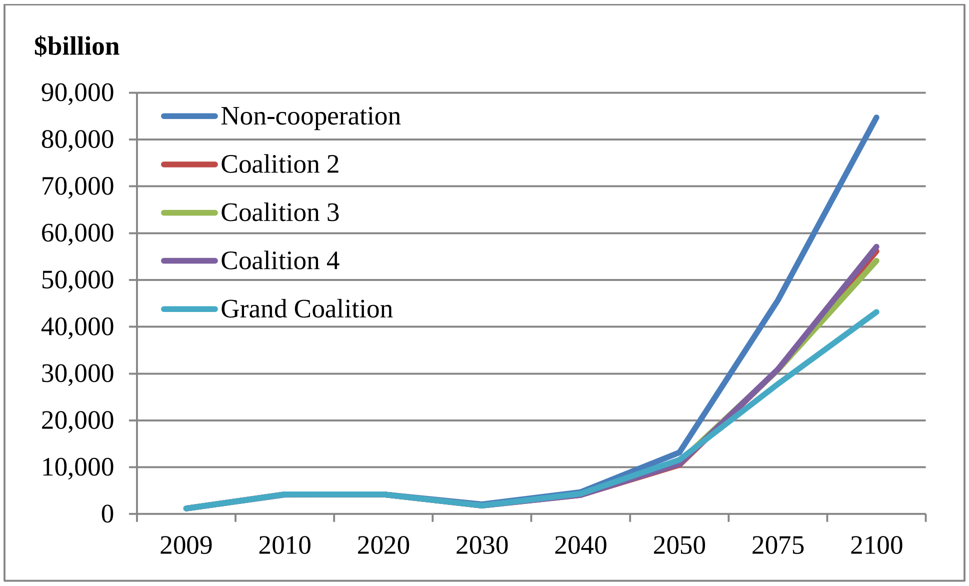

Figure B-6: Socio-Economic Impacts of Coalition 2, 3 and 4 with Non-cooperation and Grand Coalition

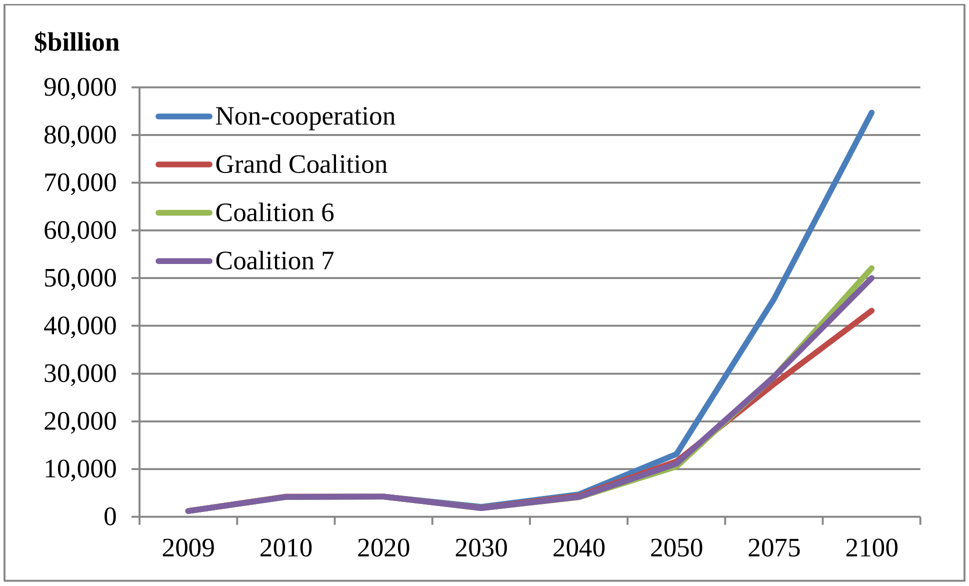

Figure B-7: Socio-Economic Impacts of Coalition 6 and 7 with Non-cooperation and Grand Coalition

