International trade and climate change cooperation

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International Trade and Climate Change Cooperation

by

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International trade and the environment have close interactions. The gains and losses in trade are a concern for each country when it is strategically choosing actions on climate change cooperation. However, such interactions have been relatively neglected in the literature. This thesis aims to study how an international environmental agreement (IEA) on climate change is formed in a globalized economy and how trade and trade policy affect the formation of such an IEA.

To study the role of trade in climate change cooperation, this thesis builds a “three-country, three-good” general equilibrium model in an open economy and defines an endogenous IEA formation game accordingly. It is found that the environmental policy of a large exporter is used to internalize environmental externalities, and more importantly, to deal with *leakage* problem and to manipulate *terms-of-trade* gains. Thus, countries that form a partial coalition can enjoy a larger market power and exploit more surplus in international trade. This model also predicts that there exists a small coalition paradox that prevents large welfare gains and emission reduction from full cooperation.

To investigate the possibility of trade linkage in IEA formation, a three-stage trade linkage game is defined in a partial equilibrium competing exporters trade model. Each country is empowered to agree or disagree to the introduction of trade linkage to the IEA in the first stage. It is found that trade linkage can deter free riding incentives and generate global welfare gains when climate change damage is moderate. Second, the presumption that trade linkage always induces participation in IEA is misleading. It can be ineffective when climate change damage is large or even counter-productive when climate change damage is small. Third, trade linkage cannot be introduced in the first place if the voting rule requires consensus approval, since the free rider is always weakly worse off with trade linkage, and thus against linkage. Trade linkage is only possible if a majority voting rule is applied.

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Abstract

International trade and the environment have close interactions. The gains and losses in trade are a concern for each country when it is strategically choosing actions on climate change cooperation. However, such interactions have been relatively neglected in the literature. This thesis aims to study how an international environmental agreement (IEA) on climate change is formed in a globalized economy and how trade and trade policy affect the formation of such an IEA.

To study the role of trade in climate change cooperation, this thesis builds a "three-country, three-good" general equilibrium model in an open economy and defines an endogenous IEA formation game accordingly. It is found that the environmental policy of a large exporter is used to internalize environmental externalities, and more importantly, to deal with *leakage* problem and to manipulate *terms-of-trade* gains. Thus, countries that form a partial coalition can enjoy a larger market power and exploit more surplus in international trade. This model also predicts that there exists a small coalition paradox that prevents large welfare gains and emission reduction from full cooperation.

To investigate the possibility of trade linkage in IEA formation, a three-stage trade linkage game is defined in a partial equilibrium competing exporters trade model. Each country is empowered to agree or disagree to the introduction of trade linkage to the IEA in the first stage. It is found that trade linkage can deter free riding incentives and generate global welfare gains when climate change damage is moderate. Second, the presumption that trade linkage always induces participation in IEA is misleading. It can be ineffective when climate change damage is large or even counter-productive when climate change damage is small. Third, trade linkage

cannot be introduced in the first place if the voting rule requires consensus approval, since the free rider is always weakly worse off with trade linkage, and thus against linkage. Trade linkage is only possible if a majority voting rule is applied.

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Chapter 1

Introduction

1.1 Background and Motivation

Climate change is one of the most pressing issues, which demands an urgent global response (Stern et al., 2006). As is scientifically supported, the climate is rapidly changing, predominantly caused by the human-induced greenhouse gas emissions such as carbon dioxide (Pachauri and Reisinger, 2007). Scientific research projects that carbon dioxide emissions would at least double the pre-industrial level by 2050, and consequently, the global temperature will rise by $2-5°C$ or even higher (Pachauri and Reisinger, 2007). This ongoing impact is expected to cause irreversible and devastating damages, such as sea level rise, the extinction of species, etc. Inevitably, these threats will imperil the basic elements of life for people and also cause huge economic loss.

Mitigating climate change is regarded as urgent. A broad consensus has been reached that, to avoid such devastating damage, the increase of global mean temperature must stay below $2°C$ relative to the pre-industrial level. However, given the fact that two-thirds of the carbon emission quota consistent with the $2°C$-goal has already been consumed, the total quota will likely be exhausted within 30 years at present rate (Friedlingstein et al., 2014). Thus, immediate and significantly strong action needs to be taken at the global level to deal with climate change.

However, it is difficult for such an absolute emission reduction at a global level due to the distinctive characteristics of climate change from other existing environmental problems. In theory, any environmental problem, including climate change, is essentially an externality issue that generates market failures. Usually, policy interventions from the government are expected to correct these externalities. However, climate change is a global externality problem in terms of its cause and consequences that cannot be tackled by one single country. Emissions from any country equally contribute to climate change, and every country with no exceptions is harmed by climate change. Unfortunately, there is no super-national authority that can force any sovereign nation to internalize the externalities. Thus standard approaches to tackle externality issues don't work for climate change. In this case, self-motivated and proactive international cooperation on climate change is critical, even though such cooperation is difficult to reach.

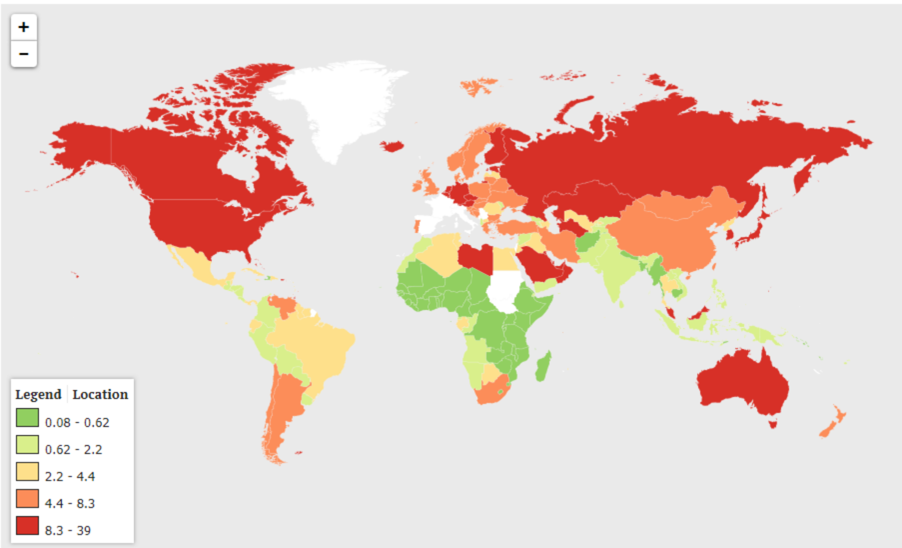

Figure 1.1: Carbon Emission per Capita by Country in 2016

[1]Source: https://knoema.com/atlas/maps/CO_2-emissions-per-capita

Moreover, the non-excludable nature of carbon emissions, which is a public good (bad), amplifies the difficulty in climate change cooperation. Countries have strong free-riding incentives to not participate in international cooperation in mitigation, but to enjoy the benefits contributed by others. Furthermore, the free-riding incentives are enhanced by the heterogeneity of sovereign countries. Countries that are most vulnerable to climate change are the poorest countries, even though they contribute the least to climate change. By contrast, large emitters, such as USA, EU, Russia and China, are more capable of responding to climate change.[2] What's worse, as we are fast approaching the temperature limit, the mitigating cost has been increasing significantly, making free-riding even more attractive. In addition to the above reasons, the uncertainty of climate change, the issue of inter-generational equity, etc. all together make the future of tackling climate change very difficult.

The close interactions between international trade and the environment compound this challenge. For small economics, international trade may strengthen their free-riding incentives, from which they obtain a two-fold advantage. In addition to the benefits from the environmental side, those non-participating nations also benefit from a rise in comparative advantage in carbon-intensive industries, at least at the margin, due to the *pollution haven effect*.[3] Put differently, the participating countries internalize the global externality of climate change to a larger extent, leading to a more stringent pollution policy within those countries. Consequently, such stringent pollution policy tends to erode those countries' comparative advantage in pollution-intensive goods if all the other factors stay the same. That being so, those small economies are reluctant to unilaterally strengthen their national environmental policy and enter into a *race to the bottom* game. On the other hand, large economies might seek *terms-of-trade* gain by manipulating their environmental policies due to the unavailability of trade policies under the current WTO framework. In this sense, large economies might be able to enjoy a larger market power in the international market by being a member of a climate change mitigation coalition, which makes participation attractive. This imperfect substitution between environmental and trade policies plays a role in climate change cooperation. Thus, it is crucial to study this topic in the context of international trade, to fully analyse the gains and losses from cooperation on climate change. However, such critical aspects have been barely investigated in the existing literature.

[2]Figure 1.1 shows the carbon emission per capita by country in 2016. As we can see, developed countries such as USA, Russia, Canada and Australia are on the top list of emission per capita, while most Asian and African developing countries have much lower carbon emission per capita.

[3]The pollution haven effect refers to the case where a particular country tightens its environmental regulation, which in turn declines its net exports of pollution-intensive goods/investment flows and shifts pollution-intensive production out to less stringent countries/regions. Chapter 2 gives it an in-depth review.

Collective welfare can be increased if all countries cooperate to fully internalize the global environmental externalities by forming an effective international environmental agreement (hereafter IEA). Therefore, a vast literature in climate change cooperation has investigated the formation of such an IEA (Barrett, 1994a; Rubio and Ulph, 2006; Finus and Rübbelke, 2013; Eichner and Pethig, 2013, etc.). However, the existing literature mainly models the gains and losses from participation in such IEAs as a simple concave function of emission reduction and overlooks the role of international trade in climate change cooperation (Eichner and Pethig, 2013, is an exception). The absence of international trade in the theoretical studies of IEA formation might lead to biased results. Although several studies (Limão, 2005; Ederington, 2002, 2001a) have considered the use of trade policy to enhance the enforcement power of IEAs, the IEA is usually assumed to be exogenously existed in those studies, thus the effects of trade on the endogenous formations of IEAs can't be captured. In this context, there is a need to study the endogenous formation of IEAs with international trade and, more importantly, to study how trade affects the formation of IEAs.

Due to the nature of a public good, the existing literature shows that there is a *Small Coalition Paradox* in IEAs (termed by William Nordhaus), which means that large welfare gains from IEAs are prevented because either only very few countries participate in IEAs or the welfare gain between non-cooperation and full-cooperation is really small. Thus, the central question is still to design a mechanism that can overcome free-riding problems. Among all options, issue linkage has been considered as a promising strategy for such an aim. The basic idea of issue linkage is to link a public good, which suffers severely from free riding problems to a club good, where the benefits from cooperation are exclusive to coalition members (Carraro, 1997). Given the interactions between trade and climate change, it is natural to propose a trade linkage for climate change issues. Indeed, if the benefit from free riding is partially offset by a loss from international trade, free riders then have to weigh the gains from environment and loss from international trade.

Obviously, the idea of linking climate change cooperation with another issue is not confined to international trade. For instance, there is also literature about R&D

(research and development) cooperation in climate change (Carraro et al., 1995; Kemfert, 2004). However, linking climate change cooperation to international trade might be one of the most influential and effective methods. First, the welfare gain from trade has become a common understanding for all countries, especially for the developing countries. Unsurprisingly, a trade-related "punishment" to all exported commodities of free riders impose a high cost on them. Therefore, this linkage is expected to be effective in terms of deterring free riding incentives. Second, the punishment in trade linkage benefits senders and harms receivers. Thus, senders have incentives to impose this punishment. Third, trade policy and environmental policy can work as imperfect substitutes when the first best policy is unavailable. Increasing concerns arise that environmental policy may be used as a *loophole* in trade agreements. This linkage can help to close such *loophole*. Nevertheless, trade linkage in climate change cooperation is considerably less explored and developed. Given the complexity in the interactions in both policy sets, attention is required to address the core questions such as how trade linkage works to deter free riding incentives, under what condition trade linkage works and whether trade linkage is favoured by all countries, etc.

To sum up, international trade and climate change cooperation have close interactions. However, the previous emphasis has long been placed on the stability and the size of IEAs in the absence of international trade. These studies overlook the role that trade plays in IEA formation, and so might be biased and misleading. To fill this research gap, a holistic and in-depth study on trade and climate change cooperation is further required from three major perspectives. First, a comprehensive literature review is needed to clarify the complex relationships between trade and climate change cooperation and to bring directions for further studies. Second, climate change cooperation should be explored within economic models that depict the economic structure with the presence of international trade, rather than based on stylized cost and benefit functions of carbon reduction. Finally, it is of great importance to investigate how trade policy can be used to foster climate change cooperation to tackle today's severe climate change problem.

1.2 Objectives

This thesis mainly aims to provide a comprehensive and in-depth analysis to address core research questions: how IEAs are formed in a globalized economy, what role that international trade plays in global climate change cooperation and how trade policy can be used to facilitate climate change cooperation? In order to answer these questions, the main objectives of this thesis are three-fold, to:

- Conduct a comprehensive and in-depth literature review regarding the interactions between trade and the environment, the state-of-art in IEA formation, and trade linkage in IEAs.
- Develop a novel modelling framework that motivates IEA formation with the presence of international trade and apply such framework to predict the types of coalitions that are likely to be observed.
- Construct a theoretical model to analytically show how international trade affects climate change cooperation, to show how trade policy can be used to induce wider cooperation on climate change, and to explore the feasibility of such policy linkage.

In pursuit of the second objective, Chapter 3 builds a "three-country, three-good" general equilibrium model in an open economy and defines an endogenous IEA formation game accordingly. Herein, greenhouse gas emission is considered as a by-product of production from each country. As a pure "public bad", emissions from any country equally harm the welfare of all three countries. Each benevolent government maximizes its total welfare by determining a production level. The gains and losses in trade are taken into consideration for each country when it is strategically choosing environmental policies. Moreover, the formation of IEAs is modelled endogenously as a two-stage game. By applying Nash equilibrium and strong Nash equilibrium coalition conditions, this model is capable of predicting the stable coalition in equilibrium that is immune to both unilateral and group deviations.

In pursuit of the third objective, a competing exporters trade model (Bagwell and Staiger, 1997) with global production externality is developed to analytically show how trade affects IEA formation and to investigate the possibility of inducing wider participation in IEAs through trade linkage. This model has several unique features. First, trade linkage is defined as adding a clause to the existing trade agreement, which states that the benefit of the trade agreement (i.e. free trade) is contingent on the participation in IEAs. Second, trade linkage is modelled endogenously as a three-stage game where existing members of trade agreement are empowered to agree or disagree to the introduction of linkage. Third, the feasibility of trade linkage is then explored by contrasting the welfare of each country under a stable coalition with and without linkage. Thus, this analytical model can explicitly show how trade-related aims affect the environmental policies, and how trade linkage could sustain wider participation in IEAs.

1.3 Outline

This thesis consists of six chapters with the structures as follows.

Chapter 2 provides an in-depth overview of the literature. It starts with a comprehensive review of the interactions between trade and the environment. Then the existing literature on the formation of IEAs is also reviewed together with a discussion about the possible improvements in this field. Finally, a general review about issue linkage, particularly in trade and the environment, is conducted. The main purpose of Chapter 2 is to clarify the complex relationships between trade and climate change cooperation and to establish directions for further research.

Chapter 3 aims to set out the basic framework to incorporate trade into IEA formation study. For this purpose, this chapter firstly develops a general equilibrium model with global production externality in an open economy, and then the IEA formation game is defined endogenously. Furthermore, the corresponding simulation results predict the types of IEA that are likely to be observed as the climate change damage levels vary.

Based on the framework introduced in Chapter 3, Chapter 4 firstly contributes to analytically show how trade affects the formation of IEAs. It also has a closer investigation into how linking to trade policy affects the outcome of IEA formation. With a partial equilibrium model, the model is then solved analytically, which can help to provide a clear analysis regarding how trade linkage works to induce wider participation in IEAs. More importantly, the feasibility of trade linkage is also explored in this Chapter.

Chapter 5 then discusses the limitations of the thesis and suggestions for further research. The model employed in this thesis has great potential to be extended in many different directions. The possible extensions discussed in Chapter 5 can enhance its realism and at the same time, provide more policy insights to facilitate climate change cooperation.

Chapter 6 concludes the thesis.

Chapter 2

Trade and Climate Change Cooperation: A Review

2.1 Introduction

Effective international cooperation is in urgent need to tackle climate change given the frequent occurrence of extreme weather events. The Paris Agreement signed by 175 parties in 2016 can be considered as an aspirational milestone. Unfortunately, the withdrawal of USA later waters this achievement down. This action leads to the following critical question: how to effectively facilitate self-motivated international cooperation to tackle climate change?

A vast literature has long emphasized the formation of an international environment agreement (IEA) about climate change, with main focus on the size of such a stable IEA. This branch of study is being rapidly developed to richer frameworks (e.g., modelling in a dynamic game with foresighted stability). However, the role that international trade plays in climate change cooperation has been neglected in most studies. Meanwhile, a substantial literature has studied the close interactions between trade and the environment. This review contributes to the literature by providing a unique perspective on trade and the environment in the context of climate change cooperation. More specifically, it explores the following questions: how does trade play a role in the formation of an IEA? And, how can trade policy be used to facilitate climate change cooperation? This review will bridge the IEA formation literature and the trade and environment literature, and more importantly, will open new doors for future efforts in both fields.

First, I review the interactions between trade and the environment in Section 2.2, which sets out the main context for this research.[1] These interactions can be sorted in the following aspects: how does the national environmental regulation impact the comparative advantage and trade patterns in international market?[2] In a globalized economy, does trade liberalization contribute to environment degradation? How do trade policy and environmental policy interact with each other?

The focus then is switched to literature on IEA formation in Section 2.3, with particular attention on works by Eichner and Pethig (Eichner and Pethig, 2013, 2015b,c; Eichner et al., 2018), who model IEA formation in the presence of trade. Most of the literature reviewed in this section is theoretical since the empirical research in climate change cooperation is considerably limited. Climate change is an issue on which practice is ahead of theory while empirical studies are far behind. Thus, empirical studies based on theories are in urgent need for policy makers, which this thesis addresses in Chapter 5.

Since trade affects climate change cooperation, it is natural to ask how trade policy can be used to facilitate cooperation on climate change. Section 2.4 reviews this question from a broader perspective including enforcement linkage, negotiation linkage and participation linkage rather than only focusing on participation linkage in IEA formation. Such an overall review is essential to distinguish the differences between these three linkages and to guide how trade policy can be used for different purposes.

[1] Please note that this section does not aim to exhaust all studies which focus on trade and the environment. See Copeland and Taylor (2004) for a comprehensive review. But instead, it aims to review corresponding studies that are closely related to trade and climate change cooperation.

[2] Since this thesis aims to explore the strategic interactions between countries, this review does not cover those recent studies which examine the adjustment on the firm-level to trade liberalization. One related review on this direction can be found in Cherniwchan et al. (2017).

2.2 Trade and the Environment

2.2.1 Environmental Stringency and Trade Patterns

Literature regarding how environmental policies affect international trade can be traced back to early 1970s when the OECD countries enacted the first environmental protection policy *Polluter Pays Principle*. With this policy in a globalized economy, concerns have been raised on whether such a principle would lead to a relocation of pollution-intensive industries from OECD countries to unregulated countries/regions. In this context, the *pollution haven hypothesis* has become a most far-reaching theory to bring trade and environmental issues together. However, this hypothesis has been widely applied with various corresponding explanations. For clarification, similar to (and as recommended by) Copeland and Taylor (2004), I will use *pollution haven effect* to specifically refer to the case where a particular country tightens its environmental regulation, which in turn reduces its net exports of pollution-intensive goods/investment flows and shifts pollution-intensive production out to less stringent countries/regions. Put differently, a *pollution haven effect* indicates that tightening up the environmental policy in a particular country, at least at the margin, leads to a loss in its competitiveness in the international market.

The empirical research on the *pollution haven effect* came in two waves in earlier 1990s and the 2000s. In earlier 1990s, those studies regressed the cross-sectional trade/investment flow data on the country/industry-specific measures of environmental stringency and other related variables (e.g., factor endowment). Most of them reached the conclusion that environmental stringency would have very little or no effect on trade patterns/investment flows. Among these pioneering studies, Tobey (1990) was one of the most important studies to conclude that there is no statistically significant evidence supporting the *pollution haven effect*. However, Copeland and Taylor (2004) argued that the result from Tobey (1990) might be misleading since most of the resource endowment coefficients in his model were also insignificant. Unlike Tobey (1990) who used country-specific data, Kalt (1985) and Grossman and Krueger (1991) linked trade flows to the industry-specific characteristics and pollution abatement costs for manufacturers in the US. Counterintuitively, they both found that pollution abatement cost could not explain trade patterns, and, in some cases, it was even positively related to the net exports. Some other literature utilized the plant locations or investment flows rather than net exports for a measurement of competitiveness. They obtained a similar conclusion that again denies the *pollution haven effect*.[3] One possible reason for such a counterintuitive result is that the environmental cost only takes a small fraction of total cost, thus can't impact trade patterns substantially. These unexpected results also booted the *porter hypothesis* (Porter and Van der Linde, 1995), which states that stringent environmental regulation would bring technology innovation, and thus raise exports or lower imports. But there is not enough evidence, either theoretical or empirical, to support the *porter hypothesis* (Copeland and Taylor, 2004).

However, Copeland and Taylor (2004) argued that the true underlying reasons about the counter-intuitive results of these studies are the endogeneity and omitted variables in the above literature. If environmental regulation is endogenous, then the absence of any variables (e.g., industry size, transport cost), which could cause simultaneous changes in pollution abatement cost and net imports to the same direction, would bring on a positive relationship between these two that is against the *pollution haven effect*. In addition, political purpose or strategic substitution between trade and environmental policies are all possible reasons.

The second wave of studies in environmental stringency and trade reveals ample evidence that supports the *pollution haven effect*. Ederington and Minier (2003) explained that the previous results might be biased because they ignored the possibility that trade might affect environmental policy. The authors solved this endogeneity issue by determining the net imports and environmental policy simultaneously. The results are striking that import penetration was raised by 30 percent by a 1-percent increase in pollution-abatement cost. By contrast, this effect is only 0.53 percent in import penetration in the fixed-effects implementation. A similar study is Levinson and Taylor (2008). Based on data from 1977 to 1986 regarding the U.S. imports of 132 sectors of manufacturing from Canada and Mexico, they found that when they instrumented for the pollution abatement cost, a much larger impact was found than

[3] See Jaffe et al. (1995) for a review.

that obtained in fixed-effects estimation: with instrument, 1% increase in pollution abatement cost raises the net imports from Mexico by 0.4% and those from Canada by 0.6%. The *pollution haven effect* is also supported by recent studies about the impact of environmental stringency on plant location (Becker and Henderson, 2000; List et al., 2003) and investment flows (Keller and Levinson, 2002) when the endogeneity issue is well considered. To sum up, the *pollution haven effect* has strong theoretical and empirical support, and can provide theoretical support for topics about *pollution haven hypothesis* and the strategic use of environmental policy for trade purpose.