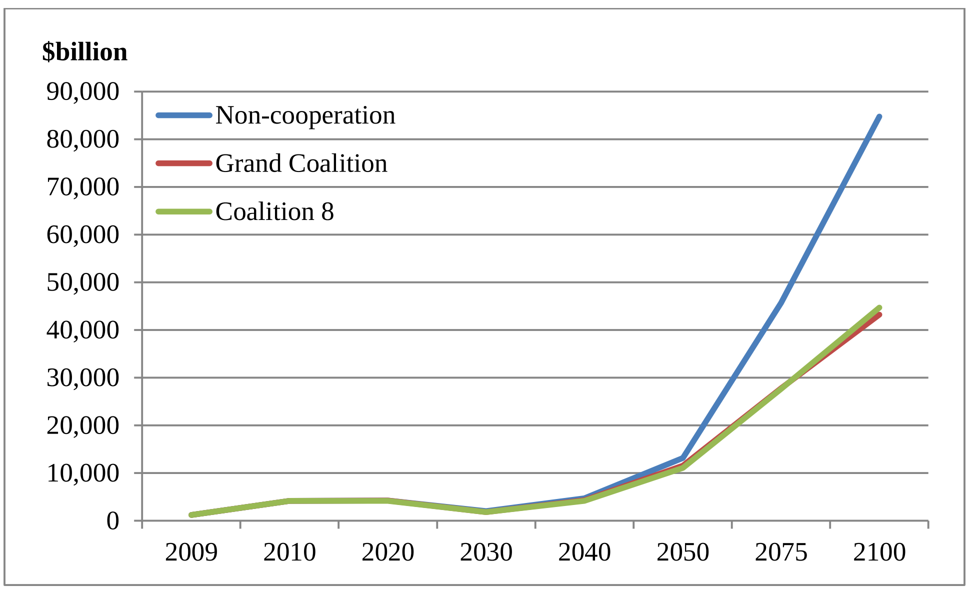

Figure B-8: Socio-Economic Impacts of Coalition 8 with Non-cooperation and Grand Coalition

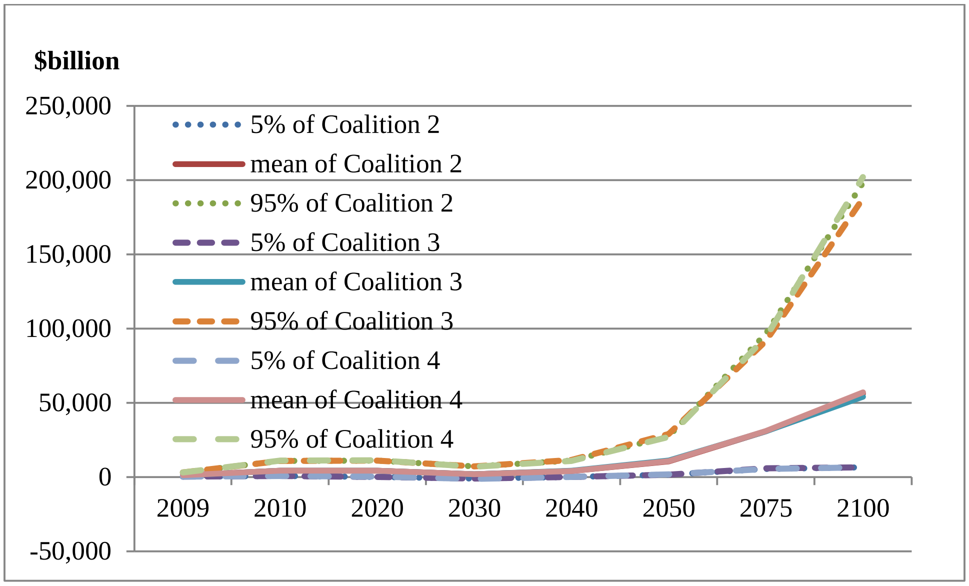

Figure B-9: Socio-Economic Impacts of Coalition 2, 3 and 4

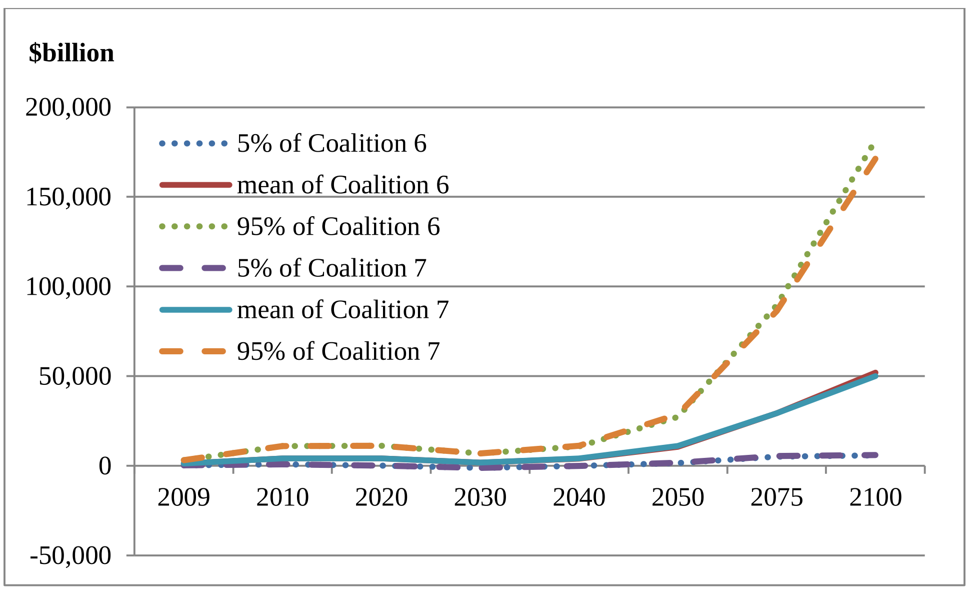

Figure B-10: Socio-Economic Impacts of Coalition 6 and 7

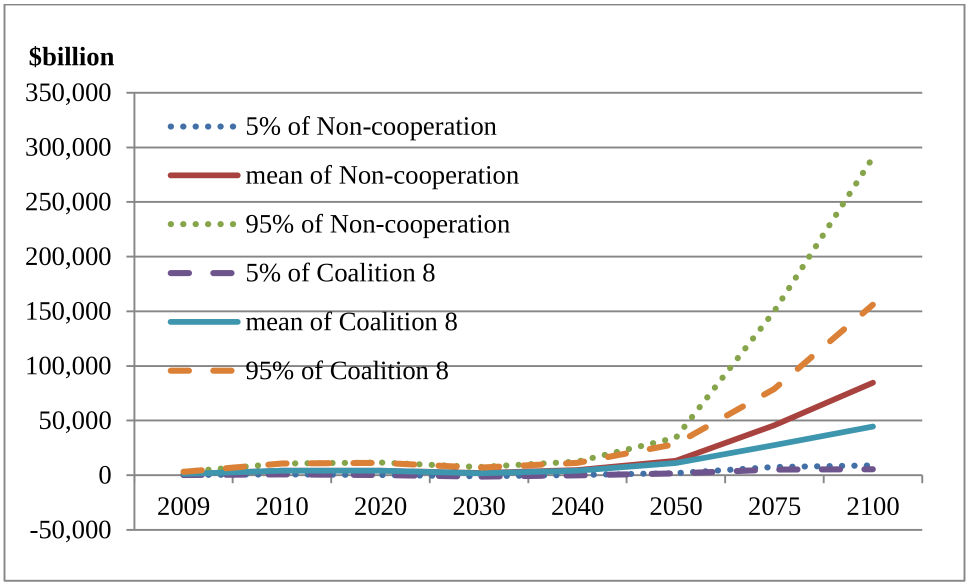

Figure B-11: Socio-Economic Impacts of Coalition 8 with Non-cooperation

Table B-1: Net Benefits of Coalitions ($billion)

	Net Benefits (with mean value)	Net Benefits (with upper level benefits)	Temperature (degree C)
Coalition 2	46,845	142,297	3.32
Coalition 3	41,502	146,017	3.21
Coalition 4	46,507	141,583	3.41
Coalition 6	52,406	164,734	3.29
Coalition 7	47,232	169,613	3.18
Coalition 8	53,734	195,016	3.05