2.2.2 Environmental Impact of Trade Liberalisation

The environmental consequences of trade liberalization emerged with the introduction of the NAFTA (North American Free Trade Agreement) and the negotiations in Uruguay Round of GATT (General Agreement on Tariffs and Trade). It is challenging to answer whether trade bring more environmental damage or not. Environmentalists claimed that globalization might lead to environmental degradation due to more economic activities. In contrast, the advocates of freer trade believed that international trade could stimulate economic growth, which eventually is good for the environment. Indeed, trade liberalization itself would contribute more carbon emissions due to increasing international transportation. However, the more interesting question is how trade impacts the environment via its indirect impact on production, consumption and technology. Thus, this subsection will focus on the theoretical and empirical research on the latter indirect impact.

The first strand of literature constructs theoretical models to address the above question. Based on comparative advantage theory, some early contributions (Pethig, 1976; Siebert, 1977; Asako, 1979) predicted that countries which specialize in clean goods would be better off in terms of environmental quality as well as welfare. By contrast, the other party which specializes in dirty goods might be worse off since the gains from trade are partly offset by the loss in the environmental quality. These studies assumed that the only difference across countries which induces international trade is the environmental policy. Notably, such a policy was exogenously given in the above studies. Thus, a more compelling method should be to permit the environmental policy to be endogenous, as these policies are responsive to trade liberalization, especially in the long run.

To address such issue, various studies have been performed. Based on Grossman and Krueger (1991)'s informal discussion about the effect of trade liberalization on the environment through the *scale, technology* and *composition effect*, Copeland and Taylor (1994) formalized the decomposition of these three effects using a static North-South general equilibrium model. In their model, the differences in environmental policy, which further determines trade patterns, were induced by the differences in income level across countries. Therein, the *scale effect* states that trade liberalization would increase pollution, holding technology and composition constant, due to the fact that freer trade will stimulate the scale of economic activities. The *technology effect* reflects a decrease in pollution since cleaner technology might be adopted if trade is freer. The intuition is that if environmental quality is a normal good, a higher trade-induced income will raise the awareness of environmental protection and the standards of the environment, which further calls for greener technology. This *technology effect* is closely related to the environmental Kuznets curv introduced in the seminal work of Grossman and Krueger (1991). The environmental Kuznets curve states that pollution rises as income increases but would eventually fall as countries get richer. However, Copeland and Taylor (2004) argued that there is no such simple relationship between income and pollution; instead, the relationship should depend on the source of income growth. The *composition effect* measures how the change of composition of goods produced in a country affects pollution level when freer trade is introduced. Most of the time, the *composition effect* dominates the other two effects in those theoretical models.

Combining these effects, Copeland and Taylor (1994) found that the North would implement a more stringent environmental policy and specialize in clean goods. Therefore, trade liberalization would lead to a decrease in the pollution in the North. In contrast, the South would adopt a weaker environmental policy and specialize in dirty production, thus, would generate higher pollutants. As a result, the total world pollution would also increase if free trade couldn't equalize factor prices. As Copeland and Taylor (1994) assumed that the pollution is purely local, they further extended the above model to a trans-boundary pollution in Copeland and Taylor (1995). They generalised the model to a large number of countries that are only different in the endowment of effective labour. Each country maximizes its national welfare non-cooperatively. The same results about pollution levels as in Copeland and Taylor (1994) were obtained if factor prices were not equalized. If factor prices were equalized, the North would always be worse off with free trade than in autarky while the South would gain from freer trade. Other similar contributions can be found in Copeland and Taylor (1997b), Copeland and Taylor (1999), Antweiler et al. (2001).

Even though *scale effect* and *technology effect* are also channels of trade liberalization effect, any economic development that raises income, will further result in these two effects. Clearly, what matters most is how trade induces a country to specialize in clean or dirty production. Herein, I will emphasize the *composition effect* that is mostly motivated by the *pollution haven hypothesis*. This hypothesis predicts that countries which have weaker environmental policy will specialize in the production of dirty goods when trade is liberalized. Pethig (1976)'s assumption about the only difference in the exogenous environmental policy across countries immediately led to the *pollution haven hypothesis*. The intuition is as follows. A country with weaker environmental policy (usually the low-income country) produces relatively more pollution-intensive good, lowering its autarky price. When it opens to trade, these low-income countries export dirty goods while the richer countries import these. Then trade induces a specialization of dirty production in low-income country, which makes them the haven for pollution. Copeland and Taylor (1994) endogenized the environmental policy, which means that environmental policy will respond to the trade-induced income change. As discussed above, they found that low-income countries implement weaker environmental policy, thus again becoming the haven for pollution. A detailed discussion about *pollution haven hypothesis* can be found in Taylor (2004).

A major weakness of the above-mentioned theoretical models is that the differences in policy is the only driving force for trade. As Cherniwchan et al. (2017)

argued, one necessary condition for the *pollution haven hypothesis* to hold is that these environmental policy differences should lead to large differences in production cost, thus, affect trade patterns. However, the production cost or comparative advantage actually depends on various factors (e.g., factor endowment, technology difference) in addition to environmental policy. If the *pollution haven effect* is not strong enough to dominate the other traditional factors that affect trade, the *pollution haven hypothesis* may fail. This is very likely to happen in reality. Rich countries are usually capital abundant and at the same time, have strict environmental standards. If the dirty goods are capital-intensive, the North tends to be an exporter of dirty goods due to its abundance in capital while its stringency in environmental policy makes it an importer of the dirty goods. Therefore, the pattern of trade really depends on which force dominates, as has been explored by Copeland and Taylor (1997a), Antweiler et al. (2001), and Copeland and Taylor (2013). If the factor endowment/technology difference dominates, dirty production will expand in the North and contract in the South, which would sharply contradict the conclusions under the *pollution haven hypothesis*.

Furthermore, the empirical evidence about the *pollution haven hypothesis* has also been widely explored. Early contributions (Ratnayake, 1998; Lucas et al., 1992; Birdsall and Wheeler, 1993) found empirical evidence of a decrease in dirty exports from richer countries, but a rise from the less-developed countries. It seems that those results support the *pollution haven hypothesis*. However, as discussed above, this composition shift is not necessarily induced by differences in environmental policy across countries, but also probably by differences in other factors, for example, the change in capital-abundance over time. Antweiler et al. (2001) examined the main driving force for the *composition effect*. The empirical results indicated that both the factor endowment and the *pollution haven hypothesis* tend to affect the *composition effect*, but in an opposite direction, which further explains why *composition effect* was estimated to be small in most studies (Levinson, 2009; Grether et al., 2009; Shapiro and Walker, 2015). Cole and Elliott (2003) adopted a similar framework but focused on pollution emission rather than pollution concentration as in Antweiler et al. (2001). Similar conclusions were drawn. In addition to the *pollution haven hypothesis* empirical studies, there is also a strand of literature that directly estimated the effects of trade liberalization on environmental quality. Whereas the *composition effect* dominates the other two effects in theoretical models, empirical studies (Antweiler et al., 2001; Levinson, 2009; Grether et al., 2009; Shapiro and Walker, 2015) found that the *composition effect* is surprisingly very small compared to the *technology effect*. The detailed discussion about those empirical studies can be found in Cherniwchan et al. (2017). The conclusion that the *composition effect* is small further makes the *pollution haven hypothesis* lame.

To sum up, international trade does affect the environment via a *scale, technology* and *composition effect*. The *scale effect* contributes to a higher pollution while the *technology effect* lowers the pollution due to income-induced technology innovation. How the *composition effect* affects a country depends on its other characteristics. However, the theoretical and empirical evidence both indicates that the differences in environmental stringency across countries are not strong enough to result in a *pollution haven hypothesis*.

2.2.3 Trade and Environment Policy Interactions

The existence of the *pollution haven effect* raises the concern of *race to the bottom*, which indicates that governments might have incentives to weaken environmental regulation to protect domestic firms from foreign competition when trade policy is unavailable due to some trade agreements. In this context, some economists have expressed the concerns that the use of environmental policy as a substitute for trade policy might lead to disguised protectionism. Consequently, the debate about whether those national environmental policies should be included in trade agreement has also gained a lot of academic attention in the past few years. Likewise, trade policy might also be used to achieve environmental objectives, especially when one country wants to reduce the pollution in another country in the presence of a global externality problem (e.g., climate change). This subsection reviews studies regarding these related topics.

To begin with, I will look at the use of trade policy as a second-best instrument for environmental purposes. This is more likely to happen in the context of a global externality problem, where the environmental externality in Foreign negatively impacts Home as well. If there exists an IEA, Foreign would like to internalize such an externality on Home in exchange for a transfer from Home or same effort of pollution reduction from Home. However, with the absence of such an IEA, Foreign does not take its production externality on Home into consideration, so that Home has incentives to partly offset this effect by using its tariff. In the seminal paper of Markusen (1975b), a two country trading model was developed to study the optimal tax structures implemented by a welfare-maximizer government with the presence of a global production-generated externality. The results indicated that if there is no instrument-constraint, production tax could fully internalize the domestic externality while tariff targets *terms-of-trade* gain, and at the same time, it also aims to partly internalize the foreign externality on Home country. Home may use its tariff to lower the world price of the dirty good, which reduces the production as well as the pollution of the Foreign exporter. Such implementation of tariff or other policies that aim to indirectly reduce the pollution in Foreign country can be considered as a *leakage effect*, which is also graphically explored by Baumol et al. (1988). Meanwhile, Copeland (1996) considered another policy instrument, a pollution content tariff, used by Home to affect Foreign's pollution for the same aim.

However, the use of Home's trade policy as a substitute for Foreign's environmental policy is not optimal from a global perspective. Theoretically speaking, the first-best policy to fully internalize a global externality is a Pigouvian tax, which equals global marginal damage, in the pollution-generating country. However, the nature of a global public good creates free riding incentives, impeding the implementation of such an ideal "Pigouvian tax". Thus, the use of trade policy as a substitute for environmental policy, even though it is not efficient, could offer one possibility to promote international environmental cooperation by linking to trade policy, which has not been well studied.

Now I turn to the use of environmental policy for trade purposes. As discussed in Copeland and Taylor (2004), governments have different motivates for protection: (1) the *terms-of-trade* motive arises when large countries can affect world price by manipulating its trade policy and further extracts gains from such manipulation in standard competitive trade models; (2) the strategic motive refers to the case where governments use environmental policy to give domestic firms a strategic advantage when there is market power in the firm level; (3) the political motive arises when government cares about interest groups and has the purpose of protecting those particular groups. This latter motive can exist even for small economies in competitive market. This thesis focuses on the first *terms-of-trade* motive for large economies in a competitive market. Thus, the main attention in the following review will focus on the associated literature. Theoretical and empirical models for the other two motives in climate change cooperation are barely studied, making these two motives important research directions for future work.

Without any policy constraints, trade policy is the first-best instrument to target the *terms-of-trade* while environmental externalities are fully internalized by the environmental policy. Governments have no incentives to use the second-best policy as each target is handled by the more effective first-best policy. However, participation in a trade agreement that limits the use of trade policy compels governments, which are under pressure of protection, to seek other available instruments. Environmental policy is one of these candidates. Markusen (1975b) showed that when tariffs are binding due to a trade agreement, production taxes then work to target the *terms-of-trade*, *leakage effect* and also the domestic externality. More specifically, the purpose of manipulating *terms-of-trade* contributes to a lower production tax if Home is an import-competing country. By contrast, Home may tighten the production tax to gain a monopolistic surplus if it is an exporter of the pollution-intensive products. No matter whether Home is exporting or importing, the *leakage effect* always leads to a lower production tax. Krutilla (1991) studied the optimal environmental tax when tariffs are unavailable in a large open economy. He obtained same *terms-of-trade* effect on the optimal environmental structure as in Markusen (1975b). In Ludema and Wooton (1994) with a free trade agreement between two countries, an exporter would tax its negative externality even though there is no domestic environmental damage. The purpose of such environmental tax is purely for *terms-of-trade*. Meanwhile, some researchers such as Ederington (2001b, 2002) have studied a related question about whether the exclusion of national environmental policies in trade agreements creates *loopholes*, which might undermine the effectiveness of trade agreements.

A few papers further study the optimal policy set (trade and environment) for each country under non-cooperative and cooperative behaviours. In a similar two country trading model with the presence of a production externality, Markusen (1975a) derived the necessary conditions that should be satisfied for the optimal tax structure under cooperative behaviour. He then compared these conditions with the ones in non-cooperative Cournot model. Markusen (2017) also contrasted the outcomes of non-cooperative and cooperative behaviours between two countries when there is a global pollutant. However, the process of how such a cooperative agreement can be formed is not the main focus in Markusen (1975a) and Markusen (2017).

The literature on trade and the environment emphasizes on the production side, while the consumption is usually neutralized by employing homothetic preferences towards the environmental quality. However, as shown in Markusen (2017), a lot of emissions come from consumption. In this case, it is necessary to explore the outcomes of different environmental policies when the standard assumption of homothetic preferences is relaxed. Markusen (2017) focused on the consumption side and introduced non-homothetic preferences where the income elasticity of demand for environmental quality is higher than one. He found that a poor country might be worse off if a large country abates, therefore, the free riding incentives are eliminated, which contrasts the literature sharply. While this thesis follows most literature by focusing on the production side, future work on consumption side is needed.

The above literature assumes that trade and environmental policies are the only available instruments, which is termed as *instrument constraint*. Because of this assumption, trade and environmental regulations can be worked as imperfect substitutes for each other. However, policy markers might have a portfolio of potential policy instruments at their disposal to achieve a particular aim when the first best policy is unavailable. For example, a consumption tax together with a production subsidy is equivalent to a tariff. By contrast, environmental policy is costlier and less efficient than those instruments to manipulate gains from trade.[4] But the

[4] The existence of a *pollution haven effect* proves that the stringency of environmental policy

issue with those efficient instruments is that a production subsidy or any other subsidies are disallowed by WTO rules. More importantly, they are so noticeable that the use of subsidies might cause trade disputes with other trading partners. Instead, environmental regulation is a better way for protection since information about domestic environmental damage is hard to be observed by other countries. From this perspective, there is still the possibility for governments to use environmental policy as the second-best instrument. The empirical evidence in this area is relatively scarce to guide theoretical assumptions.[5] This thesis takes the *instrument constraint* as given, and aims to shed light in policy cooperation in trade and environmental fields.

2.3 International Environmental Agreements

The non-excludable nature of a pure public good (e.g., climate change) creates strong free riding incentives regarding climate change cooperation for each country. Countries prefer to free ride through either non-participation in or non-compliance to climate change cooperation (Finus, 2003). It is of great importance to distinguish these two different free riding incentives as this review (thesis) only focuses on one of them.

Non-participation free riding incentive refers to the situation where a country has incentives to not participate in climate change cooperation, since it can enjoy same benefits from the IEA members' mitigation efforts, but with no costs on its own side. Non-compliance free riding incentive is the incentive to not comply with the agreed obligations of an existing IEA. Once the IEA is formed, a country can earn even higher benefits by free-riding on the virtuous behaviour of the remaining signatories. In an ideal situation, the two issues of participation and compliance should be studied together: an effective IEA is the one that induces wide participation and, moreover, is complied by all participants. However, in literature, these two issues

does affect trade patterns (Ederington and Minier, 2003; Levinson and Taylor, 2008, etc.), but this does not necessarily mean that governments will use environmental policy for trade purpose, especially when other more efficient instruments are available.

[5] Böhringer et al. (2014) decomposed the *terms-of-trade* and *leakage effect* for the optimal emission pricing. With their computable general equilibrium model they found that the *leakage effect* and *terms-of-trade* motivate are relatively small.

have been studied separately through membership models and compliance models (Finus, 2008). A membership model assumes that once a country agrees to join an IEA, it will comply with its obligations. The only challenge is the participation of climate change cooperation. On the contrary, a compliance model studies whether obligations can be enforced with credible threats, assuming that an IEA is already formed.

This review (also thesis) focuses on the former one for the following reasons. First, participation is the very first step of forming and sustaining an IEA. Only when non-participation free riding incentives are deterred, the task of overcoming non-compliance free riding comes to the table. Barrett and Stavins (2003) argued that if a country plans to not comply with its obligations of an IEA, there is no reason to participate in the first place.[6] Second, if countries are patient enough (they value future gain from cooperation highly), they have no incentives to deviate from an IEA. Therefore, this work only reviews literature regarding non-participation free riding incentives in the formation of an IEA, which clarifies the boundary of this research.

Since most of the literature in this field is based on Barrett's *basic model*, this section will firstly introduce the *basic model* in detail and then review various extensions based on this model. Since the main focus of this thesis is to explore the role of international trade in the formation of IEAs, my particular attention will be paid to the literature of IEAs with international trade in subsection 2.3.2.

2.3.1 The Basic Model and Other Related Literature

Among all studies, Barrett (1994a) is one of the pioneering research exploring the formation of IEAs. Barrett adopted the concept of cartel stability (d'Aspremont et al., 1983), which was further developed as *self-enforcing* to study the stability of an IEA. This research has a great influence in subsequent research in this field and is called the *basic model*. In recent years, this *basic model* has been set as a

[6] This does not imply that once a country participates in an IEA, there will be no problems with the compliance of its obligations. Non-compliance free riding incentive is also a big obstacle for climate change cooperation, but it is not the main interest of this thesis.

foundation for the other models to capture many important features in the IEA formation. Hence, it is useful to review the *basic model*.

In the *basic model*, there are N identical countries each with the following benefit and cost functions

$$B_i(Q) = b(aQ - Q^2/2)/N \tag{2.3.1}$$
$$C_i(q_i) = cq_i^2/2 \tag{2.3.2}$$

where a, b and c are positive parameters. Q is global abatement whereas q_i is country i's abatement.

As is evident, the benefit from each unit of abatement is equally enjoyed across all countries, which exhibits the non-excludable nature of a global public good. By contrast, the cost for each individual county only depends on its own abatement level. Consequently, each country has incentives to free ride on the climate mitigation achievements contributed by other countries. Under non-cooperation, each country works in a Cournot-Nash fashion where it chooses its abatement level to maximize the net benefit, taking the policies of all the other countries as given. Under full cooperation, countries would choose optimal Q to maximize the collective welfare. Clearly, each country is better off under full-cooperation, but has no unilaterally incentive to choose full cooperation.

Due to the assumption of symmetry, there is no need to distinguish which countries would cooperate. Thus, the research question in Barrett's paper is to identify the size of the stable coalition. Since there is no super-national authority that can force countries to join an IEA, it must be in each country's own-interest to participate. Barrett introduced the concept of *self-enforcing*, which has became the prevailing method to study IEA formations for later studies. An IEA is *self-enforcing* if and only if the signatories have no incentives to individually deviate from the IEA (*internally stable*) and non-signatories have no incentives to join the IEA (*externally stable*), either. The game is solved backwards in a Stackelberg way where signatories move first, and non-signatories choose their optimal abatement levels after observing the actions of signatories. By a simulation method, Barrett showed that the IEA can be signed by a lot of countries, from two countries to the grand coalition, as long as the net benefit gain from full cooperation is small compared to non-cooperation. When the net benefit gain is large, the IEA is sustained by very few countries. Therefore, large welfare gains are prevented. This conclusion is consistent with other studies (reviewed in the following subsection). Nordhaus (2015) termed this phenomenon as *Small Coalition Paradox*. Hoel (1992) and Carraro and Siniscalco (1993) are the other two early notable contributions to IEA formation literature.

In Barrett (1994a)'s model, he assumed that the aggregate emissions are large enough, hence there is no upper bound on abatement levels. However, as Rubio and Ulph (2006) explained, a non-negative emission for each individual country cannot be guaranteed by Barrett's assumption. They then considered the possibility of a zero-emission level and revisited the *basic model* by using Kuhn-Tucker conditions. Instead of simulation, Rubio and Ulph (2006) analytically showed that the key results of Barrett (1994a) could be maintained if corner solutions are allowed. Diamantoudi and Sartzetakis (2006) also applied non-negative constraints to emission levels by restricting parameter values, and their results indicated that there exists a unique stable IEA with either two, three or four countries when the number of countries is larger than four.

Barrett (1994a) and others (e.g., Diamantoudi and Sartzetakis, 2006; Rubio and Ulph, 2006; McGinty, 2007; Eichner and Pethig, 2013; Diamantoudi and Sartzetakis, 2015) have modelled the game in Stackelberg-fashion. They argued that the Stackelberg leadership model is more compelling since individual countries who act unilaterally prefer to act after observing the coalitional action because such coalitional decision can significantly influence the global emission. By contrast, some literature adopted the Cournot fashion, where coalition members and non-members move simultaneously in deciding the optimal policies (e.g., Hoel, 1992; Rubio and Ulph, 2007; Eichner and Pethig, 2015b; Finus and Rübbelke, 2013; Fuentes-Albero and Rubio, 2010; Pavlova and De Zeeuw, 2013). Their results indicated that the stable IEA is always very small if the game was modelled in a Cournot way. Rubio and Ulph (2006) explained the difference in outcomes between Cournot and Stackelberg models. In a Cournot model, if a signatory were to leave an IEA, the emissions of non-signatories would be expanded. However, the remaining signatories will reduce their emission to partially offset the increased emission from non-signatories. However, in a Stackelberg model, the remaining signatories would also expand their emission if a signatory were to leave an IEA. Hence, countries have stronger incentives to leave an IEA with Cournot behaviour than with Stackelberg. Thus, the modelling choices affect the corresponding results, and hence, the results of different studies should be compared with caution.

In the *basic model*, all countries were assumed to be identical for the purpose of simplicity. However, in the real world, countries are heterogeneous in their contributions to climate change, in their vulnerability to climate change, and in their unique features such as developing stages, culture, lifestyles, etc. To capture this reality, at least to some extent, some of the literature (e.g., McGinty, 2007; Fuentes-Albero and Rubio, 2010; Pavlova and De Zeeuw, 2013) has relaxed the assumption of symmetry and studies the IEA formations in an asymmetric world with transfers. Barrett (2001) adopted a quite different game where there are two types of countries differing in abatement interest. Each country has two available strategies as "Pollute" or "Abate". He showed that because of this asymmetry, a country with high interest in abatement has incentives to make a money transfer to country with low interest and the *Small Coalition Paradox* situation can be improved.

Other studies which are based on the *basic model* also investigated that how asymmetry impacts the formation of an IEA when compared to the symmetric case. McGinty (2007) relaxed the assumption by letting the marginal benefit and marginal cost vary across nations. The coalition would be stable as long as the collective payoff of the coalition exceeds the sum of payoffs of each single deviator. The surplus after each country can receive its payoff as a single deviator from the agreement is redistributed according to the θ rule. With a simulation method, he reached a promising conclusion that a much higher level of abatement can be sustained by an IEA. Fuentes-Albero and Rubio (2010) analytically solved the two-stage IEA formation model in an asymmetric world. Two different cases were considered where in the first case countries differ in abatement cost, whereas in the second case countries differ in environmental damage. It showed that if asymmetry only lies in abatement cost, the results are consistent with those under symmetry. Only when countries differ in environmental damage and an income transfer is introduced, a larger coalition is possible. Pavlova and De Zeeuw (2013) allowed asymmetries in benefits and vulnerability to climate change damage simultaneously with quadratic benefits and linear damage. Without transfer, a large coalition is achievable if this coalition includes countries with high benefit but low cost. However, those countries would contribute less in coalition, resulting in a lower emission reduction than the case without those countries. With transfers, a large stable coalition performs better in emission reduction. Besides the above literature, Biancardi and Villani (2010) and Osmani and Tol (2010) also considered asymmetries by using numerical exercises and simulation methods. In general, the above literature has indicated that a large coalition might be possible, but the gain from cooperation is not large.

The concept of internal and external stability used in the *basic model* assumes that when a country revises its participation decision - either a signatory withdraws from an IEA or a non-signatory accedes to the IEA - the decisions of all the other countries remain the same. However, because of the interdependence through the climate change channel and the international trade channel, such membership changes would affect the welfare of all countries, and other countries might change their decisions as a response. This internal and external stability is defined as "myopic stability" by De Zeeuw (2008) as a player does not foresee any changes occurring due to their own decision changing. A few studies in the literature have examined the impact of introducing farsightedness in IEA formations (Carraro, 1997; Ecchia and Mariotti, 1998; Eyckmans et al., 2001; De Zeeuw, 2008). Furthermore, Diamantoudi and Sartzetakis (2015) and Diamantoudi and Sartzetakis (2017) endogenized the reactions of the IEA members to a deviation by a group of members and an individual country, respectively. In their studies, the reactions of other countries were taken into consideration when the one party (a group of countries in Diamantoudi and Sartzetakis (2015) and an individual country in Diamantoudi and Sartzetakis (2017)) changes its membership decision. They found that if countries were foresighted, a much larger coalition than the ones found in previous studies is possible and also Pareto efficient.

Notably, most of the studies, including the *basic model*, have applied simple static models where the membership of the IEA or emission decision is determined once and for all at the outset of the agreement. However, the agreements such as Kyoto protocol is effective for signatories only for a relatively limited period of time. It is essential to analyse the endogenous formation of the IEA when countries exist in infinite period. Rubio and Ulph (2007) extended the *basic model* to a dynamic model where the membership of the IEA may change endogenously over time. The damage cost would increase with the stock of pollution. Given the initial emission stock, it is a two-stage game for each period. Instead of maximizing the static welfare, players would maximize lifetime welfare given a discount factor by dynamic programming in the dynamic game. The results showed that there exists a steady-state emission stock and steady-state IEA membership. As the damage cost increases, the gains from cooperation would also increase, but the size of IEA decreases. Further extensions can be found on the uncertainty and learning (Kolstad, 2007; Kolstad and Ulph, 2011) and political cost (Hoel and Schneider, 1997).

2.3.2 IEA with International Trade

In the IEA formation literature reviewed above, countries are interdependent with each other only via climate change, and the linkage with international trade has not been considered. However, trade and the environment have close interactions, which could have great impact on IEA formation. Thus, it is of great importance to review the work of Eichner and Pethig who model IEA formation in the presence of international trade.

Rather than adopting the reduced form cost-benefit analysis in the *basic model*, Eichner and Pethig (2013) modelled the world economy in a detailed way by adding structures for production, consumption, markets as well as international trade. The introduction of international trade connects countries in a second channel other than climate change only. They built a n-country, two-good open economy model. Each country produces a consumption good X (quantity x_i), and a fossil good $fuel$ (quantity e_i). These two goods are produced and consumed by the representative consumers in each country and also traded internationally. Utility comes from the consumption of two goods. Greenhouse gas emission is produced jointly with the consumption of fuel, causing welfare loss due to climate damage. Government sets an emission cap on domestic fuel consumption, which is auctioned with π_i being the permit price in country i. Consumers have to acquire the permits to consume fuel. In the business-as-usual scenario, each country chooses the emission cap e_i to maximize its own welfare, taking the emission caps of all the other countries as given. There exists a unique Nash equilibrium where emission cap is the same for each country and international trade does not take place even though the borders are open.

Eichner and Pethig then studied the formation of an IEA. They defined the game in a Stackelberg fashion that a group of countries move first as a Stackelberg leader to maximize collective welfare, while the remaining countries would act as Stackelberg followers to maximize their own welfare after they observe the actions of the Stackelberg leader. By using a *self-enforcing* concept, the authors showed that a larger coalition might be formed, but the welfare gain and emission reduction from cooperation are both small compared to business-as-usual scenario. Another important finding in this paper is that international trade does affect the formation of IEAs since the size of stable coalitions is larger under free trade than in autarky no matter what values the parameters take. The second conclusion further proved that the IEA studies which overlook international trade might lead to biased results. However, this paper did not show how trade explicitly affects the formation of an IEA. Instead, it studied the role that international trade plays only by comparing the stable coalition size with free trade and in autarky.

They further extended this new framework of IEA formation to many directions. They firstly replaced the Stackelberg assumption by the Cournot fashion and compared the results with regard to the size and welfare change of stable coalition (Eichner and Pethig, 2015b). They found that the size of stable coalition is at most two in Cournot game both under free trade and autarky, which would contradict the results in a Stakelberg game where the size of stable coalition can be much larger with free trade. Although an environmental coalition in the context of free trade sets up their mitigation effort, world emission rises due to the trade liberalization, which further results in a welfare loss. Secondly, Eichner et al. (2018) studied whether the grand coalition is stable or not, other than the formation outcome of IEAs, in an asymmetric world. They expanded the "IEA with trade model" by introducing two different groups of countries regarding climate damage or demand for fuel. However, countries are identical within the group. They found that climate asymmetry discourages grand cooperation, while the effects of fuel-demand asymmetry depends on the abundance of fossil fuel. Asymmetry stablizes the grand coalition if fuel is scarce. Furthermore, Eichner and Pethig (2015c) also compared the effectiveness of an emission tax and cap-and-trade in a symmetric open economy world. They found that the socially optimal global IEA may be *self-enforcing* if an emission tax is implemented.

The work by Eichner and Pethig contributes to the literature significantly by taking trade into consideration in IEA formation studies. However, due to the intractability of the model employed in their work, Eichner and Pethig can't explicitly show how trade affects the formation of IEAs. Their conclusions about the role that trade plays is obtained implicitly by comparing the size of stable IEA with trade to that in autarky. Nevertheless, these studies confirm that trade does affect climate change cooperation and this effect should be modelled in IEA formation studies. A more important scientific question about the mechanism of trade effects in the process of climate change negotiation should be explored to provide guidance in practice.

2.4 Issue (Trade) Linkage in IEAs

The basic idea of *issue linkage* is to link a public good, which suffers severely from free riding problems, to a club good where the benefits from cooperation are exclusive to coalition members (Carraro, 1997). Therefore, the incentives to free-ride on the non-excludable public good is partially offset by the potential loss from the excludable club good. This section aims to review the literature on issue linkage in environmental cooperation. Notably, as the scope of this review is to explore the role that international trade plays in IEA formation, the literature related to the trade linkage in IEAs will be reviewed in this section, whereas other types of issues linkage such as technology linkage are not considered.

The literature of issue linkage between trade and international environmental agreements is distinguished by Maggi (2016) in the book *The Handbook of Commercial Policy* as three types: *enforcement linkage*, *negotiation linkage* and *participation linkage*, while Ederington et al. (2010) only distinguished the first two, due to the fact that literature in *participation linkage* is relatively rare. For a comprehensive review, this study will cover the literature of all three trade linkage types, even though the main focus is *participation linkage*. The other reason for reviewing all three linkage types is to distinguish *participation linkage* from other linkage papers. This review will focus mostly on the theoretical literature rather than empirical literature due to the fact that the empirical research is relatively less developed.

2.4.1 Enforcement Linkage

Enforcement linkage refers to the case where a violator of an agreement in area A will be punished both in area A and the linking area B. Therefore, it is natural to assume that the violations will happen in both areas in the presence of *enforcement linkage* once a violator makes her mind to cheat. This linkage can be viewed as adding a clause to the agreement which specifies how to link two areas to punish the violators. In practice, negotiators will bargain over such a clause. As is clear from the above explanation, *enforcement linkage* aims to enhance enforcement power to deter non-compliance free riding incentives. Therefore, it is usually assumed that all countries have participated in an agreement and the only issue left is the enforcement of the agreement.

Among all studies, Bernheim and Whinston (1990) and Spagnolo (1999) were the first two to apply *enforcement linkage* to firm collusion. In particular, they studied whether linking punishments across markets can generate higher profits when firms collude over several markets. Bernheim and Whinston (1990) found that if the profit functions were symmetric and separable in different markets, then there would be no gains from *enforcement linkage*, because the linkage only doubles the punishments. However, since the deviator will cheat on both issues, *enforcement linkage* would also double the gains from cheating on both issues. This research provides important insights that only when asymmetry across issues exists can strict welfare gains be obtained by *enforcement linkage*. This welfare gain comes at a reallocation of the enforcement power, which increases the cooperation in one issue, but at the cost of the other (Maggi, 2016). On the contrary, Spagnolo (1999) argued that even if the asymmetries are absent, there would still be gains from *enforcement linkage* provided that the payoff functions are non-separable. Spagnolo (1999) considered an oligopoly market where the prices charged in different markets are substitutes. He showed that firms collude more effectively with *enforcement linkage*. The intuition is that linking two structurally interacted issues can create enforcement power under some conditions.

Trade and environmental cooperation issue is an area that *enforcement linkage* can fit in. In addition to the asymmetries between trade and environment cooperation issues in nature, trade and the environment are also closely connected to each other as reviewed earlier. Theoretically, an enhancement in the enforcement of environmental cooperation is expected by linking trade to the environment in agreement. Researchers adopted the *self-enforcing* concept in an infinitely repeated game to study whether *enforcement linkage* can enhance enforcement or not. Limão (2005) studied the enforcement in trade and environmental agreements with terms-of-trade externalities and trans-boundary environmental externalities. In his model, each government maximizes the weighted welfare with different weights on consumer and producer groups by choosing trade tariffs and pollution taxes. The results indicated that linkage between trade and environment is strictly optimal to non-linkage. However, such enforcement may come from different sources. If tariff and pollution taxes are independent and one issue is easier to enforce than the other, then *enforcement linkage* leads to a reallocation of enforcement power from the easier issue to the other. However, if the two policies were complements in government's objective function, more enforcement power would be created by this linkage, which could raise cooperation in both areas. Meanwhile, Ederington (2002) assumed that environmental pollution is local and showed that, if the punishment was a permanent reversion to interior Nash policies, policy linkage is not superior since the most-cooperative equilibrium can be supported in both linked and non-linked agreements. However, when environmental pollution is trans-boundary, issue linkage is more likely to be beneficial if countries have a strategic incentive to set environmental standards high (Ederington, 2001a). While the above literature shows there are gains from *enforcement linkage* in trade and environment cooperation, if the asymmetry between countries, incomplete information and imperfect monitoring are taken into consideration, there might be potential losses as well.

2.4.2 Negotiation Linkage

Negotiation linkage introduces a different bargaining protocol, where countries negotiate two issues (trade and the environment) jointly in one single bargaining game, as opposed to bargaining one-by-one. If there is asymmetry across countries, *negotiation linkage* leads to a Pareto improvement compared to the non-linked scenario. In an unlinked negotiation, the disagreement points for each country are its respective Nash equilibrium policies in each separate bargain. However, when negotiations are linked, a country who gains more from trade agreement is willing to make concessions in trade area in exchange for benefits from the environmental area due to the concessions made by the other negotiator; and vice versa.

Horstmann et al. (2005) showed that negotiation linkage is Pareto improving when there is a strong asymmetry between countries. However, Maggi (2016) showed that asymmetry is the *only* reason for efficiency gain in linked negotiation. In this way, negotiation linkage works more as a transfer when asymmetry exists, but less efficiently. Horstmann et al. (2005) also argued that countries do not necessarily share equally in the gains. Indeed, Copeland (2000) found that if a freer trade agreement was committed prior to the negotiation of an environmental agreement, the importing country of pollution-intensive goods would have a disadvantage in the negotiation of an environmental agreement of a global pollution. Thus, this importing country always tries to link environmental agreement with trade agreement while the exporting country prefers an unlinked negotiation with a prior commitment to freer trade. Therefore, *negotiation linkage* might not be possible if it is an endogenous choice for each negotiator. Furthermore, Carraro and Marchiori

(2003) modelled the *negotiation linkage* as an endogenous choice for countries and studied the possibility of linking two issues in one negotiation in a three stage non-cooperative sequential game where whether linking the two issues is discussed in the first stage. If linkage was introduced, governments then would negotiate in one bargain; otherwise, they will bargain in two separate agreements. They found that the benefit from mitigating the free riding problem is at the cost of less cooperation in club good area. More surprising, they found that *negotiation linkage* might lead to a worse situation for all players. Markusen (2017) used a simulation model to study the welfare and abatement outcomes under different *negotiation linkage* scenarios in an asymmetric world. He found that when a large and a small countries bargain over tariff and tax together, both parties are better off compared to non-linked case.

2.4.3 Participation Linkage

Participation linkage aims to induce wider participation in the free-riding area. In the context of trade and environmental cooperation, *participation linkage* is to add a clause to the existing trade agreement, specifying that the agreed trade concessions to trade members are contingent on the participation of the IEA. The purpose of this review (thesis) is to explore the role that trade plays in the formation of such an IEA, or put differently, it focuses on deterring the non-participation free riding incentives in climate change cooperation. Thus *participation linkage* becomes the powerful vehicle for encouraging wide participation in IEAs.

Among all studies, Barrett (1997) is the first study to propose the application of trade sanctions to sustain wider cooperation in IEAs. He found that full cooperation might be possible if trade is banned between signatories and non-signatories, provided that a minimum participation clause is in effect with trade sanctions. However, trade sanctions were exogenously given in his paper and using embargo as a sanction was too severe and not credible. Eichner and Pethig (2015a) studied the topic in a very different setting where all countries but one have signed an IEA and they are obliged to impose a trade ban on the only free rider. The outsider would sign the IEA only if the threat of embargo imposed by coalition members is credible and signing the IEA generates a better outcome for itself. They found that an embargo might be unnecessary, ineffective, but on some subset of parameters, trade sanctions stabilize the unstable global agreement. However, the trade sanction is not credible. Kuhn et al. (2017) adopted Eichner and Pethig (2013)'s multi-stage, multi-sectoral Stackelberg model with international trade to study the effectiveness of linking climate change cooperation to a Preferential Free Trade Area.[7] In their paper, climate coalition members could join a free trade area and enjoy the excludable trade privileges provided. They found that the free trade area can strongly promote the formation of a climate coalition, where the coalition size increases from 3 to 7 (10 in total). Moreover, based on their simulation results, the emission level with linkage decreases and the global welfare increases. Nordhaus (2015) showed that establishing a climate club might be effective in overcoming free riding in IEAs. The *climate club* is an agreement that obliges all participants to undertake the same emission reductions and a uniform percentage tariffs on imports of non-participants into the club region is imposed by the climate club. According to his C-DICE model, relatively low tariffs (2 percent or more) are sufficient to sustain full participation and guarantee efficiency when the abatement responsibility is low. As the abatement responsibility increases, a higher tariff is needed to induce participation. However, he also pointed out that some of the countries might be worse off with this climate club.

The above literature about *participation linkage* provides very useful implications of linking trade policy to IEA formations. However, they have the drawbacks of not solving for the trade sanctions endogenously and not analysing the linkage endogenously. Barrett (1997) and Eichner and Pethig (2015a) assumed that signatories of an IEA impose trade ban on non-signatories, which was too severe and not in the self-interest of signatories (not credible). Nordhaus (2015) used a much softer punishment on free riders, but it is also exogenously determined by the researcher. Moreover, questions of how to link trade policy and whether this linkage is supported by the existing trade members are not well explored in the above literature.

[7] Strictly speaking, Kuhn et al's work is not participation linkage according to the concept of *participation linkage* defined in this review. As in their model, trade agreement and environmental agreement are jointly formed. However, the purpose of the linkage in Kuhn et al. (2017) is also to induce wider participation in the environmental agreement. On the other hand, scholars are not unanimous in the concept of *participation linkage*. This review only provides one possibility of these.

Nordhaus (2015) argued that the coalition formation process is a top-down coalition where an optimal regime is there to attract countries to join. However, it is difficult to determine who the designer is and how the process would start in reality. Maggi (2016) also concluded that this research is incomplete and future work that models the trade sanction endogenously is needed.

As these three linkages are closely related to each other, it is essential to clarify the similarities and differences between them. Firstly, these three linkages take place at different phases of trade and environmental agreements. *Participation linkage* is in the first stage where governments choose which agreement they would like to participate in, while in the second stage governments bargain the two issues in one go with *negotiation linkage*. Then in the last stage, *enforcement linkage* takes place to enhance the enforcement power of the two linked agreements.

Secondly, these three linkages have different specific aims, but they each promote cooperation in issues with free riding problems. *Participation linkage* aims to induce wider participation in IEAs in the first stage while *enforcement linkage* enhances the enforcement of the agreement in the last stage once the agreement has been formed. *Negotiation linkage* in the middle expands the negotiation payoff set. Despite the different forms of linkage, they all aim to promote environmental cooperation.

Thirdly, these linkages are not necessary to be introduced all at once. *Participation linkage* is meaningful only when the negotiation is not linked. That's because if negotiation is linked, each country will choose to participate in the linked negotiation or not (the trade agreement and environmental agreement negotiated in one go), there is no need to induce participation in one agreement (environment) by the threat of losing concessions in another agreement (trade). If negotiation is linked, it is natural to link two issues in the enforcement stage as well.

Lastly, the gains and loss from three kinds of linkage are quite different from each other as reviewed above. This review explores how trade and trade policy can be used to induce wider cooperation in the formation of IEAs, thus is mainly about *participation linkage*.

2.5 Summary and Research Outlook

The above literature review presents the current understanding regarding the interactions between trade and the environment, the IEA formation and the issue linkage between trade and the environment. The main implications and research gaps are summarised as follows.

The first main point of this review is that international trade does affect the international cooperation on climate change, and its effects should be considered in IEA formation studies. However, how trade might affect a country's incentives to participate in climate change cooperation really depends on the characteristics of this country. On one hand, the existence of the *pollution haven effect* amplifies the free riding incentives of small economies in climate change cooperation. The *pollution haven effect* indicates that a more stringent environmental policy might cause a loss of competitiveness in pollution-intensive products for a country in the international market. Therefore, in addition to the welfare gain from a better environment without any cost on their sides, the free riders also gain a comparative advantage in international trade due to the absence of or sub-optimality of an environmental policy. In this sense, trade hampers climate change cooperation.

On the other hand, the use of environmental policy by large economics as a second-best instrument to manipulate gains from international trade affects their participation incentives in IEAs. A large import-competing country tends to loosen domestic environmental regulation (Markusen, 1975b), so it is reluctant to join an IEA where the environmental externality is internalized to a higher degree, which requires a more stringent domestic environmental policy. By contrast, a large export-competing country prefers a higher environmental tax, which generates a monopolistic gain. By acceding to an IEA, the market power of these large export-competing economies is enhanced, and an even higher *terms-of-trade* gain is obtained. This potential benefit from participating in IEAs partly offset the free riding incentives, thus, will facilitate cooperation on climate change.

The interactions between countries via international trade open the door for a country to influence the carbon emission of other countries by manipulating its own policy (i.e., *leakage effect*). A large economy always prefers a lower environmental tax to indirectly reduce the emission in other emitting countries, irrespective of its trade patterns (Markusen, 1975b). This *leakage effect* also impacts a country's choice of optimal environmental policy, which further impacts its incentives for climate change cooperation.

The second main point of this review is that the role that trade plays in IEA formation is relatively neglected in current studies. Barrett (1994a) and other related literature measures the gains and losses of climate change cooperation by stylized benefit and cost functions of abatement levels. The structure of the economy together with trade in these studies is not well-modelled. The work by Eichner and Pethig takes trade into consideration. However, due to the intractability of the model employed in their work, Eichner and Pethig can't explicitly show how trade affects the formation of IEAs. Their conclusions about the role that trade plays is obtained implicitly by comparing the size of stable IEA with trade to that in autarky. The mechanism of trade effects in the process of climate change negotiation should be explored explicitly to provide guidance in practice.

The third main point of this review is that there is great potential to tackle climate change by using trade/trade policy. Given the close interactions between trade and the environment, linking IEA formation to trade policy, which aims to induce wider participation in IEA, is a natural idea with great potential. Unfortunately, studies in this area are still very limited. This review can be used as a starting point for future efforts.

The first research gap in prior trade/environment literature is the interdependence between trade policy and environmental policy in climate change cooperation. More specifically, the question about how countries play strategically in an integrated world economy in the IEA formation game and what coalition arises in equilibrium need to be explored. This research gap motives the study of IEA formation in an open economy in Chapter 3. Chapter 3 examines how the IEA is formed in a "three-country, three-good" open economy and how trade affects the formation outcomes. The second research gap is how trade policy can be used to tackle climate change. More specifically, how trade linkage works to deter free riding incentives, under what condition trade linkage works and whether trade linkage is favoured by all countries, etc. are barely studied by prior literature. This second research gap motives the study of trade linkage in IEA formation in Chapter 4, which investigates the effects of trade linkage in IEA formation and the possibility of introducing such a linkage.