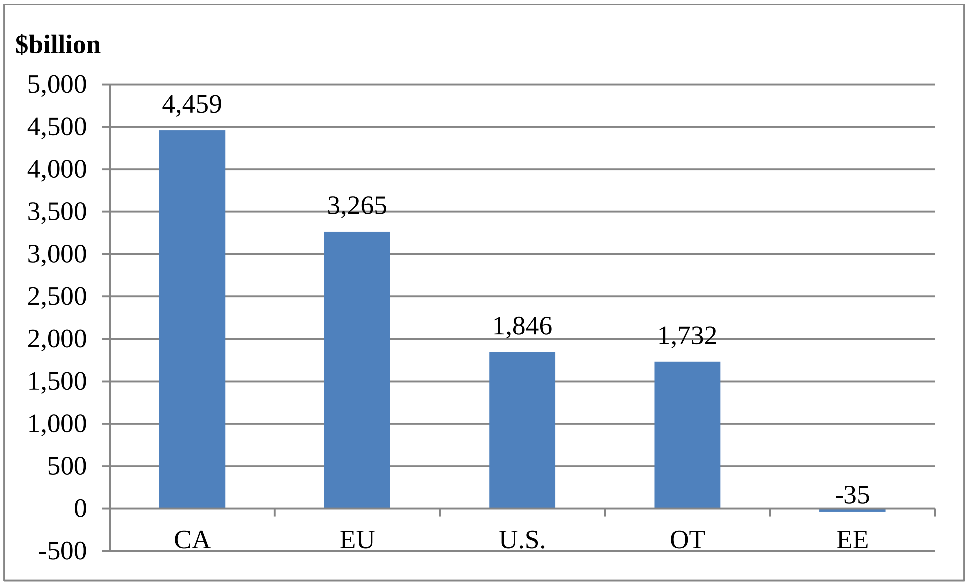

Figure B-12: Free-rider Incentives from Coalition 2 ($billion)

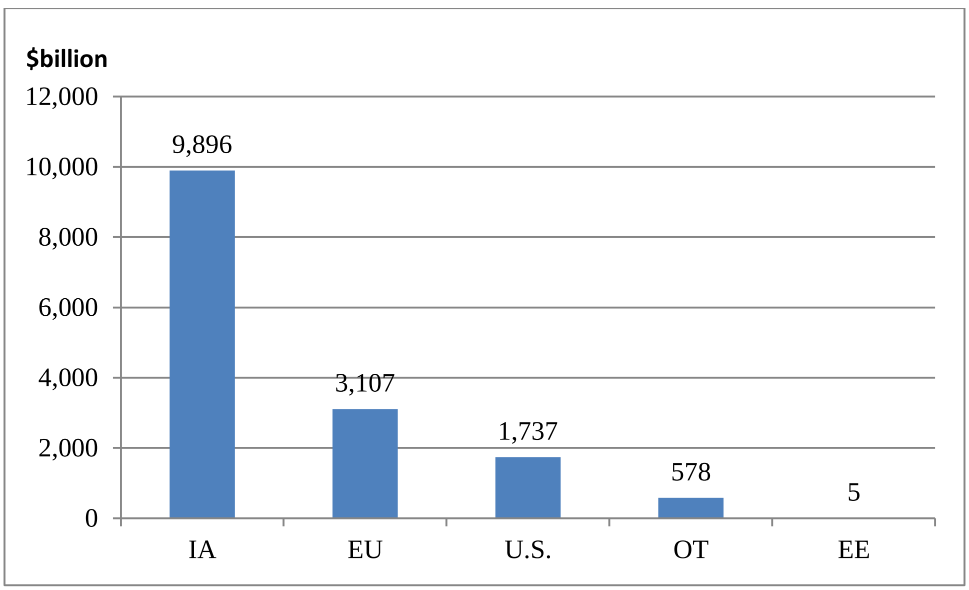

Figure B-13: Free-rider Incentives from Coalition 3 ($billion)