Chapter 3

IEA Formation in the Open Economy

3.1 Introduction

Most of the existing literature in IEA formation is in Barrett (1994a)'s fashion where the gains and losses of climate change cooperation are represented by stylized benefit and cost functions of abatement levels. The structure of the economy together with trade in these studies is not well-modelled. Consequently, the role that international trade plays in climate change cooperation has been relatively neglected. However, as reviewed and discussed in Chapter 2, trade and the environment (e.g., climate change) have close interactions and such interactions should be taken into consideration in IEA formation studies.

A notable study in IEA formation with the presence of international trade is Eichner and Pethig (2013). They built a n-country, two-good open economy model. Each country produces a consumption good and a fossil good, which are consumed in each country and traded internationally. Greenhouse gas emissions are produced jointly with the consumption of fossil good, causing welfare loss due to climate damage. Government regulates emissions by setting an emission cap on domestic fuel consumption. They then studied the formation of an IEA by using the *self-enforcing* concept. The authors showed that a larger coalition might be formed in the presence of international trade. Based on this model, Eichner and Pethig extended this work to different directions, such as modelling the game in Cournot way (Eichner and Pethig, 2015b), in asymmetry world (Eichner et al., 2018).

The main characteristics that distinguish this study with Eichner and Pethig (2013) are three-fold. First, this chapter proposes a different framework to study the formation of IEAs. It introduces a three-country, three-good general equilibrium model in an open economy, in which the effects of international trade on IEA formation can be well considered. More importantly, this three-country, three-good model enables me to look at the strategic behaviours of each country in IEA formation, which is not explicitly analyzed in Eichner and Pethig (2013). Second, Eichner and Pethig (2013) adopted the prominently used concept in IEA formation, *self-enforcing*, which only deals with unilateral deviations. However, a group deviation that can benefit all members might be possible. With regard to this concern, this study uses Nash and strong Nash coalition conditions to deal with unilateral as well as group deviations. With this novel model and framework, this chapter is able to analyse how the outcome of IEA formation arise endogenously and how the equilibrium results are affected by various parameters. Finally, Eichner and Pethig (2013) reached the conclusion that trade helps to sustain wider climate change cooperation by only comparing the stable coalition size with free trade and in autarky. This chapter takes a closer look at how environmental policy is used for trade purpose and how such use affects the outcomes of climate change cooperation.

This chapter builds a "three-country, three-good" general equilibrium model in an open economy. A country is only endowed with resources to produce two goods but demands three, thus it imports one good from its trading partners and exports two to them. Greenhouse gas emissions are considered as a by-product of production from each country. As a pure "public bad", emissions from any country cause utility loss of a representative consumer in three countries. Each benevolent government maximizes its national welfare by determining a production level. In this model, countries are connected with each other not only through climate change but also via international trade. This chapter defines an endogenous IEA formation game accordingly. By using Nash equilibrium coalition and strong Nash equilibrium coalition conditions, the stable coalition in this model is immune to both unilateral and group deviations.

The structure of this chapter is as follows: Section 3.2 sets out the model. The coalition formation game and coalitional stability are then introduced in Section 3.3. Section 3.4 solves the optimal policies for each coalition structure. Section 3.5 simulates how an IEA is endogenously formed and analyses the welfare gain and emission reduction from cooperation. In this subsection, I also discuss how international trade affects IEA formation results. The last section then concludes.

3.2 The Economy and Equilibrium

In order to model IEA formation with the presence of international trade, this section sets out a three-country, three-good competitive general equilibrium trade model. Country i is endowed with zero unit of resources to produce good I and a fixed amount of resources (e_i) for the other two goods. A greenhouse gas is jointly produced with the production of these goods. Each country demands all three goods, hence, country i needs to import good I from the other two trading partners. The model employed here allows for the endogenous determination of both tariff and production policies.

3.2.1 Model Structure

Household Sector

The consumers in three countries share similar preference over consumption goods and climate change. A representative consumer in country i has the following utility function (adopted from Bagwell and Staiger (1997) and Copeland and Taylor

(1995)), in which preferences over good w_i and c_i^Is are quasilinear and addictive:[1]

$$U_i = w_i + \sum_{I,J,K} [\alpha_i c_i^I - \frac{1}{2} {c_i^I}^2] - \beta_i \frac{Z^{\gamma_i}}{\gamma_i} \tag{3.2.1}$$

where w_i is a numeraire good with the world and domestic prices being 1. The quadratic utility function of consumption results in a linear demand function, making the model tractable. Marginal utility of consumption is non-decreasing if $\alpha_i \geq c_i^I \geq 0$ holds.

The impact of climate change on consumers is captured by $\beta_i \frac{Z^{\gamma_i}}{\gamma_i}$, where β_i and γ_i are positive constants that are exogenously given.[2] Z is the global greenhouse gas emissions. Utility is decreasing in global emission Z since $\partial U_i / \partial Z = -\beta_i Z^{\gamma_i - 1} < 0$. Greenhouse gas emissions are a pure public bad so that consumers in all countries are harmed by the emission released from any one country. β_i is the representative consumer's preference over a better environment in country i.[3] Consumers with a higher β_i suffer more welfare loss from climate change than that of a consumer with a lower β_i, taking γ_i as constant. $\gamma_i \geq 1$ must be assured such that the marginal willingness to pay for emission reduction is non-decreasing since $\partial^2 V_i / \partial Z^2 = -\beta(\gamma_i - 1) Z^{\gamma_i - 2}$. Following other literature (Eichner and Pethig, 2013, 2015a), γ_i takes the value of 2, implying that climate change damage is convex in the global emission.

The representative consumer in country i maximizes her utility over consumptions subject to her budget constraint $w_i + \sum p_i^I c_i^I = M_i$, where M_i is the representative consumer's income. From the first-order condition,

$$c_i^I = \alpha_i - p_i^I \tag{3.2.2}$$

Equation (3.2.2) is the demand function for good I in country i. The "choke price", α_i, is the lowest price at which the quantity demanded becomes zero. A larger

[1] In this thesis, the subscripts (i, j, k) represent countries while the superscripts (I, J, K) represent goods.

[2] Greenhouse gas emissions also have a negative effect on productions. See a paper by Kotsogiannis and Woodland (2013) in which climate change affects the production possibility. But in this chapter, I only consider the effects on consumers.

[3] The preference is affected by the level of physical damage from climate change and also other factors, such as income level. In this chapter (also thesis), the preference is assumed to be affected mainly by the physical damage level.

"choke price" leads to a higher marginal utility of good I. Therefore, the welfare from consumption with a larger "choke price" is relatively higher than the one with a lower α, with all the other parameters fixed. Herein, α_i represents consumers' preference over consumption of good I relative to the environment and the numeraire. Thus, α_i is defined as the "relative preference" term. By substituting the demand function into equation (3.2.1), the indirect utility of country i given income (M_i), prices and global emission (Z) is obtained as

$$V_i(p_i^I, p_i^J, p_i^K, M_i, Z) = M_i + \frac{1}{2}\sum_{I,J,K}(\alpha_i - p_i^I)^2 - \beta_i \frac{Z^2}{2} \tag{3.2.3}$$

Production Sector

It is assumed that country i is endowed with zero unit of resources to produce good I, and e_i units of resources for the production of good J and K. The production of one unit of good J (or K) requires one unit of endowment. Greenhouse gas emissions are produced jointly with the goods. For each e_i units of resources used for production, a_i (i.e., a parameter describing how dirty the production of that good is) units of greenhouse gas emissions are produced jointly. a_i represents the technology of country i, and it is the same across industries within country i. Even though greenhouse gas emissions negatively impact consumers, producers have no incentives to voluntarily take the negative externalities into consideration. Without any regulation, producers always use all endowments for production to acquire the maximal profits.[4] Therefore, the production function and emission function of good J and K without any regulation in country i are

$$y_i = e_i, \qquad z_i = a_i \tag{3.2.4}$$

where $e_i > 0,\ a_i > 0$ are exogenously given and they are the same across industries within country i. The global emission is the sum of emissions in all three countries such that $Z = \sum_{i,j,k}\sum_{I,J,K} z_j^I$.

[4]Resources that are not used in production will be discarded.

Government

Because of the environmental externalities, market equilibrium fails to achieve efficiency. Accordingly, the government has to intervene if it wishes to correct this market failure. Government i sets a policy of θ_i, which is the proportion of resources used for production in country i, to regulate the production. Firms in country i should obey this regulation and use $\theta_i e_i$ units of endowments for production. Each country's production of goods and emission under government's regulation become

$$y_i = \theta_i e_i \tag{3.2.5}$$

$$z_i = \theta_i a_i \tag{3.2.6}$$

where $0 \leq \theta_i \leq 1$.[5] When $\theta_i = 0$, no resources are used for production, hence the greenhouse gas emissions are also zero, whereas $\theta_i = 1$ indicates all resources are used for production and the emission level is a_i.

International Trade

Each country is endowed with resources to produce two goods but consumes three, which induces trade. Country i imports good I from the other two trading partners. Let t_{ij} be the tariff imposed by country i on its imports of good I from country j.[6] Provided that tariffs are non-prohibitive, no-arbitrage conditions for good I imply

$$p_i^I = p_j^I + t_{ij} \tag{3.2.7}$$

$$p_i^I = p_k^I + t_{ik} \tag{3.2.8}$$

Let m_i^I be country i's imports of good I. Since country i has no endowment to produce good I,

$$m_i^I = d(p_i^I) = \alpha_i - p_i^I \tag{3.2.9}$$

[5]Since two goods are equally dirty, a country will set same θ_i on two goods.
[6]It is assumed that all countries have no access to export policies.

Each country's export of a good must equal its production of that good minus its local consumption:

$$x_j^I = y_j^I - d(p_j^I) \tag{3.2.10}$$

Market clearing for good I requires that country i's imports equal the total exports of the other two countries:

$$m_i^I = \sum_{j \neq i} x_j^I \tag{3.2.11}$$

3.2.2 Equilibrium Prices

Assumption 1(Free trade): All tariffs are zero under a free trade agreement.

It is assumed that all countries are always practising free trade in terms of trade cooperation. The price of good I in each country is world price, therefore, I will omit subscripts for countries. By using demand function (3.2.2), production function under regulation (3.2.5), (3.2.9) and (3.2.10), the prices of good I under free trade are solved as

$$p^I = \frac{1}{3}\left(\sum_i \alpha_i - \sum_{j \neq i} \theta_j e_j\right) \tag{3.2.12}$$

This expression shows that the price of good I, p^I, is a function of endowments (e_j, e_k) and emission policies (θ_j, θ_k) of the two producing countries (country j and k). Price is decreasing in policy θ since $\partial p^I / \partial \theta_j < 0$, where $j \neq i$. Larger θ indicates a higher world supply of that good, resulting a lower price for all consuming countries. Therefore, large export competing countries have incentives to lower their production, which at the same time lower their emission, in order to manipulate a *terms-of-trade* gain. When the first best policy is unavailable due to a binding agreement, countries use environmental policies (in this chapter θ) as imperfect substitutes to manipulate trade gains. This chapter will study how this interaction affects the outcome of climate change cooperation.

I further assume symmetry for the purpose of tractability as well as simplifying the coalition formation game, which will be discussed when the game is defined in Section 3.3.1.

Assumption 2 (symmetry): Countries are *ex-ante* identical with same endowments $e_i = e$, equally dirty production $a_i = a$, same "relative preference" $\alpha_i = \alpha$, and same preference over climate change $\beta_i = \beta$, for all $i = i, j, k$.

With the assumptions of free trade and symmetry, price of good I now is simplified as

$$p^I = \alpha - \frac{e}{3}\sum_{j \neq i} \theta_j \tag{3.2.13}$$

Prices of the other two goods can be obtained analogously. The non-negativity of prices requires that $\alpha \geq 2e/3$. With the simplified prices, country i's income M_i is

$$M_i = (p^J + p^K)\theta_i e = (2\alpha - \frac{2e}{3}(2\theta_i + \theta_j + \theta_k))\theta_i e \tag{3.2.14}$$

while the indirect utility (3.2.3) is simplified as

$$\begin{aligned} V_i(\theta_i, \theta_j, \theta_k, \alpha, \beta, a, e) \quad = \quad & \{2\alpha - \frac{e}{3}(2\theta_i + \theta_j + \theta_k)\}\theta_i e \\ & + \frac{e^2}{18}\{(\theta_j + \theta_k)^2 + (\theta_i + \theta_k)^2 + (\theta_i + \theta_j)^2\} \\ & - 2\beta a^2(\theta_i + \theta_j + \theta_k)^2 \end{aligned} \tag{3.2.15}$$

3.3 IEA Formation Game and Stability

This section defines the coalition formation game and its stability conditions. The first part sets out the coalition formation game as a two stage non-cooperative game in the context of three countries, while the second part discusses the conditions to screen the stable coalition in equilibrium.

3.3.1 IEA Formation Game

IEA formation in this chapter is modelled as a non-cooperative two-stage game. In the first stage, each of the three countries announces a list of the countries that they want to form a coalition with. Country i's pure strategy set Ψ_i consists of four possible strategies:

$$\Psi_i = \{\{i\}, \{i,j\}, \{i,k\}, \{i,j,k\}\}$$

where $\{i\}$, $\{i,j\}$ (or $\{i,k\}$) and $\{i,j,k\}$ mean that country i is in favour of stand-alone, a pair with country j (or k), and a grand coalition with all countries, respectively. The pure strategies of country j and k can be defined analogously.

Because of symmetry, it is assumed that only country i and country j can form a pair, which allows me wasting no time in symmetric scenarios. In a symmetric world, any two players have the chance to form a pair while the third country free rides. It is challenging to explicitly determine which two players have to cooperate. Thus, I simplify the game by assuming that only country i and j can form a pair, where i and j actually represent any two arbitrary countries. From a different perspective, this assumption has practical implication when timing asymmetry exists. For example, suppose i and j are France and Germany, which are already in an IEA. Country k, Turkey, is attempting to join this coalition. This example of timing asymmetry resembles my assumption here.

It is reasonable to assume that there is a cost to announce another country's name. Then with the assumption that only country i and country j can form a pair, country i will not bother playing $\{i,k\}$, because this strategy is costlier than strategy $\{i\}$, but leads to the same result as strategy $\{i\}$. Same logic applies to country j. Country k will not play $\{i,k\}, \{j,k\}$ as it can't form a pair with any of the other two countries. In this context, the pure strategies of country i, j, k are as follows

$$\begin{aligned}
\Psi_i &= \{\{i\}, \{i,j\}, \{i,j,k\}\} \\
\Psi_j &= \{\{j\}, \{i,j\}, \{i,j,k\}\} \\
\Psi_k &= \{\{k\}, \{i,j,k\}\}
\end{aligned}$$

Three policy regimes can be expected from the coalition formation game: each country works by itself (i.e., *Stand-alone*); two countries cooperate while the third country is a singleton (i.e., *the Pair*); all three countries cooperate (i.e., *Grand Coalition*).

Herein, it is essential to have a discussion about the membership rules as different coalition might be formed by applying different membership rules. There are three distinct membership rules in the existing literature of coalition formation: the *open membership rule*, the *exclusive membership rule*, and the *coalition unanimity rule*. The *open membership rule* states that each country can freely join or withdraw from the coalition without the consensus of other coalition members, implying that a new member who wants to join a coalition is always welcomed. By contrast, the *exclusive membership rule* states that a player can join a coalition provided that it gets approval by all existing members. Hart and Kurz (1983)'s Δ game also belongs to this category where each player proposes a list of countries that it wants to form a coalition with. Then a coalition forms if and only if all members have chosen it, which is not necessarily the same as each country's list. In the *exclusive membership rule*, players are still free to exit the coalition. On the contrary, players can neither freely join nor leave the coalition if the *coalition unanimity rule* is applied. A coalition is formed only when all players have proposed this specific coalition structure and any defects will collapse the coalition. Hart and Kurz (1983)'s Γ game applies this *coalition unanimity rule*.

The difference between the *open membership rule* and the other two is quite straightforward. However, it is blurred to distinguish the latter two membership rules. The following example shows how the latter two membership rules lead to different coalition structures. Let $\psi_i = \{i, j, k\}$, $\psi_j = \{i, j, k\}$ and $\psi_k = \{k\}$. If the *exclusive membership rule* (or Hart and Kurz (1983)'s Δ game) is applied, then the coalition structure is *the Pair* $[\{i, j\}, k]$. *Grand Coalition* is not formed since country k refuses to join Grand; country i and country j then form a pair because they both have chosen to cooperate with each other. In the Δ game, strategy $\psi_j = \{i, j, k\}$ for country i means the largest set of players that she would like to be with in the same coalition. On the contrary, *Stand-alone* will emerge if the game is modelled by *coalition unanimity rule* (or Hart and Kurz (1983)'s Γ game) because the defect of country k from the *Grand Coalition* breaks down the coalition and every player becomes a singleton. Compared between these two, the *exclusive membership rule* (or Δ game) seems to be more reasonable as players are not passive when free riding problem exists in climate change cooperation. A good example in the real world is that EU and China still stick to take responsibility while US withdrew from the Paris agreement.

Most of the literature in the fashion of Barrett (1994a)'s *basic model* adopts the *open membership rule*. However, I model the coalition formation by following Hart and Kurz (1983)'s Δ game. The *open membership rule* simplifies coalition formation game, but it is at the risk of not fully capturing the nature of IEAs. Theoretically, for a pure environmental externality problem, the more countries join the IEA, the higher the welfare is for coalition members. Put differently, the welfare function is monotonic in coalition size. Therefore, it is reasonable to assume an *open membership rule* that accepts any new members. However, as I reviewed in the previous chapter, the interactions between each country in international trade brings complexity to climate change cooperation. The welfare function might be hump-shaped with an optimal coalition size. Diamantoudi and Sartzetakis (2006) showed that the welfare of the signatories does not increase monotonically with respect to the number of signatories. Therefore, countries are sensitive to the coalition structures and should have some sort of control over the coalition structures. In this sense, the Hart and Kurz (1983)'s Δ game is preferred in this thesis.

The following figure summarises all possibilities of IEA formation outcomes. Country i chooses rows, country j chooses columns, and country k chooses boxes. The assumption that only country i and country j can form a pair must be kept in mind. Why does that matter? Take the following case as an example: country i plays $\{i\}$ while country j and country k both play $\{i, j, k\}$. Since it is an *exclusive membership model*, *Grand Coalition* is not obtained because country i refuses to join. However, it might be the case that country j and country k cooperate to form a pair. The assumption that only country i and j can form a pair eliminates this possibility, and in this context, the outcome is *Stand-alone*, which is represented by Φ in the following figure.

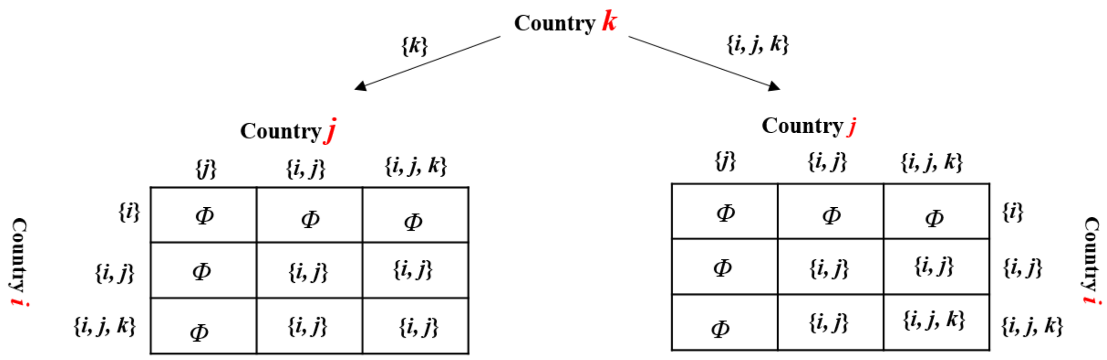

Figure 3.1: Possible Coalition Structures

In stage 2, signatories of an IEA, if any is formed, cooperate on the available policies to maximize their joint welfare taking the actions of non-signatory as given; the non-signatory decides its own policies non-cooperatively. The game is solved backwards to obtain a sub-game perfect Nash equilibrium.

An advantage of assuming symmetry is that an equally sharing rule of payoff within a coalition can be applied. That is, for a given coalition, each country receives same payoff as the other members of the coalition in a symmetric world. Therefore, there is no need to consider the income transfers between coalition members with symmetry, since every member gets the same welfare from cooperation. As discussed before, countries are heterogeneous in various aspects regarding climate change. Such heterogeneity brings new challenges for international cooperation on climate change and thus should be considered in studies. However, the introduction of heterogeneity will complicate the model to a large extent. Therefore, this chapter takes advantage of the symmetry assumption and aims to analyse the formation of IEA in the open economy.

Some features of the game deserve more comments. First, it is a one-shot game rather than a repeated game. The nature of public goods exhibits the property of a Prisoners' Dilemma Game. If the game is played repeatedly, the inefficient one-shot equilibrium outcome is only one of the possible equilibria. When countries can reward or punish others in a repeated game, there might be other more efficient outcomes. However, the main interest in this thesis is the role that international trade plays in the formation of IEAs. This simple one-shot game enables me to uncover the theory without loss of the general results.

Second, it is assumed that each player is proposed to sign one single agreement. Countries can only choose to participate in this agreement or not without an option to form a different one, thus those who do not join this agreement play as singletons. This commonly employed assumption in IEA literature seems restrictive in the theoretical framework, but it is legitimate for a global externality problem like climate change. The externality in a global scale calls for widely international cooperation, thus those agreements are usually negotiated and implemented under the United Nations' auspices.

Another frequently asked question is how this non-cooperative game framework employed here is different from a cooperative game framework. There is indeed a strand of literature that models IEA formation as a cooperative game, for example Chander and Tulkens (1995), Chander and Tulkens (2006), Chander (2007), Chander et al. (2016). In a cooperative game, players would form a coalition with some binding agreements, which implies that there might be a third party that can enforce the agreements. The players then act as a coalition to collectively choose the optimal strategy which maximizes the coalitional welfare. Hence, each player can be better off from cooperating within the coalition. The cooperative game mainly focuses on the socially optimal allocation of players, while the efficiency is determined in aggregate terms, rather than individual ones. However, the way that players cooperate does not imply that each player is not selfish. Whether to participate in such a binding agreement depends on the payoff from cooperation. If a subset of players can benefit by forming a different coalition, the socially optimal coalition is not achievable and thus not stable.

The main method to determine stable coalition predominantly used in a cooperative game is the core. A core is an imputation (i.e., efficient and rational allocations of payoff) of the socially optimal coalition (i.e., grand coalition in the context of a global environmental externality issue) that is not dominated by any other sub-coalitions which only consist of a subset of countries. A cooperative game starts with the socially optimal coalition (i.e., grand coalition) with enough enforcement power, and then explores the possibility of a group deviation to form a sub-coalition if it can benefit all the deviating countries. If any imputation of the socially optimal coalition is not dominated by all possible sub-coalitions, this imputation is in the core.

It is not obvious which framework is superior to the other since each of the two frameworks has their advocates. However, there are some reasons that non-cooperative game might be more adequate for climate change cooperation issue (Finus (2008) drew a similar conclusion).

First, the non-cooperative game has a higher potential to depict the free riding problems in climate change cooperation. It is not rational to assume that once a deviation happens, the remaining players will implement the policy that hurts the sub-coalition (the deviating players) the most (α core used in cooperative game). Therefore, the γ core proposed by Chander and Tulkens (1995) and Chander and Tulkens (2006) is more widely used in IEAs. However, the γ core has its own drawbacks by assuming that the remaining players will break up to singletons once a deviation happens. The following example is a good illustration of the point.

Suppose that three identical players i, j, k cooperate to tackle climate change. The initial coalition structure is grand coalition $[\{i,\ j,\ k\}]$. Because of symmetry, there can be considered as two types of deviations: one is that player i, j deviate to form $\{i,\ j\}$; while the other one is that player k deviates to be a free rider. The potential issues of γ core come from the latter case. According to the γ core, when player k deviates, it presumes that $\{i,\ j\}$ will break up into singletons. Consequently, the resulting coalition structure will be $[\{i\}, \{j\}, \{k\}]$, the Nash equilibrium between three players. Because country k is strictly worse off under Nash equilibrium, it will not deviate, leading to the conclusion that grand coalition is stable.

But why should $\{i,\ j\}$ break up into singletons when player k deviates? In some cases, it generates higher benefit for country i and j to stick together $\{i,\ j\}$ rather than breaking up to singletons. That's exactly what is happening in the real world. US, which resembles player k, withdrew from the Paris agreement. The other countries, especially China and EU, are still cooperating to tackle climate change. It is not reasonable to exogenously assume that $\{i,\ j\}$ break up into singletons.

Chander (2007) argued that $\{i,\ j\}$ might have some sort of far-sightedness and thus break up to induce the temporary Nash equilibrium, which further eliminates the incentives of player k to deviate and thus stabilizes the grand coalition. However, this argument is not compelling since player k might also foresee this result and refuse to join the grand to induce the other two countries to form $\{i, j\}$ since this is the best choice for country i, j given that player k won't cooperate. Therefore, whether breaking up to singletons or not depends on which coalition generates higher payoff for player i, j. More possibly, i, j will form a partial cooperation agreement and be free ridded by country k. Unfortunately, cooperative game models fail to depict this free riding problems in climate change cooperation. Finus (2008) also argued that the punishment that the remaining countries break apart into singletons are too strong, therefore, in a cooperative model, grand coalition can be stabilized.

Second, cooperative game models are unlikely to predict which coalition structure will be stable in equilibrium if the grand coalition has an empty core. As indicated above, cooperative game models focus on the socially optimal coalition structure (i.e., grand coalition in climate change issue). The main interest is whether this socially optimal coalition is dominated by other coalition structures or not. If dominated, cooperative game models can only conclude that the socially desirable coalition is not stable. In such a framework, it is impossible to determine which coalition will prevail if grand coalition does not. However, in the real world, it is quite hard to form a grand coalition with full participation. Thus, it is necessary to study which coalition will eventuate in equilibrium if the grand cannot.

Due to the discussions above, this thesis adopts the non-cooperative game framework. Non-cooperation does not indicate that countries will not cooperate at all. Cooperation is a possible outcome of a non-cooperative strategic behaviour of the negotiators.

3.3.2 Coalitional Stability

One key aspect in this coalition formation game is to determine the conditions that screen stable coalition in equilibrium. Herein, I focus on stable coalition, rather than the dynamic process because any dynamic process will converge to stable coalition structure. Barrett (1994a) and other papers in his fashion applied the concept of *self-enforcing* where members have no incentives to withdraw from a coalition (*internally stable*) and non-members have no incentives to join the coalition either (*externally stable*). The concept only considers unilateral deviations given the strategies of all the other countries. However, in an environment where players can communicate freely but can't make a binding commitment, a self-enforcing group deviation which benefits all group members might be possible. Hence, a stable coalition has to be immune to individual deviation as well as group deviation. This thesis adopts Nash equilibrium to deal with unilateral deviation and strong Nash equilibrium to deal with group deviation.

Nash Equilibrium Coalitions

A coalition is called the Nash equilibrium coalition if it is sustained by at least one Nash equilibrium. It is straightforward that there are no incentives for each player to unilaterally deviate from *Stand-alone* if other countries don't announce its name. Hence, *Stand-alone* is a Nash equilibrium coalition, irrespective of the values of parameters. What about *the Pair* and *Grand Coalition*? Are they always sustained by at least one Nash equilibrium?

Let s, p, g represent *Stand-alone*, *the Pair* and *Grand Coalition*, respectively. P is the set of countries in coalition *the Pair* $P = \{i, j\}$. G is the set of countries in *Grand Coalition*, $G = \{i, j, k\}$. Let $\omega_i^*(r)$ be the welfare of country i under coalition structure r with relevant optimal policy. Let $\Delta\omega_i^*(p - s)$ be the welfare difference for country i between *Stand-alone* and *the Pair* if optimal policies have been implemented. Country i (or j) would not unilaterally deviate from *the Pair* if its welfare of *the Pair* weakly dominates that of being *Stand-alone*, taking that country j (or i) plays $\{i, j\}$. The *Pair* is a Nash equilibrium coalition if and only if

$$\Delta\omega_i^*(p - s) \geq 0, \forall i \in P \tag{3.3.1}$$

The *Grand Coalition* prevails only when all countries announce the other two countries' names. Given country i and country j play $\{i, j, k\}$, country k can play either $\{k\}$ or $\{i, j, k\}$. The former strategy of country k results in *the Pair* while the latter case leads to *Grand Coalition*. Hence, in order to make *Grand Coalition* be sustained by a Nash equilibrium, acceding *Grand* must be the best choice for country k

$$\Delta\omega_k^*(g - p) \geq 0 \tag{3.3.2}$$

Condition (3.3.2) excludes the incentives of country k to deviate from the last cell in the second box to the last cell in the first box in Figure 3.1. If (3.3.2) is satisfied, country k has no incentives to free ride on *the Pair*. Thus, condition (3.3.2) which excludes the "free riding incentive" is the first key condition in this coalition formation game. However, this condition is not sufficient to ensure that *Grand Coalition* is a Nash equilibrium coalition. In the meanwhile, the incentives of country i (j) to deviate from strategy $\{i, j, k\}$ to $\{i, j\}$ or $\{i\}$ (for country j, it's $\{j\}$) also need to be excluded. *The Pair* will emerge from the former deviation while *Stand-alone* is formed due to the latter deviation. It is clear that country i (j) will not deviate if *Grand* weakly dominates *Stand-alone* (condition (3.3.3)) and *the Pair* (condition (3.3.4)). Therefore, *Grand Coalition* is a Nash equilibrium coalition if and only if conditions (3.3.2)-(3.3.4) are satisfied.

$$\Delta\omega_i^*(g - s) \geq 0, \forall i \in P \tag{3.3.3}$$

$$\Delta\omega_i^*(g - p) \geq 0, \forall i \in P \tag{3.3.4}$$

If condition (3.3.4) holds, country i and j have no incentives to exclude country k from *Grand* and form a *Pair* between themselves. Therefore, (3.3.4) indicates the absence of the "exclusion incentive" of country i and j, which is another key condition in this coalition formation game.

Here is an example provided to show how Nash equilibrium coalition is found. Suppose that the payoffs for each country under different coalition structures are given as follows: $[\{i\}, \{j\}, \{k\}] = (3, 3, 3)$; $[\{i, j\}, \{k\}] = (9, 9, 11)$ and $[\{i, j, k\}] = (15, 15, 15)$. Then the corresponding payoffs in each cell are filled as in Figure 3.2. By applying the Nash equilibrium conditions specified in (3.3.1)-(3.3.4), multiple

Nash equilibrium coalitions arise in this example - *Stand-alone, the Pair* and *Grand coalition* are all Nash equilibrium coalitions. However, a stable coalition should be immune to not only unilateral deviations but also group deviations, which is termed as coalition Nash equilibrium by Nordhaus (2015). Thus, the following subsection specifies the conditions to deal with group deviation by using the concept of strong Nash equilibrium.

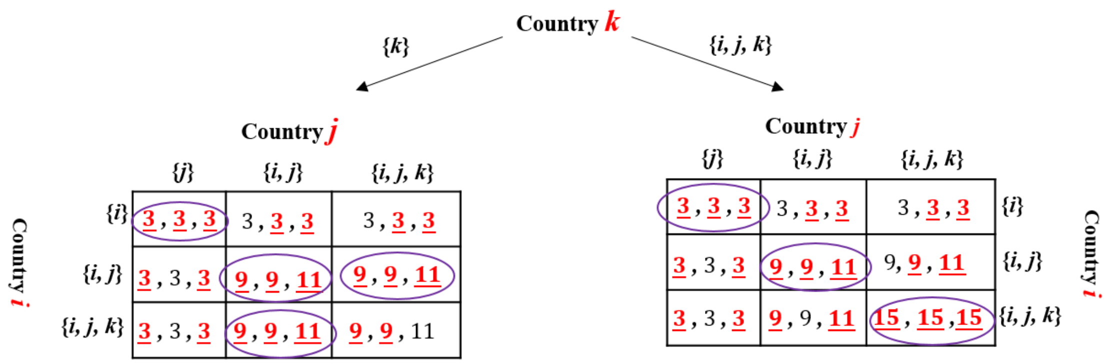

Figure 3.2: An Example to Find Nash Equilibrium Coalitions

Strong Nash Equilibrium Coalitions

Aumann (1959) first defined strong Nash equilibrium as a Nash equilibrium in which no coalition, taking the actions of its complements as given, can cooperatively deviate in a way that benefits all of its members. Hart and Kurz (1983) and Nordhaus (2015) also applied strong Nash equilibrium in studying coalition stability.[7]

A Nash equilibrium *Stand-alone* coalition is strong Nash equilibrium if and only if there are no incentives for group deviations.

$$\Delta\omega_i^*(s-p) \geq 0, \forall i \in P \tag{3.3.5}$$

$$\Delta\omega_i^*(s-g) \geq 0, \forall i \in G \tag{3.3.6}$$

[7]Another frequently used concept in non-cooperative game is coalition-proof Nash equilibrium (CPNE). Bernheim et al. (1987) compared coalition-proof and strong Nash equilibrium (SNE). They argued that strong Nash is too "strong", since the coalition must be resistant to deviations which are not themselves resistant to further deviations. Therefore, the set of SNE should be a subset of the set of CPNE. For example, in Chapter 4, it is shown that *Grand coalition* is not a SNE for $\beta \in [\beta_f^2, \bar{\beta}_f]$, because country k would deviate to be the non-signatory where the coalition structure becomes *the Pair*. If the concept of CPNE is applied, *Grand coalition* is not a CPNE if *the Pair* itself is not further immune to any deviations. As shown in the calculations, for $\beta \in [\beta_f^2, \bar{\beta}_f]$, *the Pair* is immune to further deviations. Therefore, *Grand coalition* is both SNE and CPNE for $\beta \in [\beta_f^2, \bar{\beta}_f]$. A SNE coincides with CPNE according to my numerical calculations in this thesis. Rigorous proofs in a game-theoretical framework are beyond the scope of this thesis.

Condition (3.3.5) excludes group deviation of country i and j to form a Pair while condition (3.3.6) excludes group deviation of all three countries to form *Grand Coalition*. It is evident that in the above example the Nash equilibrium *Stand-alone* coalition is not immune to a group deviation of country i and j to form a Pair since deviation generates a higher payoff for deviators ((3.3.5) is violated since $3 < 9$). At the same time, there are also incentives for three countries to group deviate to form a *Grand Coalition* ((3.3.6) is violated since $3 < 15$). Therefore, *Stand-alone* is not stable in the above example.

In order to let *the Pair* Nash equilibrium coalition be strong Nash equilibrium coalition, the group deviation of country i and country j to *Stand-alone* has to be firstly excluded. Because it is an *exclusive membership* game, either a group deviation of two countries or a unilateral deviation by one member of *the Pair* to *Stand-alone* both results in *Stand-alone* coalition. Fortunately, this incentive has been excluded by (3.3.1). Thus, only the group deviation of three countries to form *Grand* needs to be eliminated. If any of the two following constraints are satisfied, a group deviation of three countries is impossible, thus *the Pair* is a strong Nash equilibrium coalition.

$$\Delta\omega_i^*(p-g) \geq 0, \qquad \forall i \in P \tag{3.3.7}$$

$$\Delta\omega_k^*(p-g) \geq 0 \tag{3.3.8}$$

In the example (Figure 3.2), by applying the two conditions, it is clear that both the Pair members and non-member prefer *Grand Coalition* since $\Delta\omega_i^*(p-g) = -6$ and $\Delta\omega_k^*(p-g) = -4$. Thus *the Pair* is not stable in equilibrium, either.

For a Nash *Grand Coalition* to be strong Nash equilibrium coalition, group deviation to *the Pair* and *Stand-alone* must be eliminated. One benefit of an *exclusive membership* model is that a unilateral deviation by country $i(j)$ to *Stand-alone* or *the Pair* leads to same results of group deviations. These unilateral deviation incentives have been excluded by Nash equilibrium conditions. Hence, a Nash *Grand Coalition* must be a strong Nash equilibrium coalition in this coalition formation game. Therefore, *Grand Coalition* is the only stable coalition in equilibrium in the above example.

3.4 Optimal Policies under Each Coalition Structure

This section solves the optimal policy θ for each country under different coalition structures. In each country or coalition, the benevolent government maximizes the welfare that it is interested in by choosing the optimal policy θ. Some literature abandons the assumption of welfare-maximising governments and adopts a political framework where governments care about particular interest groups, for example Grossman and Helpman (1995), Fredriksson (1997), Limão (2007). This thesis is not one of them and more related discussion can be found in Chapter 5.

3.4.1 *Stand-alone* Equilibrium

The *Stand-alone* equilibrium prevails when no two countries match, or all three countries choose non-cooperation. Then each country undertakes independent production policy and maximizes its welfare by choosing policy θ, taking the policies of other countries as given. The maximization problem for country i is

$$\nu_i^s(\theta_j, \theta_k, \alpha, \beta, a, e) = \max_{\theta_i}\{V_i(\theta_i, \theta_j, \theta_k, \alpha, \beta, a, e) : 0 \leq \theta_i \leq 1\} \tag{3.4.1}$$

It is a maximization problem with two inequality constraints. Since $V_i(\cdot)$ and inequality constraints are both differentiable and concave, this maximization problem can be solved by applying the Kuhn-Tucker Theorem. Details about calculations can be found in Appendix A at the end of this chapter. Because of symmetry, the optimal policy for each country under *Stand-alone* is the same and denoted as θ^s

$$\theta^s(\alpha, \beta, a, e) = \begin{cases} \kappa^s(\alpha, \beta, a, e), & if \quad \kappa^s(\alpha, \beta, a, e) < 1 \\ 1, & if \quad \kappa^s(\alpha, \beta, a, e) \geq 1 \end{cases} \tag{3.4.2}$$

where

$$\kappa^s(\alpha, \beta, a, e) \equiv \frac{9\alpha e}{7e^2 + 54\beta a^2} \tag{3.4.3}$$

which is expressed in terms of "relative preference" α, endowment e, technology level a and climate change severity level β.

The interior solution for θ is strictly decreasing in β since $\partial\kappa^s(\cdot)/\partial\beta < 0$. The intuition is straightforward. As the climate change severity level increases, the welfare loss from production outweighs the welfare gain, so countries choose to produce less. If β is counter-factually set as zero, which implies that no welfare loss from climate change occurs, there will be no need to control greenhouse gas emissions. Consequently, the optimal policy is expected to be one if θ is purely for environmental purpose. However, the optimal policy equals one only when the relative preference parameter is large enough compared to endowment ($\alpha \geq 7e/9$). In contrast, when $\alpha < 7e/9$, a country only uses part of its resources for production ($\theta^s < 1$) even though climate change doesn't cause any utility loss, which indicates that policy θ^s is used to manipulate *terms-of-trade* gain from international trade. As a large supplier, an exporting country with market power implements a more stringent environmental policy (θ^s), reducing the world supply of this good, which further increases the world price and generates a larger monopolistic surplus for such an exporting country. This result proves that trade does play a role in determining climate change policy.

The interior solution is strictly increasing in α since $\partial\kappa^s(\cdot)/\partial\alpha > 0$. The intuition is as follows. A higher "choke price" represents a higher consumers' preference over consumption relative to the environment and the numeraire. The ratio of non-climate welfare to the disutility caused by climate change is higher with a large α compared to the case with a small α, holding β as constant. Therefore, countries would like to produce and consume more (κ^s is bigger) with a higher α. In contrast, the interior solution is strictly decreasing in a since $\partial\kappa^s(\cdot)/\partial a < 0$. With all the other parameter fixed, a measures the emission intensity (technology level). More global emission is obtained if a is big, resulting in higher utility loss caused by climate change. Therefore, as a increases, less resources are used for production.

As is shown from the above analysis, a decrease in α or an increase in a both lead to the same outcome from a increase in β, which is that less resources would be used for production. In order to make the results sharp, this thesis will take special interest in β, instead of varying all parameters. Since the parameter of interest in this chapter is β, I will graphically depict the optimal policies by varying β, with the values of other parameters being given in Table 3.1:

Table 3.1: Values of Parameters

Description	**Parameter**	**Value**
Endowment	e	1
Technology	a	1
Relative Preference	α_1	2/3
	α_2	1

Relative preference parameter α is set as 2/3 and 1 for the following reasons. First, it should satisfy the constraint that $\alpha \geq 2e/3$ to assure non-negative prices and non-decreasing marginal utility. Second, as shown from the analytical solution, when $\alpha < 7e/9$, countries tend to use their production policy to manipulate *terms-of-trade*. Hence, two cases where $\alpha = 2/3$ and 1 are chosen to study the decisions of each country when they have different preferences over consumption relative to the environment. β is varied from 0 to 0.0695 with each step of 0.0005 to analyse the response of policy variable to variations.[8]

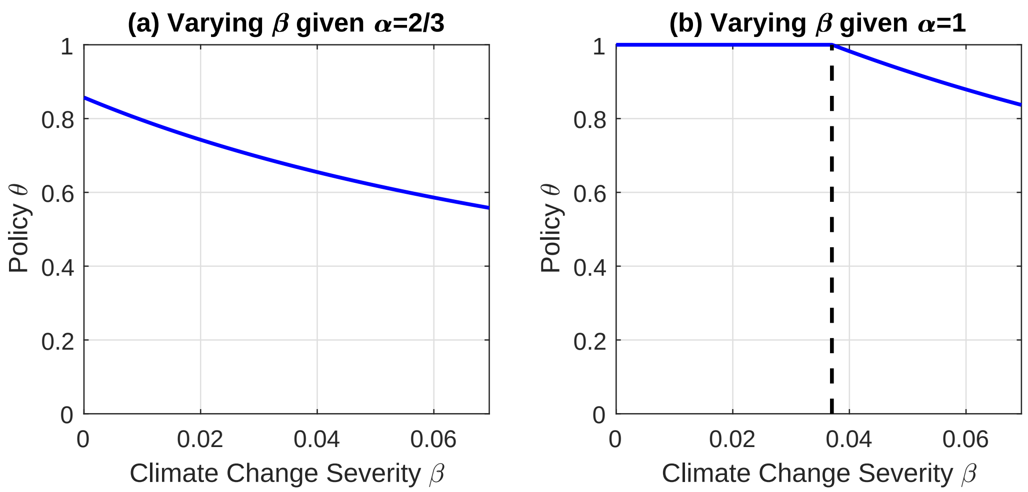

Figure 3.3: *Stand-alone* Equilibrium Policy

Figure 3.3 provides the optimal policy θ by varying climate change severity level

[8] β takes values from this particular range to ensure that trade patterns are consistent with the assumption in the model. More discussion will be given in *the Pair* equilibrium section.

β given $\alpha = 2/3$ and $\alpha = 1$. The simulation results in Figure 3.3 graphically show that when the relative preference over consumption is low ($\alpha = 2/3$), production policy is used to gain *terms-of-trade* in the absence of climate change ($\theta < 1$). When the relative preference increases (α=1), for $\beta \leq 0.0370$, the optimal policy for each country is to emit and produce at their full capacity. Moreover, each country always implements a higher emission policy when relative preference is higher. This is shown by comparing the optimal policy θ in Figure 3.3(a) with that in (b) given same values of β. The intuition is that a higher marginal utility of consumption is obtained with a larger "choke price", α. The *non-climate* welfare in Figure 3.3 (b) is higher than that in Figure 3.3 (a) for same climate damage level β. Therefore, a larger α given β represents a higher preference over consumption of goods relative to the environment. Country i thus uses more resources for production. The above analysis leads to the following proposition.