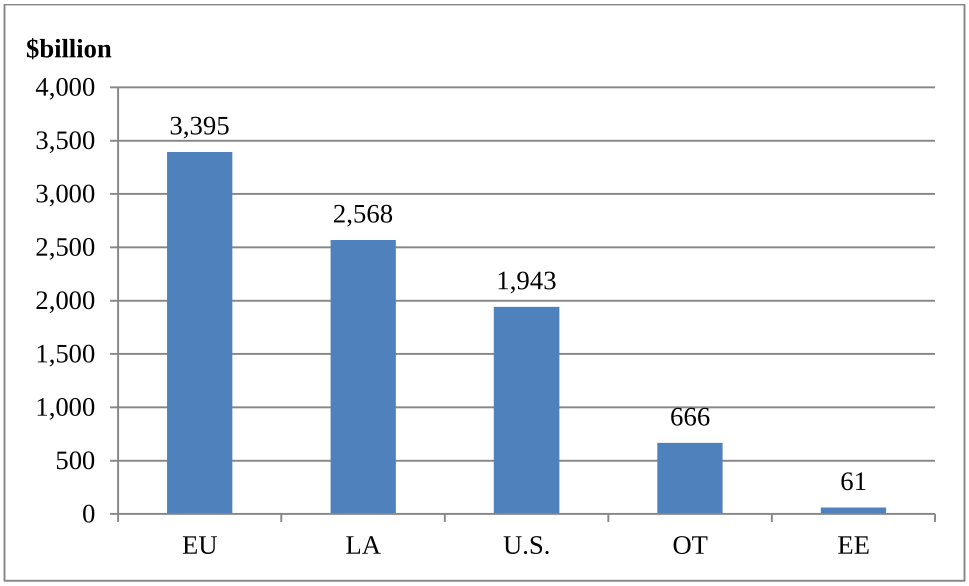

Figure B-14: Free-rider Incentives from Coalition 4 ($billion)

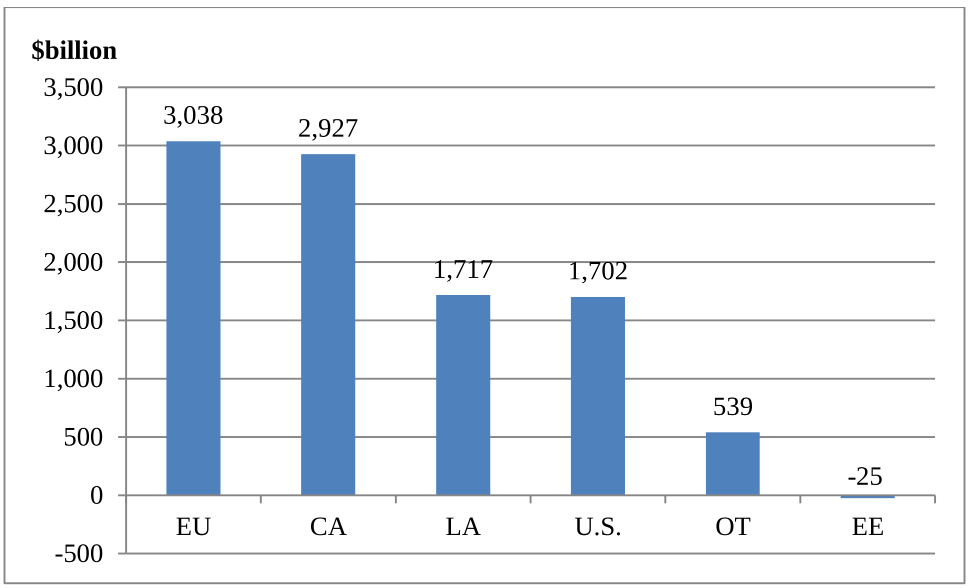

Figure B-15: Free-rider Incentives from Coalition 6 ($billion)

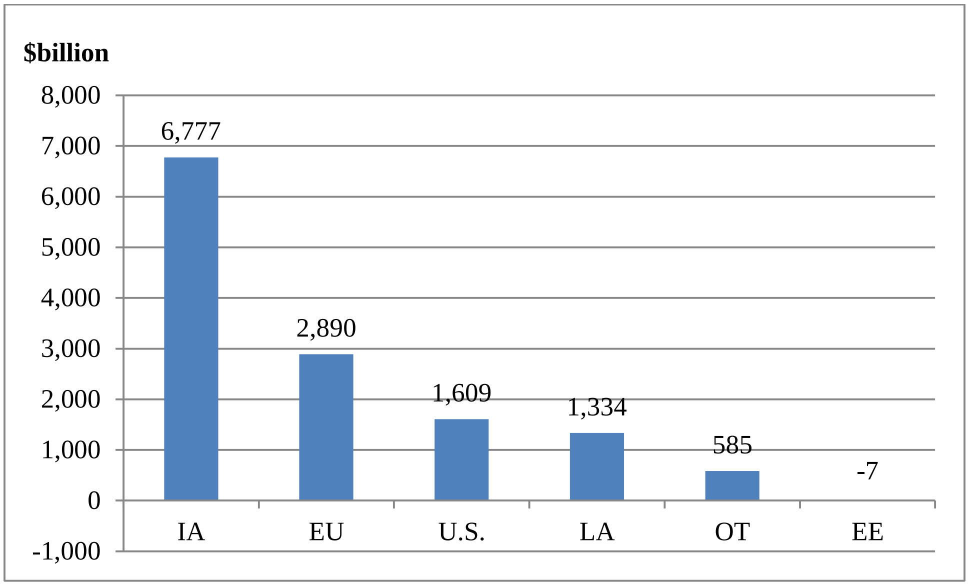

Figure B-16: Free-rider Incentives from Coalition 7 ($billion)