Proposition 1. *Under Stand-alone equilibrium, an individual country is more likely to use all resources for production when consumers have higher preference over consumption relative to the environment. The interior solution is decreasing in climate change severity level and it is manipulated for both emission control and gains from international trade.*

3.4.2 *The Pair* Equilibrium

The Pair equilibrium arises when two countries want to form a coalition with each other or the third country refuses to join *Grand Coalition*. If two countries, country i and j, form an IEA, they will cooperate to maximize their joint welfare. However, it is essential to specify how signatories of *the Pair* cooperate on policy. One of the options is that countries cooperate but each of them still has the right to implement their own policy. The other option is that signatories of an IEA should implement same policy to mitigate climate change. This chapter adopts the latter one.[9]

Within the latter framework, signatories choose the same policy θ^p (policy of signatories) to maximize their joint welfare, taking policy of non-signatory, θ_k, as

[9] Same framework is applied when *Grand Coalition* is formed.

given. The maximization problem for signatories is

$$\nu_{ij}^p(\theta_k, \alpha, \beta, a, e) = \max_{\theta^p}\{V_i^p(\theta^p, \theta_k, \alpha, \beta, a, e) + V_j^p(\theta^p, \theta_k, \alpha, \beta, a, e) : 0 \leq \theta^p \leq 1\} \tag{3.4.4}$$

Meanwhile, the non-signatory (i.e., country k) also maximizes its own welfare by choosing θ_k given the policy of the signatories, with the maximization problem given as

$$\nu_k^p(\theta^p, \alpha, \beta, a, e) = \max_{\theta_k}\{V_k^p(\theta^p, \theta_k, \alpha, \beta, a, e) : 0 \leq \theta_k \leq 1\} \tag{3.4.5}$$

Details about calculations can be found in Appendix B. The solutions for the policy parameter for the signatories and non-signatories under *the Pair* equilibrium are

$$(\theta^p, \theta_k) = \begin{cases} (\kappa_1^p(\alpha,\beta,a,e), \kappa_2^p(\alpha,\beta,a,e)), & if \quad 0 < \quad k_1^p(\alpha,\beta,a,e) < 1, \\ & \qquad k_2^p(\alpha,\beta,a,e) < 1 \\ (\kappa_3^p(\alpha,\beta,a,e), 1), & if \quad \kappa_4^p(\alpha,\beta,a,e) > 1, \quad \kappa_5^p(\alpha,\beta,a,e) < 1 \\ & \qquad \kappa_2^p(\alpha,\beta,a,e) \geq 1 \\ (1, \kappa_6^p(\alpha,\beta,a,e)), & if \quad \kappa_7^p(\alpha,\beta,a,e) > 1, \quad \kappa_8^p(\alpha,\beta,a,e) < 1 \\ & \qquad \kappa_1^p(\alpha,\beta,a,e) \geq 1 \\ (1,1), & if \quad \kappa_5^p(\alpha,\beta,a,e) \geq 1, \quad \kappa_8^p(\alpha,\beta,a,e) \geq 1 \end{cases}$$

where

$$\begin{aligned} \kappa_1^p(\alpha,\beta,a,e) &\equiv \tfrac{81\alpha(e^2-4\beta a^2)}{2e(29e^2+378\beta a^2)} & \kappa_2^p(\alpha,\beta,a,e) &\equiv \tfrac{36\alpha(e^2+9\beta a^2)}{e(29e^2+378\beta a^2)} \\ \kappa_3^p(\alpha,\beta,a,e) &\equiv \tfrac{18\alpha e-e^2-72\beta a^2}{12e^2+144\beta a^2} & \kappa_4^p(\alpha,\beta,a,e) &\equiv \tfrac{18\alpha e}{e^2+72\beta a^2} \\ \kappa_5^p(\alpha,\beta,a,e) &\equiv \tfrac{18\alpha e}{13e^2+216\beta a^2} & \kappa_6^p(\alpha,\beta,a,e) &\equiv \tfrac{9\alpha e-2e^2-36\beta a^2}{5e^2+18\beta a^2} \\ \kappa_7^p(\alpha,\beta,a,e) &\equiv \tfrac{9\alpha e}{2e^2+36\beta a^2} & \kappa_8^p(\alpha,\beta,a,e) &\equiv \tfrac{9\alpha e}{7e^2+54\beta a^2} \end{aligned}$$

A few implications can be drawn from the above analytical solution. First, countries never implement extreme policy to produce nothing ($\theta = 0$) no matter how severe the climate change problem is, since all these solutions have been ruled out due to contradictions.[10] Second, the interior solution (κ_1^p, κ_2^p) is strictly decreas-

[10]The contradictions are discussed in Appendix B.

ing in β so that both parties will tighten their policies as climate change problem becomes severe. Third, when interior solution is obtained, non-signatory emits more greenhouse gas emissions and free rides on the mitigation efforts contributed by signatories for $\beta > \frac{1}{108}$.[11] However, when $\beta < \frac{1}{108}$, signatories emits more than the free rider, but the policy is mainly used to manipulate gains from international trade. Put differently, signatories implement a less stringent policy than the environmentally optimal one for the purpose of gains from international trade.[12] Last, under some circumstances, signatories also free ride on non-signatory $(1, \kappa_6^p)$, where $1 > \kappa_6^p$, or both parties produce at their full capacity (1,1).

Figure 3.4 depicts when each solution is obtained for different values of β and α given that $a = 1, e = 1$. It is noteworthy that β takes values from 0 to 0.0695 since larger β contradicts the assumption of trade patterns assumed in the model. The model assumes that country i exports good J/K to its trading partners while it imports good I from them. However, when climate change becomes destructive (β is big), signatories have to implement a relatively stringent policy, making it beneficial for signatories (e.g., country i) to import good J from the free rider, rather than producing and exporting by itself. Due to this contradiction, I restrict the values of β to be between 0 and 0.0695.[13]

[11]The value of β is solved by $\kappa_2^p - \kappa_1^p > 0$.

[12]This point is not very clearly proved with the solution here. But it will be clear when I derive optimal policy structures in Chapter 4.

[13]The exogenously determined trade pattern simplifies the analysis by ruling out the values of parameters that contradict the assumption of trade pattern. One should keep in mind that this exogenously assumed trade pattern implies that trade pattern (direction) will not respond to the formation of IEAs. The *pollution haven effect* proves that the stringency of environmental policy does affect trade pattern (Ederington and Minier, 2003; Levinson and Taylor, 2008, etc.). However, the comparative advantage actually depends on various factors (e.g., factor endowment, technology difference) in addition to environmental policy. If the *pollution haven effect* is not strong enough to dominate the other traditional factors that affect trade, the *pollution haven hypothesis* may fail. As shown in the literature, *the pollution haven hypothesis* is not supported from both theoretical and empirical perspectives. Therefore, it is reasonable to assume that the differences in environmental regulation will not change trade directions in this chapter.

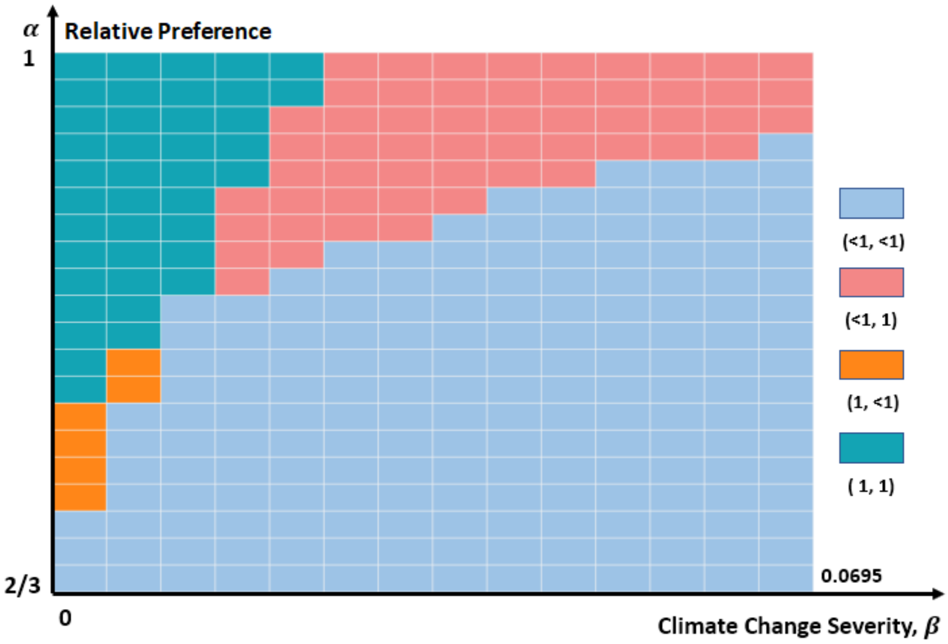

Figure 3.4: *The Pair* Equilibrium Policy by Varying α, β

[14]Note: notations on the right of the above figure represent the policy sets (θ^p, θ_k) of signatories and non-signatories. For example, $(< 1, 1)$ represents $\theta^p < 1, \theta_k = 1$.

Figure 3.4 shows that non-signatory free rides on signatories when climate change is severe or the relative preference is really small (the red and blue grids), while signatories only free ride when climate change is not severe and relative preference is big (the orange grids and green ones). This latter case shares similar reason with the other cases when signatories use a higher θ to manipulate gains from trade. When consumers prefer consumption more relative to the environment (α is big), and at the same time, climate change damage is not severe, both signatories and non-signatory produce at their full capacity since the gains from production outweigh the losses from climate change. Figure 3.4 also shows that for any α, the higher the β is, the less the countries will produce, but usually signatories start reducing emissions first. In contrast, for any given β, as the relative preference increases (α), countries start producing more and the free rider increases emissions firstly.

Given the values of parameters in Table 3.1, the optimal policies for both signatories and non-signatory under *the Pair* given $\alpha = 2/3$ and 1 are shown in Figure 3.5. This figure further confirms the conclusions drawn above. Given $\alpha = 2/3$, signatories implement laxer environmental regulation than non-signatory when β is small. This manipulation is mainly for gains in trade. As β increases, non-signatory free rides on signatories. For same values of β, more resources are used for production both for signatories and non-signatories when consumers have a higher preference over consumption relative to the environment. This is again because the *non-climate* welfare is higher relative to the disutility caused by climate change when the "choke price" α is larger.

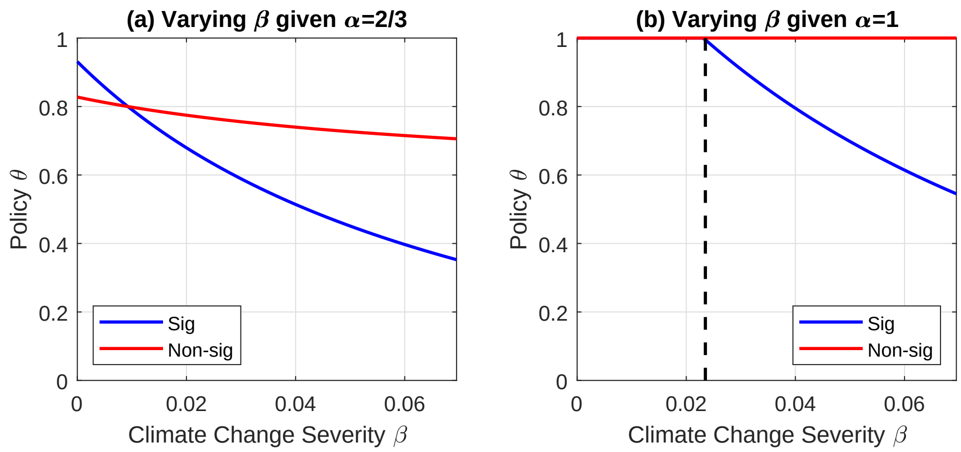

Figure 3.5: *The Pair* Equilibrium Policy

The above discussions lead to the following proposition.

Proposition 2. *Under the Pair equilibrium, non-signatory emits more greenhouse gas emissions and free rides on signatories most of the time. In contrast, signatories implement less stringent policy only when climate change is not severe. This high production policy is mainly used to manipulate gains from international trade.*

3.4.3 *Grand Coalition* Equilibrium

Grand Coalition is achieved when all three countries choose to cooperate with the other two countries. Under *Grand Coalition*, three countries cooperate by setting same policy $\theta_i^g = \theta_j^g = \theta_k^g = \theta^g$ to maximize the global welfare. The welfare maximization problem is

$$\nu^g(\alpha, \beta, a, e) = \max_{\theta^g}\{\sum_{i,j,k} V_i(\theta^g, \alpha, \beta, a, e) : 0 \leq \theta^g \leq 1\} \tag{3.4.6}$$

which is solved by (details can be found in Appendix C)

$$\theta^g(\alpha,\beta,a,e) = \begin{cases} \kappa^g(\alpha,\beta,a,e), & if \quad \kappa^g(\alpha,\beta,a,e) < 1 \\ 1, & if \quad \kappa^g(\alpha,\beta,a,e) \geq 1 \end{cases} \tag{3.4.7}$$

where

$$\kappa^g(\alpha,\beta,a,e) \equiv \frac{3\alpha e}{2e^2 + 54\beta a^2} \geq 1 \tag{3.4.8}$$

The optimal solution under *Grand Coalition* has similar structure to that under *Stand-alone*. Given the values of parameters in Table 3.1, the optimal policy under *Grand* is shown in Figure 3.6. Under *Grand Coalition*, there is no need to manipulate *terms-of-trade* gain, so $\theta^g = 1$ when climate change does not cause any utility loss ($\beta = 0$), as is shown in Figure 3.6(a). Compared to the optimal policies under *Stand-alone*, the externality is internalized to a larger degree under *Grand Coalition*, and thus countries implement relatively stringent policy under *Grand*. The above analysis leads to Proposition 3.

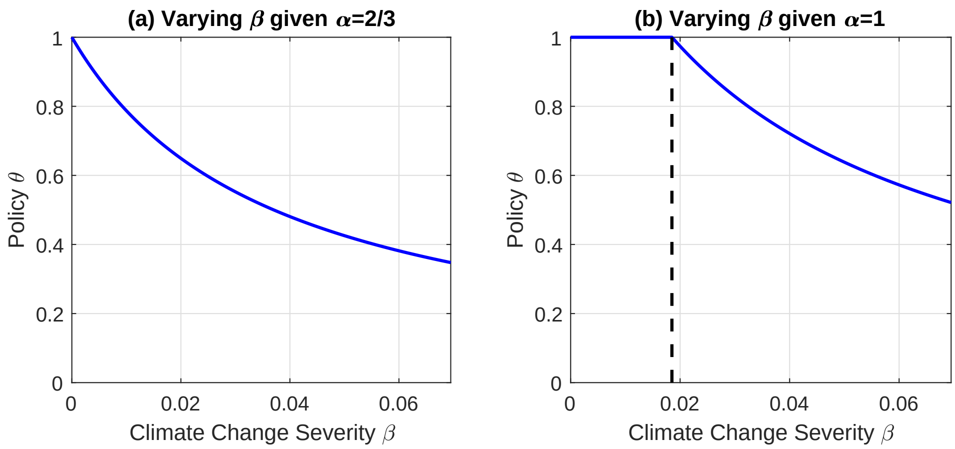

Figure 3.6: *Grand Coalition* Equilibrium Policy

Proposition 3. *Under Grand Coalition equilibrium, there is no need to manipulate gains from international trade. The policy is only for environmental purpose.*

3.5 IEA Formation Outcomes

The optimal policy for each country under different coalition structures has been calculated. The welfare for each country with the optimal policy being implemented can be obtained by substituting those optimal polices into indirect utility function (3.2.15). However, the welfare cannot be calculated analytically because the optimal policies under *the Pair* are too complex. Thus, a simulation method is used to study the endogenous formation of an IEA when climate change severity level changes given the values of relative preference α, endowment e and technology a specified in Table 3.1.[15] More specifically, this section answers how climate change severity level affects the stable coalition in equilibrium given the values of other three exogenous variables. Based on the stable coalition, this section takes non-cooperation as a starting point and compares the global welfare gain and the global emission reduction of *the Pair* and *Grand Coalition* from non-cooperation. Lastly, this section discusses how trade affects the climate change coalition formation outcomes in a competing exporters trade model.

3.5.1 Stable Coalition in Equilibrium

Before I calculate the welfare, it is useful to compare the optimal policies of each country under different coalition structures. According to the optimal policies obtained in the previous section (as shown in Figure 3.3, Figure 3.5 and Figure 3.6), when the climate change severity level is low ($\beta \leq 0.015$), all three countries produce and emit the most, irrespective of the coalition structures. As the climate change problem becomes severe, countries implement different policies under three coalition structures. From $\beta = 0.020$, *Grand Coalition* starts internalizing the externality by choosing an interior solution. However, *Stand-alone* and *the Pair* are still producing and emitting at their full capacity. As the climate change problem is becoming worse ($\beta > 0.020$), *the Pair* members also start reducing emissions while the non-signatory emits the most and free rides all the time. Only when the welfare loss from climate change is large enough ($\beta > 0.035$), countries under *Stand-alone* start to reduce emissions.

With these optimal polices, the welfare of each country under all coalition structures is firstly computed and presented in Table 3.2. In this table, the second

[15] α takes the value of one as an example in this section. The reason is that with α being 1, the scenarios with corner solution can be considered.

column represents the values of β while the third to last columns show the welfare of each country under three different coalition structures. Because of symmetry, countries under *Stand-alone* get same welfare. I will not distinguish country i, j, k. Same argument holds for *Grand Coalition*. This section then firstly applies Nash equilibrium coalition concept (3.3.1-3.3.4), which was introduced in Section 3.3.2, to exclude the unilateral deviations in the formation of the IEA. The red contents in Table 3.2 imply this it is a Nash equilibrium coalition.

Table 3.2: Nash Equilibrium Coalitions

No.	β	**Stand-alone**	**Pair**(i,j)	**Pair**(k)	**Grand**
1	0	1.3333	1.3333	1.3333	1.3333
2	0.005	1.2433	1.2433	1.2433	1.2433
3	0.010	1.1533	1.1533	1.1533	1.1533
4	0.015	1.0633	1.0633	1.0633	1.0633
5	0.020	0.9733	0.9733	0.9733	0.9740
6	0.025	0.8833	0.8839	0.8931	0.8955
7	0.030	0.7933	0.8008	0.8392	0.8287
8	0.035	0.7033	0.7247	0.7973	0.7712
9	0.040	0.6264	0.6548	0.7651	0.7212
10	0.045	0.5637	0.5903	0.7407	0.6772
11	0.050	0.5070	0.5307	0.7226	0.6383
12	0.055	0.4554	0.4753	0.7098	0.6036
13	0.060	0.4086	0.4239	0.7012	0.5725
14	0.065	0.3658	0.3759	0.6961	0.5445

For $\beta \in \{0, 0.005, 0.010, 0.015\}$ (No.1-4 in the table), since all three countries produce and emit the most, there is no difference in the welfare between different coalition structures. Any coalition is a Nash equilibrium coalition because no one has incentives to deviate from current coalition structure.[16]

For $\beta \in \{0.020, 0.025\}$ (No.5-6 in the table), *Stand-alone*, *the Pair* and *Grand*

[16]Since every coalition is a Nash equilibrium coalition due to the fact that countries all choose corner solutions, I will not highlight those four rows.

Coalition are all Nash equilibrium coalitions. *Stand-alone* is a Nash equilibrium coalition, irrespective of the values of β, since the best choice for the third country is to stand-alone, given that the other two countries choose non-cooperation.

The Pair is a Nash equilibrium coalition as the members of *the Pair* are weakly better off with *the Pair*, thus each of them has no incentives to unilaterally deviate (3.3.1 holds). Take No.6 as an example. Given country j announces $\{i, j\}$, if country i plays $\{i\}$, the payoff is 0.8833. However, a higher payoff 0.8839 can be achieved if country i plays $\{i, j\}$. Same argument holds for country j. Hence, as long as the incentives for country i and country j to deviate to stand-alone have been eliminated, *the Pair* is a Nash equilibrium coalition.

Grand Coalition is also a Nash equilibrium coalition. Incentives for country k to free ride is excluded because being a member of *Grand Coalition* generates higher welfare (0.8955) than under *the Pair* (0.8931). On the other hand, given that country k and country j play $\{i, j, k\}$, incentives for country i to play $\{i\}$ or $\{i, j\}$ are all eliminated since *Grand Coalition* gives it the highest payoff. Same argument holds for country j. Hence, taking the other countries strategies as given, the best choice for the third country is always to play $\{i, j, k\}$.

However, as β increases (No.7-14 in the table), *Grand Coalition* is no more a Nash equilibrium coalition. Because condition (3.3.2) is no more satisfied. Given that country i and country j all play $\{i, j, k\}$, country k has incentives to deviate from *Grand* to be the outsider of *the Pair*, where a higher welfare is obtained. As the welfare loss from emission becomes higher, which indicates that the cost for climate change mitigation also becomes high, country k has strong incentives to free ride on the mitigation achievements of the others. This free-riding hampers the welfare of the other two signatories since they implement stringent emission policies at their own costs while the free-rider enjoys the welfare of low emissions without any costs at its own side. Even though signatories have been free rided by the third country, they are still better off to form *the Pair*. Thus, *the Pair* is a Nash equilibrium coalition for No.7-14 in the table.

By applying Nash equilibrium concept, multiple Nash equilibrium coalitions exist. However, which one will eventuate in equilibrium? I then apply the strong

Nash equilibrium concept to deal with group deviations in the following part. The red contents in Table 3.3 imply that it is a stable coalition in equilibrium.

Table 3.3: Strong Nash Equilibrium Coalition

No.	β	**Stand-alone**	**Pair**(i,j)	**Pair**(k)	**Grand**
1	0	1.3333	1.3333	1.3333	1.3333
2	0.005	1.2433	1.2433	1.2433	1.2433
3	0.010	1.1533	1.1533	1.1533	1.1533
4	0.015	1.0633	1.0633	1.0633	1.0633
5	0.020	0.9733	0.9733	0.9733	0.9740
6	0.025	0.8833	0.8839	0.8931	0.8955
7	0.030	0.7933	0.8008	0.8392	0.8287
8	0.035	0.7033	0.7247	0.7973	0.7712
9	0.040	0.6264	0.6548	0.7651	0.7212
10	0.045	0.5637	0.5903	0.7407	0.6772
11	0.050	0.5070	0.5307	0.7226	0.6383
12	0.055	0.4554	0.4753	0.7098	0.6036
13	0.060	0.4086	0.4239	0.7012	0.5725
14	0.065	0.3658	0.3759	0.6961	0.5445

There are three Nash equilibrium coalitions when $\beta \in \{0.020, 0.025\}$. Among these three Nash equilibrium coalitions, only *Grand Coalition* is stable if unlimited communications between countries are allowed. Because there are no incentives for the three countries to jointly deviate to form *Stand-alone* or *the Pair*. As β increases to be above 0.030, two Nash equilibrium coalitions are obtained. However, *Stand-alone* is not strong Nash equilibrium coalition since country i and country j have incentives to jointly deviate to form *the Pair* (condition (3.3.5) is violated). To sum up, *Grand Coalition* is stable when β is relatively small. As climate change problem becomes severe, the incentives to free ride become strong, *Grand Coalition* is no more stable, therefore, *the Pair* is in equilibrium.

The above discussions can be summarized as the following proposition.

Proposition 4. *Given the values of parameters in Table 3.1, Grand Coalition is a strong Nash equilibrium when climate change problem is not severe. As climate change problem becomes worse, the incentives to free ride get stronger and the Pair becomes a strong Nash equilibrium.*

3.5.2 Welfare Gain and Emission Reduction

This section takes the non-cooperation case (i.e., *Stand-alone*) as the business-as-usual scenario and compares the welfare gain and emission reduction between cooperation (i.e., *Grand Coalition*, *the Pair*) and non-cooperation from a global perspective. The purpose of this analysis is to show how much we could potentially gain if a climate change cooperation coalition is formed and what the effects of such a coalition are in terms of emission reduction.

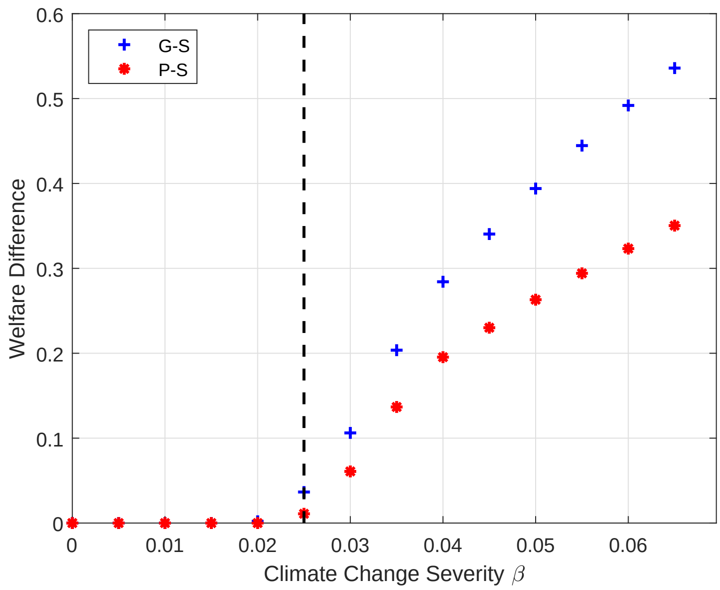

Figure 3.7: Welfare Gain from Non-cooperation

[17]Note: $G-S$ is the welfare difference between *Grand Coalition* and *Stand-alone*, while $P-S$ is the welfare difference between *the Pair* and *Stand-alone*.

Figure 3.7 depicts the welfare gain from *Grand Coalition* and *the Pair* compared to *Stand-alone* from a global perspective as climate change severity level changes. It shows that there is no difference in welfare between three coalition structures as countries always produce and emit at their full capacity when climate change severity level is low. The global welfare gain from cooperation becomes large as the climate change severity level β increases. Moreover, the welfare gain from full co-operation (i.e., *Grand Coalition*) is much higher than that from partial cooperation (i.e., *the Pair*). More importantly, this gap is enhanced as β becomes larger, which implies that full cooperation is highly needed and also welfare-improving when climate change problem is very severe. However, full cooperation is only achievable when the welfare gain is small (to the left of the vertical dashed line). As β increases, *Grand Coalition* is no more in equilibrium. That's because under *Grand Coalition*, countries are required to implement a much more stringent policy to internalize the externality, which results in a high mitigation cost. Then free riding becomes attractive since the free rider can enjoy the benefit from abating efforts contributed by other countries without any cost on its side.

This puts IEA formation in a dilemma situation where *Grand Coalition* is in equilibrium with relatively low welfare gain and as the welfare gain increases, *Grand Coalition* is no more in equilibrium. There is an inverse relationship between the number of signatories and the gains to cooperation. *Grand Coalition* might be possible only when the welfare gain is small. This finding is consistent with other literature, for example Barrett (1994a), McGinty (2007).

Figure 3.8 depicts the global emission reduction results from climate change cooperation. *Grand Coalition* is quite effective in terms of emission reduction. The global emission of business-as-usual can be reduced by as high as 30% if full cooperation is achieved.[18] In contrast, partial cooperation can only reduce the business-as-usual emission by 14%. The emission reduction outcomes from cooperation further confirm that full cooperation matters more when climate change problem becomes severe.

[18]This emission reduction is calculated by $\frac{Z_g - Z_s}{Z_s}$, where $Z_g = 6\theta^g a$, $Z_s = 6\theta^s a$. Same calculation method applies for the comparison between partial cooperation and non-cooperation.

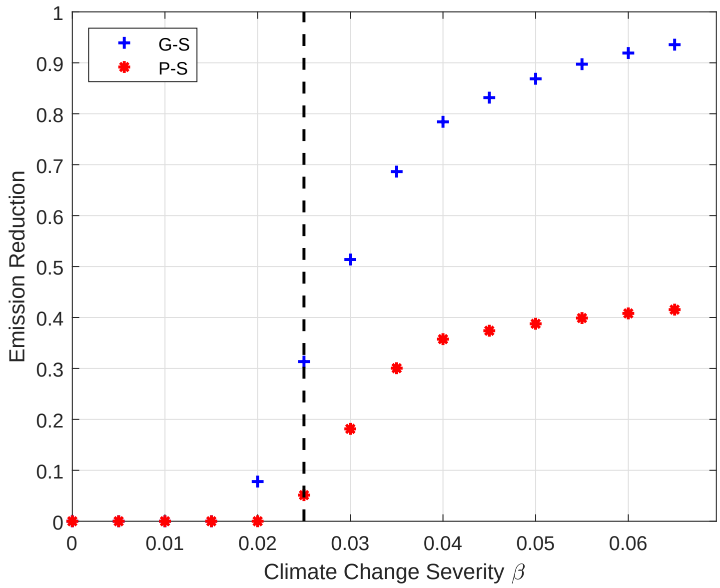

Figure 3.8: Emission Reduction from Non-cooperation

[19]Note: $G - S$ is the emission reduction between *Grand Coalition* and *Stand-alone*, while $P - S$ is the emission reduction between *the Pair* and *Stand-alone*.

The above discussions can be summarized as the following proposition.

Proposition 5. *Given the values of parameters in Table 3.1, when the climate change problem is not severe, welfare gain and emission reduction from Grand Coalition is small even though Grand Coalition is a strong Nash equilibrium. As the climate change problem becomes severe, welfare gain and emission reduction from Grand Coalition become large. However, the incentives for the free rider to deviate increases at the same time, and Grand Coalition no more a strong Nash equilibrium.*

3.5.3 Trade Effects on Climate Change Cooperation

As is discussed in the Literature Review Chapter, the close interactions between international trade and the environment complicate the mechanism of climate change cooperation, since countries are connected not only via climate change but also by international trade. In an environment where trade policy is binding due to a trade agreement, countries have incentives to use environmental policy as a second-best policy to manipulate gains from trade (Markusen, 1975b). As a result, the gains and losses from international trade should be taken into consideration when countries are making decisions about cooperation on climate change. Theoretically, a large import-competing country tends to loosen the domestic environmental regulation, which aims to provide an advantage to domestic firms in competition, thus it is reluctant to join an IEA. Because with an IEA, the environmental externality is internalized to a higher degree, requiring a more stringent domestic environmental policy. By contrast, a large export-competing country prefers to tighten the environmental policy, because this export-competing country can enjoy a monopolistic gain from a stringent environmental policy. By acceding to an IEA, the market power of these large export-competing economies is enhanced, and an even higher *terms-of-trade* gain is obtained. This potential benefit from participating in IEAs partly offset the free riding incentives. Thus, trade will facilitate cooperation on climate change.

The model employed in this chapter is a large export competing trade model with global environmental externality. This model shows that these export competing countries do use environmental policy for *terms-of-trade* gains. For example, under *Stand-alone*, each country only uses part of the resources for production even when climate change does not cause any welfare loss (shown in Figure 3.3(a)). By contrast, when the incentives for trade gains are eliminated, countries then use all resources for production, which is shown in *Grand Coalition* Figure 3.6(a).

The use of environmental policy for *terms-of-trade* affects the outcomes of climate change cooperation. The coalition structure of *Stand-alone* resembles a three-firm Cournot market while the formation of *the Pair* resembles a merger of two firms. Then the market power of *the Pair* is enhanced via merger, so that members of *the Pair* enjoy an even higher monopolistic gain by manipulating the environmental policy. Especially when the climate change problem is not severe, the environmental policy works more as a second-best policy for trade gains. Thus, when $\beta \in \{0.020, 0.025\}$, the free rider is worse off by free riding *the Pair* than being a member of *Grand Coalition*. Consequently, *Grand Coalition* is in equilibrium. The intuition is as follows: when β is small, *the Pair* uses environmental policy mainly to exploit *terms-of-trade* gains in international trade while the free rider is being exploited and loses from trade even though it free rides on the mitigation efforts of *the Pair*. The welfare loss from being exploited in international trade by *the Pair* outweighs the gains from free riding on environmental side. Thus, the free rider prefers to join *Grand Coalition*. However, if the climate change problem becomes severe, the welfare gain from free riding on environment outweighs the welfare loss of being exploited, and so the free rider again chooses to deviate from *Grand Coalition*. Then *the Pair* is in equilibrium. To sum up, I come to the following proposition.

Proposition 6. *In an export-competing economy, countries which form a partial coalition implement stringent environmental policy to generate a monopolistic gain from international trade when trade policies are binding. When climate change severity level is low, the environmental policy of the Pair is mainly used to manipulate terms-of-trade from the free rider, which eliminates the free riding incentives of country k.*

3.6 Conclusion

This chapter modelled the IEA formation in an open economy by building a "three-country, three-good" general equilibrium trade model with a global externality, where the effects of trade on climate change cooperation can be analysed. Another key contribution of this study is that it introduced a novel framework to study IEA formation. The coalition formation is defined as a two-stage game where in stage one, each country proposes a list of countries that it wants to form a coalition with and the coalition is formed according to the *exclusive membership rule* (or Hart and Kurz (1983)'s Δ game). Then in second stage, countries maximize the welfare that they are interested in by choosing optimal policies. With this framework, the strategic behaviour of each country in forming an IEA is determined.

The optimal policies for each country under different coalition structures were firstly solved. I show that countries implement relatively laxer policy under *Stand-alone* than that of *Grand Coalition*. The non-signatory of *the Pair* free rides on the emission reduction efforts contributed by signatories of *the Pair*. As the climate change problem becomes severe, the environmental policy is tightened no matter what coalition structure is in place. Environmental policy is used both for emission reduction and *terms-of-trade* gains in international trade under *Stand-alone* and *the Pair*.

By applying Nash and strong Nash equilibrium conditions, I can predict which coalition is likely to be formed in equilibrium. Given the values of parameters in Table 3.1, the model implies that when the climate change problem is not severe, welfare gain and emission reduction from *Grand Coalition* is small even though *Grand Coalition* is in equilibrium. As the climate change problem becomes severe, welfare gain and emission reduction from *Grand Coalition* becomes large. However, the incentives for the free rider to deviate increases at the same time, and *Grand Coalition* cannot be achieved any more.

I also discussed how trade affects the formation outcomes of an IEA. Countries which form a partial coalition implement stringent environmental policy to generate a monopolistic gain from international trade due to more market power when trade policies are binding. When climate change severity level is low, the use of environmental policy to exploit *terms-of-trade* from the free rider eliminates the free riding incentives of country k. In this sense, international trade facilitates climate change cooperation. However, the analysis of trade effects are mainly based on numerical examples. Further work that explicitly analyses trade effects on climate change cooperation will be conducted in the next chapter.

Appendix

A: ***Stand-alone*** Equilibrium

This section solves the optimal production policy for countries under *Stand-alone*. The Kuhn-Tucker condition for welfare maximization problem under *Stand-alone* is applied to obtain

$$2\alpha e - (\frac{10}{9}e^2 + 4\beta a^2)\theta_i - (\frac{2}{9}e^2 + 4\beta a^2)\theta_j - (\frac{2}{9}e^2 + 4\beta a^2)\theta_k - \lambda_i \leq 0 \leq \theta_i$$
$$1 - \theta_i \geq 0 \leq \lambda_i$$

With symmetry, each country chooses same optimal policy such that $\theta^s = \theta_i = \theta_j = \theta_k$ and $\lambda^s = \lambda_i = \lambda_j = \lambda_k$. Now the above two constraints are simplified as

$$2\alpha e - \frac{14e^2}{9}\theta^s - 12\beta a^2\theta^s - \lambda^s \leq 0 \leq \theta^s \tag{3.6.1}$$

$$1 - \theta^s \geq 0 \leq \lambda^s \tag{3.6.2}$$

Condition (3.6.1) implies that the two inequality constraints hold and when they are multiplied together, it yields zero. Same argument holds for condition (3.6.2). The above system is solved by discussing different cases. Since $\theta^s = 0$ contradicts the assumption that α and e are positive, the case that a country implements extreme policy to produce nothing can be ruled out.

By assuming $\theta^s = 1$, $\lambda^s \geq 0$ is indicated from (3.6.2). In order to further have the multiplied term being zero in condition (3.6.1), the left hand of equation (3.6.1) should equalize 0, indicating that $\lambda^s = 2\alpha e - \frac{14}{9}e^2 - 12\beta a^2 \geq 0$, from which I further obtain $\kappa^s(\alpha, \beta, a, e) \equiv \frac{9\alpha e}{7e^2+54\beta a^2} \geq 1$. By checking the contradiction with the constraint that $\alpha \geq 2e/3$, it concludes that as long as $\kappa^s(\alpha, \beta, a, e) \geq 1$ holds, the constraint on α is satisfied.[20]

I then consider the interior solution by assuming $0 < \theta^s < 1$. The multiplied terms in condition (3.6.1) and condition (3.6.2) being zero indicate that $\lambda^s = 0$ and also $2\alpha e - \frac{14}{9}e^2\theta^s - 12\beta a^2\theta^s = 0$, from which θ^s is solved as $\theta^s(\alpha, \beta, a, e) = \kappa^s(\alpha, \beta, a, e)$, where $\kappa^s(\alpha, \beta, a, e) \equiv \frac{9\alpha e}{7e^2+54\beta a^2}$. Thus, $\theta^s = \kappa^s(\alpha, \beta, a, e)$ provided that $\kappa^s(\alpha, \beta, a, e) < 1$.

B: ***The Pair*** Equilibrium

This section solves the optimal production policies for both signatories and non-signatory under *the Pair*. The Kuhn-Tucker conditions for welfare maximization

[20] I did contradiction check for all solutions with the constraint on α in this chapter. Results show that there it no contradiction in the following solutions as well. For simplicity, I will not provide details about the contradiction check in the following section.

problem of signatories of *the Pair* is applied to obtain

$$4\alpha e - \frac{8e^2}{3}\theta^p - \frac{2e^2}{9}\theta_k - 16\beta a^2(2\theta^p + \theta_k) - \lambda_{ij} \leq 0 \leq \theta^p \tag{3.6.3}$$

$$1 - \theta^p \geq 0 \leq \lambda_{ij} \tag{3.6.4}$$

while those for the non-signatory are given as

$$2\alpha e - \frac{4e^2}{9}\theta^p - \frac{10e^2}{9}\theta_k - 4\beta a^2(2\theta^p + \theta_k) - \lambda_k \leq 0 \leq \theta_k \tag{3.6.5}$$

$$1 - \theta_k \geq 0 \leq \lambda_k \tag{3.6.6}$$

The system (3.6.3) to (3.6.6) defines the equilibrium policies for both signatories and non signatory under *the Pair* equilibrium.

A few cases can be firstly ruled out due to contradiction. $(\theta^p, \theta_k) = (0, 0)$ again is ruled out since this solution contradicts the assumption that α, e have to be positive. $\theta^p = 0, 0 < \theta_k < 1$ and $\theta^p = 0, \theta_k = 1$ also are ruled out because they contradict the trade patterns assumed in this study. As is assumed, country i export good J to the signatory of *the Pair*. When signatories implement extreme policy as $\theta^p = 0$, country i has to import good J from the other exporting country k, rather than exporting it. The two cases that signatories use all/part of their endowed resources for production while non-signatory doesn't produce at all (i.e., $(0 < \theta^p < 0, \theta_k = 0)$, $(\theta^p = 1, \theta_k = 0)$) are also ruled out because these solutions contradict the assumption of exogenous parameters.

By assuming that both polices are interior, the above system (3.6.3-3.6.6) indicates that $\lambda_{ij} = \lambda_k = 0$ and $4\alpha e - \frac{8e^2}{3}\theta^p - \frac{2e^2}{9}\theta_k - 16\beta a^2(2\theta^p + \theta_k) = 0, 2\alpha e - \frac{4e^2}{9}\theta^p - \frac{10e^2}{9}\theta_k - 4\beta a^2(2\theta^p + \theta_k) = 0$. The two equations are solved simultaneously to arrive $\theta^p = \kappa_1^p(\alpha, \beta, a, e) \equiv \frac{81\alpha(e^2 - 4\beta a^2)}{2e(378\beta a^2 + 29e^2)}$ and $\theta_k = \kappa_2^p(\alpha, \beta, a, e) \equiv \frac{36\alpha(9\beta a^2 + e^2)}{e(378\beta a^2 + 29e^2)}$. In order to satisfy the assumption about interior solution, $0 < \kappa_1^p(\alpha, \beta, a, e) < 1$ and $0 < \kappa_2^p(\alpha, \beta, a, e) < 1$. Since all the parameters are positive, hence $\kappa_2^p(\alpha, \beta, a, e) > 0$.

By assuming $0 < \theta^p < 1$ and $\theta_k = 1$, condition (3.6.3-3.6.4) implies that $\lambda_{ij} = 0$ and $4\alpha e - \frac{8e^2}{3}\theta^p - \frac{2e^2}{9} - 16\beta a^2(2\theta^p + 1) = 0$, from which θ^p is solved as $\theta^p = \kappa_3^p(\alpha, \beta, a, e) \equiv \frac{18\alpha e - e^2 - 72\beta a^2}{12e^2 + 144\beta a^2}$. The assumption of being an interior solution of

θ^p requires $\kappa_4^p(\alpha,\beta,a,e) \equiv \frac{18\alpha e}{e^2+72\beta a^2} > 1$ and $\kappa_5^p(\alpha,\beta,a,e) \equiv \frac{18\alpha e}{13e^2+216\beta a^2} < 1$. In the meanwhile, condition (3.6.5- 3.6.6) also imply $\lambda_k = 2\alpha e - \frac{4e^2}{9}\theta^p - \frac{10e^2}{9} - 4\beta a^2(2\theta^p + 1) > 0$, which can be further expressed as $\kappa_2^p(\alpha,\beta,a,e) = \frac{36\alpha(e^2+9\beta a^2)}{e(9e^2+378\beta a^2)} \geq 1$.

By assuming $\theta^p = 1, 0 < \theta_k < 1$, condition (3.6.5- 3.6.6) also imply $\lambda_k = 0$ and $2\alpha e - \frac{4e^2}{9} - \frac{10e^2}{9}\theta_k - 4\beta a^2(2+\theta_k) = 0$, from which θ_k is solved as $\theta_k = \kappa_6^p(\alpha,\beta,a,e) \equiv \frac{9\alpha e - 2e^2 - 36\beta a^2}{5e^2+18\beta a^2}$. The assumption of being interior solution of θ_k requires that $\kappa_7^p(\alpha,\beta,a,e) \equiv \frac{9\alpha e}{2e^2+36\beta a^2} > 1$ and $\kappa_8^p(\alpha,\beta,a,e) \equiv \frac{9\alpha e}{7e^2+54\beta a^2} < 1$. Meanwhile, condition (3.6.3-3.6.4) implies that $\lambda_{ij} = 4\alpha e - \frac{8e^2}{3} - \frac{2e^2}{9}\theta_k - 16\beta a^2(2+\theta_k) > 0$. By substituting θ_k back, the following constraint is obtained $\kappa_1^p(\alpha,\beta,a,e) \geq 1$.

By assuming $\theta^p = 1, \theta_k = 1$, condition (3.6.3) to (3.6.6) imply $\lambda_{ij} = 4\alpha e - \frac{26e^2}{9} - 48\beta a^2 \geq 0$ and $\lambda_k = 2\alpha e - \frac{14e^2}{9} - 12\beta a^2 \geq 0$, which can be further expressed as $\kappa_5^p(\alpha,\beta,a,e) \equiv \frac{18\alpha e}{13e^2+216\beta a^2} \geq 1$ and $\kappa_8^p(\alpha,\beta,a,e) \equiv \frac{9\alpha e}{7e^2+54\beta a^2} \geq 1$.

The solutions under pairs are summarised as follows:

$$(\theta^p,\theta_k) = \begin{cases} (\kappa_1^p(\alpha,\beta,a,e), \kappa_2^p(\alpha,\beta,a,e)), & if \quad 0 < \quad k_1^p(\alpha,\beta,a,e) < 1, \quad k_2^p(\alpha,\beta,a,e) < 1 \\ (\kappa_3^p(\alpha,\beta,a,e), 1), & if \quad \kappa_4^p(\alpha,\beta,a,e) > 1, \quad \kappa_5^p(\alpha,\beta,a,e) < 1 \\ & \qquad \kappa_2^p(\alpha,\beta,a,e) \geq 1 \\ (1, \kappa_6^p(\alpha,\beta,a,e)), & if \quad \kappa_7^p(\alpha,\beta,a,e) > 1, \quad \kappa_8^p(\alpha,\beta,a,e) < 1 \\ & \qquad \kappa_1^p(\alpha,\beta,a,e) \geq 1 \\ (1,1), & if \quad \kappa_5^p(\alpha,\beta,a,e) \geq 1, \quad \kappa_8^p(\alpha,\beta,a,e) \geq 1 \end{cases}$$

where

$$\begin{aligned} \kappa_1^p(\alpha,\beta,a,e) &\equiv \frac{81\alpha(e^2-4\beta a^2)}{2e(29e^2+378\beta a^2)} & \kappa_2^p(\alpha,\beta,a,e) &\equiv \frac{36\alpha(e^2+9\beta a^2)}{e(29e^2+378\beta a^2)} \\ \kappa_3^p(\alpha,\beta,a,e) &\equiv \frac{18\alpha e - e^2 - 72\beta a^2}{12e^2+144\beta a^2} & \kappa_4^p(\alpha,\beta,a,e) &\equiv \frac{18\alpha e}{e^2+72\beta a^2} \\ \kappa_5^p(\alpha,\beta,a,e) &\equiv \frac{18\alpha e}{13e^2+216\beta a^2} & \kappa_6^p(\alpha,\beta,a,e) &\equiv \frac{9\alpha e - 2e^2 - 36\beta a^2}{5e^2+18\beta a^2} \\ \kappa_7^p(\alpha,\beta,a,e) &\equiv \frac{9\alpha e}{2e^2+36\beta a^2} & \kappa_8^p(\alpha,\beta,a,e) &\equiv \frac{9\alpha e}{7e^2+54\beta a^2} \end{aligned}$$

C: *Grand Coalition* Equilibrium

This section solves the optimal production policy for countries under *Grand Coalition.* The Kuhn-Tucker condition for welfare maximization problem under *Grand Coalition* is applied to obtain

$$6\alpha e - 4e^2\theta^g - 108\beta a^2\theta^g - \lambda_g \leq 0 \leq \theta^g \tag{3.6.7}$$

$$1 - \theta^g \geq 0 \leq \lambda_g \tag{3.6.8}$$

Since there is contradiction by assuming $\theta^g = 0$, the case that all countries implement extreme policy to produce nothing can be ruled out.