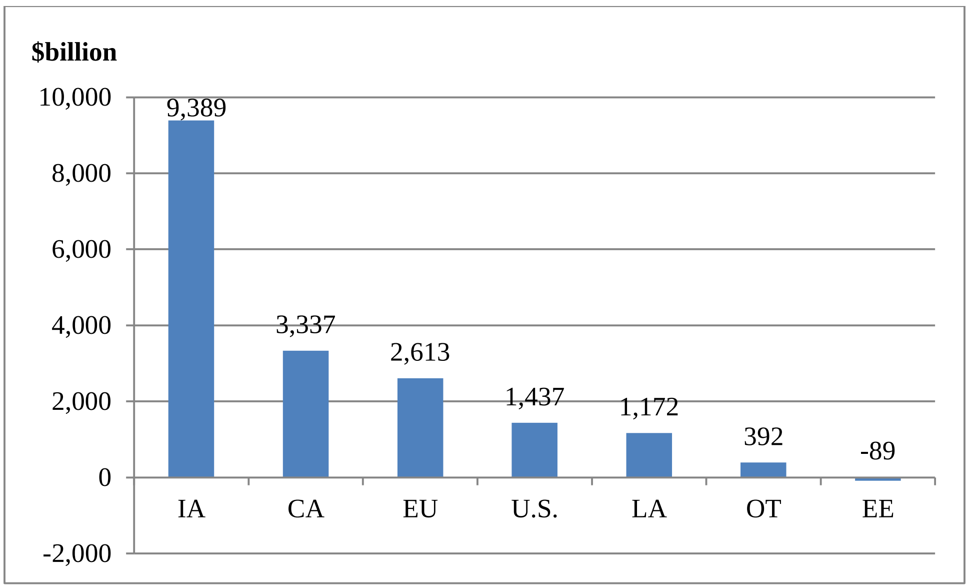

Figure B-17: Free-rider Incentives from Coalition 8 ($billion)

Appendix C

PERMISSION LETTER

Chris Hope <c.w.hope.76@cantabgold.net> 2/10/14
to me, Chris

Dear Jinmi Kim,

Thank you for your interest in my work and the PAGE model. Your work sounds fascinating.

You will need to have access to @RISK (an add-in to Excel) to run the PAGE model. If you let me know when you have this, I will arrange to send you the model, along with a brief user guide.

The model will be provided on the understanding that it will not be used or copied for any commercial activities, and that I will be informed about any research paper that is written using results from the model, and will have the option of being included as a co-author of the paper. No guarantee will be offered or implied about the accuracy of the model, and you should satisfy yourself that the default parameter values are suitable for your work.

Best wishes

Chris

Jinmi Kim <jinmi@udel.edu> 2/24/14
to Chris, Chris

Dear Professor Hope,

Thank you much for your approval to use the PAGE model. I would like to inform you that I have now @RISK installed in my pc and am looking forward to receiving the PAGE.

As you indicated, no commercial interest will be involved in the use of the model. I will certainly inform you if any research paper will be written using the results from the PAGE.

Best regards,
Jinmi

Chris Hope <chris.hope@jbs.cam.ac.uk> 2/27/14
to me, Chris

Dear Jinmi,

Here is the model and the brief user guide.

It is provided on the understanding that it will not be used or copied for any commercial activities, and that I will be informed about any research paper that is written using results from the model, and will have the option of being included as a co-author of the paper. No guarantee is offered or implied about the accuracy of the model, and you should satisfy yourself that the default parameter values are suitable for your work.

You will need @RISK from Palisade to run the model. The model is sent with 1000 runs performed, otherwise it would be too big to email. You should save the model with a different name, so that you always have this default model available. At some point you will need to use @RISK to do 10000 runs, as this is the minimum number for reasonably accurate results.

Best wishes

Chris