The other corner solution is to assume that $\theta^g = 1$, then condition (3.6.8) indicates that $\lambda_g \geq 0$. The multiplied term being zero in condition (3.6.7) implies that $\lambda_g = 6\alpha e - 4e^2 - 108\beta a^2 \geq 0$, which can be rearranged as $\kappa^g(\alpha, \beta, a, e) \equiv \frac{3\alpha e}{2e^2+54\beta a^2} \geq 1$.

The interior solution assumes that $0 < \theta^g < 1$. Condition (3.6.7) and condition (3.6.8) then imply $\lambda_g = 0$ and $6\alpha e - 4e^2\theta^g - 108\beta a^2\theta^g = 0$. Then θ^g is solved by $\theta^g(\alpha, \beta, a, e) = \kappa^g(\alpha, \beta, a, e)$ where $\kappa^g(\alpha, \beta, a, e) \equiv \frac{3\alpha e}{2e^2+54\beta a^2}$. Since α, β, e and a are all positive, $\theta^g(\alpha, \beta, a, e) > 0$, and the parameter should also satisfy the constraint that $\kappa^g(\alpha, \beta, a, e) < 1$.

Chapter 4

Trade and Trade Linkage in IEAs

4.1 Introduction

Literature has shown that there is a small coalition paradox in IEA formation that large welfare gain is prevented due to the free riding incentives (Barrett, 1994a; McGinty, 2007; Nordhaus, 2015). Thus, the central question in climate change cooperation is to design a mechanism that can overcome free-riding problems.

Among all options, *issue linkage* has been considered as a promising strategy for achieving such an aim. The basic idea of *issue linkage* is to link a public good, which suffers severely from free riding problems to a club good, where the benefits from cooperation are exclusive to coalition members (Carraro, 1997). Given the close interactions between trade and climate change (as is reviewed in Chapter 2), it is natural to propose a trade linkage for climate change issues. Indeed, if the benefit from free riding is partially offset by a loss from international trade, free riders then have to weigh the gains from environment and loss from international trade from free riding.

The literature of *issue linkage* between trade and the environment is distinguished by Maggi (2016) as three types: *enforcement linkage*, *negotiation linkage* and *participation linkage*. Among these three, *participation linkage* aims to induce wider participation in the free-riding area. In the context of trade and climate change cooperation, *participation linkage* is to add a clause to the existing trade agreement, specifying that the agreed trade concessions to trade members are contingent on the participation of the IEA. This chapter focuses on deterring the non-participation free riding incentives in climate change cooperation. Thus *participation linkage* becomes the powerful vehicle for encouraging wide participation in IEAs.

Barrett (1997), Eichner and Pethig (2015a) and Nordhaus (2015) assumed that trade linkage can be introduced and studied the effectiveness of such a linkage in sustaining a full cooperation on climate change. They found that trade linkage is effective and can stabilize the unstable *Grand Coalition* under some conditions. These studies provide useful implications of linking trade policy to IEA formation. However, they have the drawbacks of not solving for the trade sanctions endogenously and not analysing the linkage endogenously. Barrett (1997) and Eichner and Pethig (2015a) assumed that signatories of an IEA impose trade ban on non-signatories, which was too severe and not in the self-interest of signatories (not credible). Nordhaus (2015) used a much softer punishment on free riders, but it is also exogenously determined by the researcher. Moreover, questions of how to link trade policy and whether this linkage is supported by the existing trade members are not well explored in the above literature. Nordhaus (2015) argued that the coalition formation process is a top-down coalition where an optimal regime is there to attract countries to join. However, it is difficult to determine who the designer is and how the process would start in reality. Maggi (2016) also concluded that this research is incomplete and future work that models the trade sanction endogenously is needed.

To my best knowledge, this study is the first one that endogenously model trade linkage in IEA formation. It is assumed that the *status quo* in terms of trade cooperation is a free trade agreement with full participation. Countries are facing the challenges of forming an effective environmental agreement to tackle climate change. Without linkage, *Small Coalition Paradox* inevitably exists such that full cooperation is not achievable. A proposal that links trade policy to IEA formation comes to the table. If trade linkage is introduced, countries which participate in IEA still have free trade within themselves, but will impose an external tariff against free riders. Free riders either keep free riding but have to take the trade sanctions, thus lose from trade, or join the IEA thus cannot free ride any more. Free riders have to balance the gains from free riding and the loss from trade sanctions. A country favours trade linkage only if it is weakly better off with linkage. Thus, the introduction of trade linkage is also endogenously determined in this study.[1]

The other contribution of this chapter to the literature is that trade sanction is also endogenously determined. In contrast, trade sanction is exogenously assumed in Barrett (1997), Eichner and Pethig (2015a), and Nordhaus (2015). It is pivotal to endogenously determine the credible levels of trade sanction because different levels of trade sanction might lead to opposite conclusions: If credible trade sanction is a severe punishment, linkage will induce full cooperation in IEA with no trade sanction in equilibrium. This ideal outcome is clearly a Pareto improvement since cooperation in IEA is strictly better off while the trade agreement stays the same. However, if credible trade sanction is not severe enough, there are still countries staying out of the IEA and taking trade sanctions, then trade linkage might incur a cost from a global perspective since countries are moving away from the Pareto efficient trade policy-free trade. Therefore, the effectiveness and welfare changes of trade linkage closely depend on the level of trade sanctions, which definitely need to be endogenously determined.

Another feature about the framework of this study that deserves special comments is the free trade assumption. This chapter aims to show how trade and trade policy affect climate change cooperation, especially when the environmental policy is used as a substitute for trade policy. This research question calls for an existing trade agreement that binds the use of trade policy. A free trade agreement, for the purpose of simplicity, is a reasonable assumption since Saggi et al. (2013) show that even when large economies get the chance to manipulate *terms-of-trade* gain, global free trade is the only stable trade agreement in a symmetric world.[2] Thus, it is

[1] An alternative framework is that countries which cooperate on the IEA can form a freer trade agreement within themselves and enjoy the excludable trade privileges provided, for example, Kuhn et al. (2017). With this framework, a freer trade agreement and an IEA are endogenously joint-formed, thus, the introduction of trade linkage to IEA formation is not an issue. However, the transaction cost for jointly designing a trade agreement and an IEA is high, since the negotiations should span multiple dimensions and target multiple issues. More importantly, if the size of such a coalition is not big enough, the privileges from freer trade can't outweigh the benefits from free riding, thus this linkage will be ineffective.

[2] This chapter also assumes symmetry.

reasonable to assume a world where trade agreement is stable.

With this new framework, this chapter shows that trade linkage is effective to overcome free riding incentives and it generates global welfare gain when the climate change damage is moderate. However, this welfare gain is at the cost of a lower *non-climate* welfare. With regards to the introduction of trade linkage to IEA, countries who used to free ride in the absence of linkage are strictly worse off with linkage and against linkage. If unanimity is required for the introduction of trade linkage to IEA, such linkage is not possible despite of the effectiveness and welfare gain. This result partially explains the current situation in climate change cooperation and trade linkage.

The structure of this chapter is as follows: Section 4.2 sets out the basic structure of the economy and defines trade linkage game. Section 4.3 studies IEA formation without linkage while section 4.4 focuses on the formation outcome with trade linkage. Section 4.5 discusses the effectiveness of trade linkage, the endogeneity of linkage and also the links to WTO rules. The last section concludes.

4.2 The Model and Trade Linkage Game

4.2.1 The Model

This chapter studies the effectiveness of trade linkage in IEA formation and more importantly, the possibility of introducing trade linkage to IEAs. For the tractibility of anaylitical solutions, I adopt the simple partial equilibrium competing exporters trade model of Bagwell and Staiger (1997) in this chapter, but allow a pure public bad "greenhouse gas emission" to be generated jointly with the production of goods.

The world economy consists of three countries, a, b, c and there are three non-numeraire goods A, B and C. Demand for good Z (d_i^Z, $Z{=}A, B, C$) in country i ($i{=}a, b, c$) is given by the demand function $D_i^Z(p_i^Z)$, where p_i^Z is the domestic consumer price of Z and the slope of the demand function $D_i^{Z\prime}(p_i^Z) < 0$. Additionally, demand for good Z is independent of prices of the other two goods. Each country i is a producer of two goods except good I. Production of good Z in country i (s_i^Z)is defined by a supply function $S_i^Z(q_i^Z), Z \neq I$, where q_i^Z is the domestic producer price of Z and the slope of the supply function $S_i^{Z\prime}(q_i^Z) > 0$.[3]

I focus on the production-generated emission. All three goods are "dirty" goods in a sense that the production of good Z, $S_i^Z(q_i^Z)$, generates greenhouse gas emission one for one in country i. The global emission is then denoted by the total world output of all goods $s_w \equiv \sum_{i,j,k}^{I,J,K} s_i^Z(q_i^Z)$.[4]

The government in country i sets a unit production tax τ_i^Z on production of good Z, which drives a wedge between domestic consumer and producer prices. Thus, the domestic producer price is a function of consumer price and production tax, which is denoted as $\mu_i^Z(p_i^Z, \tau_i^Z)$.

$$q_i^Z = \mu_i^Z(p_i^Z, \tau_i^Z) = p_i^Z - \tau_i^Z, Z \neq I \tag{4.2.1}$$

Since each country produces two goods but demands three, country i has to import good I from the other two trading partners. Let t_{ij} and t_{ik}) be the tariffs imposed by country i on its imports of good I from country j and country k, respectively.[5] The tariffs are assumed to be nonprohibitive and they derive a wedge between domestic consumer prices in importing and exporting countries

$$p_j^I = \rho_{ij}(p_i^I, t_{ij}) = p_i^I - t_{ij} \tag{4.2.2}$$

$$p_k^I = \rho_{ik}(p_i^I, t_{ik}) = p_i^I - t_{ik} \tag{4.2.3}$$

Let m_i^Z be country i's excess demand of good Z. For the good that a country produces, $Z \neq I$, the excess demand of good Z equals its local consumption minus its production

$$m_i^Z = M_i^Z(p_i^Z, \tau_i^Z) = D_i^Z(p_i^Z) - S_i^Z(\mu_i^Z(p_i^Z, \tau_i^Z)) \tag{4.2.4}$$

[3]Since country i is not producing good I, there will be no supply function for good I in country i.

[4]There will be only six production functions, since country i is not producing good I.

[5]It is assumed that all countries have no access to export policies.

where

$$\partial M_i^Z(p_i^Z, \tau_i^Z)/\partial p_i^Z < 0, \quad \partial M_i^Z(p_i^Z, \tau_i^Z)/\partial \tau_i^Z > 0, Z \neq I$$

For the good that a country has to import ($Z = I$), the excess demand is just the demand

$$M_i^Z(p_i^Z) = D(p_i^Z) \tag{4.2.5}$$

where $dM_i^Z(p_i^Z)/dp_i^Z = D_i^{Z\prime}(p_i^Z) < 0$. Market clearing for good Z requires that

$$\sum_i M_i^Z(p_i^Z, \tau_i^Z) = 0 \tag{4.2.6}$$

By using price wedges (4.2.1)-(4.2.3), market clearing condition (4.2.6), the demand and supply functions, one can derive the domestic price of good I in country i as a function of tariff policies and production tax policies $\hat{p}_i^I(\tau_j^I, \tau_k^I, t_{ij}, t_{ik})$. The prices in other two trade partners, demand, supply and trade volume can be easily calculated.

Implicitly differentiating market clearing condition (4.2.6) for good I with respect to t_{ij}, it shows that any increase of the tariffs against one exporting country of good I will raise the domestic price in country i ($\partial p_i^I/\partial t_{ij} > 0$). However, the burden of price increase is partly taken by the exporting country ($\partial p_j^I/\partial t_{ij} < 0$). At the same time, this increase also raises the domestic price in the other exporting country ($\partial p_k^I/\partial t_{ij}$), which exhibits trade diversion effect. Derivations with respect to t_{ik} can be obtained analogically.

$$\frac{\partial p_i^I}{\partial t_{ij}} = \frac{M_{j\,p}^I}{\sum_{z=i,j,k} M_{z\,p}^I} > 0, \quad \frac{\partial p_j^I}{\partial t_{ij}} = \frac{-(M_{i\,p}^I + M_{k\,p}^I)}{\sum_{z=i,j,k} M_{z\,p}^I} < 0, \quad \frac{\partial p_k^I}{\partial t_{ij}} = \frac{M_{j\,p}^I}{\sum_{z=i,j,k} M_{z\,p}^I} > 0 \tag{4.2.7}$$

where $M_{j\,p}^I$ is the partial derivative of $M_j^I(p_j^I, \tau_j^I)$ with respect to p_j^I.

Implicitly differentiating market clearing condition (4.2.6) for good I with respect to τ_j^I, one can derive that an increase in the production tax in one exporting country raises consumer prices in importing country ($\partial p_i^I/\partial \tau_j^I > 0$) since production tax in exporting country decreases world supply.[6] For the exporting country, an increase in its production tax raises its consumer price ($\partial p_j^I/\partial \tau_j^I > 0$) and decreases its producer price ($\partial q_j^I/\partial \tau_j^I < 0$). However, the consumer and producer prices in the other exporting country k is raised by an increase in production tax τ_j^I in country j ($\partial p_k^I/\partial \tau_j^I = \partial q_k^I/\partial \tau_j^I > 0$).

$$\frac{\partial p_i^I}{\partial \tau_j^I} = \frac{\partial p_j^I}{\partial \tau_j^I} = \frac{\partial p_k^I}{\partial \tau_j^I} = \frac{\partial q_k^I}{\partial \tau_j^I} = -\frac{M_{j\,\tau}^I}{\sum_{z=i,j,k} M_{z\,p}^I} > 0, \frac{\partial q_j^I}{\partial \tau_j^I} = -\frac{M_{j\,\tau}^I + \sum_{z=i,j,k} M_{z\,p}^I}{\sum_{z=i,j,k} M_{z\,p}^I} < 0 \tag{4.2.8}$$

where $M_{j\,\tau}^I$ is the partial derivative of $M_j^I(p_j^I, \tau_j^I)$ with respect to τ_j^I.

Each country's welfare is defined as the sum of consumer surplus, producer surplus, tariff revenue and tax revenue less the welfare loss from greenhouse gas emission.[7]

$$\omega_i = \sum_z CS_i + \sum_z PS_i + TR_i - E_i(s_w) \tag{4.2.9}$$

The welfare without climate change damage is defined as *non-climate welfare.* The *non-climate welfare* for country i over import good (I) and export goods (J or K), respectively, are given by

$$\kappa_i^I(\tau_j^I, \tau_k^I, t_{ij}, t_{ik}) \equiv \int_{\hat{p}_i^I}^{\infty} D_i^I(p)dp - t_{ij}M_j^I(p_j^I, \tau_j^I) - t_{ik}M_k^I(p_k^I, \tau_k^I) \tag{4.2.10}$$

$$\kappa_i^J(\tau_i^J, \tau_k^J, t_{ji}, t_{jk}) \equiv \int_{\hat{p}_i^J}^{\infty} D_i^J(p)dp + \int_0^{\hat{q}_i^J} S_i^J(q)dq + \tau_i^J S_i^J(q) \tag{4.2.11}$$

$$\kappa_i^K(\tau_i^K, \tau_j^K, t_{ki}, t_{kj}) \equiv \int_{\hat{p}_i^K}^{\infty} D_i^K(p)dp + \int_0^{\hat{q}_i^K} S_i^K(q)dq + \tau_i^K S_i^K(q) \tag{4.2.12}$$

where the excess supply of good I in country j, $(-M_j^I(p_j^I, \tau_j^I))$, is the imports of good I of country i from country j, due to the fact that country i is the only importer of good I.[8] Then the aggregate welfare for country i is the sum of *non-*

[6] The domestic price of importing country is independent of its own production tax since it is not a supplier of that good.

[7] The welfare function follows tradition in the literature, for example, Saggi et al. (2013). The consumer surplus measures the area below the demand curve up to the equilibrium price while the producer surplus measures the area above the supply curve up to the price received by the producers (i.e., equilibrium price less the production tax).

[8] M_j^I is the excess demand of good I in country j. Because country j is an exporter of good I, M_j^I is negative. More importantly, country j exports good I only to country i. Thus, the import of good I from country j to country i is then represented by $-M_j^I$, which is positive.

climate welfare from three goods less the welfare loss from emissions, $\omega_i(\boldsymbol{\tau}, \boldsymbol{t}) = \sum_{I,J,K} \kappa_i^I(\boldsymbol{\tau}, \boldsymbol{t}) - E_i(s_w)$.[9]

4.2.2 Trade Linkage Game

It is of great importance to define trade linkage game clearly, which has been relatively missing in the trade linkage literature. In Barrett (1997), countries decide whether or not to employ trade sanctions at the first stage, but how the decision is made and under what conditions trade sanction is employed are not fully specified. Eichner and Pethig (2015a) assumed that all countries except one have signed the IEA and agreed to employ trade ban between IEA and the only free rider. The use of trade ban is exogenously given in their paper. Nordhaus (2015) argued that a top-down IEA coalition that is optimized to attract a large number of participants is better than the small and unstable bottom-up coalition. The main task in his paper is to design such a top-down coalition. Thus there is no need to consider the endogenous trade linkage at all. However, such a well-defined top-down coalition is not quite plausible since there is a process in forming the optimal climate club. The welfare of each country highly depends on the number of club members. For a particular sub-club (sub set of the optimal club), it might be not attractive for new members to join and thus the club stops at the sub-club and never reaches to optimality.

In this study, trade linkage is endogenously modelled as a three stage game. In stage 1, countries decide whether to link trade agreement to IEA or not. It is assumed that the *status quo* in terms of trade cooperation is a free trade agreement with full participation. The trade linkage proposal is that adding a clause to the existing free trade agreement, which states that the benefits of free trade are contingent on participation of the IEA. Each country is empowered to agree or disagree to this linkage proposal. In stage 2, each country proposes a list of countries that it wants to form an IEA with. The coalition formation is also endogenously determined by the coalition formation game defined in Chapter 3. In stage 3, if trade linkage is introduced, signatories of an IEA, choose production taxes and tariffs to maximize their

[9] $\boldsymbol{\tau}$ and $\boldsymbol{t}$ are the vectors of production tax and tariff, respectively.

collective welfare, taking the actions of non-signatory as given; The non-signatory decides its own environmental policy and trade policy non-cooperatively. If trade linkage is not approved in the first stage, countries within an IEA cooperate on environmental policy only. The game is solved backwards to obtain a sub-game perfect Nash equilibrium.

4.3 IEA Formation without Linkage

A country will support trade linkage to IEAs if and only if it is weakly better off with trade linkage. Thus, the welfare of a country under the stable coalition structure with and without trade linkage should be firstly solved. Then countries will make decisions based on the welfare difference between these two cases. This section solves the equilibrium when trade linkage is not approved in the first stage of the game. Since trade linkage is assumed to be not introduced, this section becomes an IEA formation game. By applying the coalition formation game introduced in Chapter 3, this section studies IEA formation under free trade without linkage. All trade barriers are removed because of the existing free trade agreement, therefore, production tax is the only available policy.

4.3.1 Optimal Production Taxes

Stand-alone Equilibrium

The IEA formation game is solved backwards, thus optimal production taxes of different coalition structures are examined firstly. Under *Stand-alone*, countries choose their production taxes non-cooperatively to maximize their own national welfare, taking the policies of others as given.

Taking derivatives of country i's welfare, $\omega_i(\boldsymbol{\tau}, \boldsymbol{t})$, with respect to τ_i^J yields the following optimal production tax structure

$$\tau_i^J(s) = \underbrace{\frac{\partial E_i}{\partial s_i^J}}_{\text{Pigouvian tax (+)}} + \underbrace{\frac{M_{k\ \tau}^J}{\sum_z M_{z\ p}^J + M_{i\ \tau}^J} \cdot \frac{\partial E_i}{\partial s_k^J}}_{\text{leakage effect (-)}} + \underbrace{\frac{M_{i\ p}^J}{\sum_z M_{z\ p}^J + M_{i\ \tau}^J} \cdot \epsilon_i^J}_{\text{terms-of-trade (+)}} \quad (4.3.1)$$

where $\epsilon_i^J = M_i^J / M_{i\ p}^J > 0$ is inversely related to the elasticity of country i's export supply. Other ϵs are defined in similar manner.

As is shown, production tax under *Stand-alone* serves multiple purposes. The first term in equation (4.3.1) is the well-known standard Pigouvian tax, which equals domestic marginal environmental damage. The second term is related to the production in the other producer, country k. It is negative, thus contributes to a lower production tax τ_i^J, which further aims to reduce production in country k.[10] This term is defined as *leakage effect*. The higher the climate change damage of production in country k to country i ($\partial E_i / \partial s_k^J$ is big), the larger the *leakage effect* is. The last term (positive) represents the *terms of trade* effect.[11] For large economies, if a full set of policies are available, tariffs or other equivalent domestic policy combination would be used to exploit market power in the international market. Since tariff is inaccessible due to the existing free trade agreement in this chapter, the environmental policy is used as a second-best policy to manipulate *terms-of-trade* gain. The optimal production tax in (4.3.1) is higher than the one that only aims to correct environmental externality due to *terms-of-trade* effect. When a higher production tax is introduced, domestic production declines, raising the world price. In addition to the environmental benefit gained from reduction in production, reduction in excess supply also generates a monopolistic surplus gain. The less elastic the export supply of the country is, the higher the production tax will be.

To conclude, international trade does affect the outcomes of climate change cooperation through the use of domestic environmental policy being manipulated to deal with *terms-of-trade* externality and *leakage* problem. First, environmental policy is used as a second-best instrument to manipulate *terms-of-trade* gain if trade policy is unavailable due to a binding trade agreement. This is consistent

[10] $M_{k\ \tau}^J / (\sum_{z=i,j,k} M_{z\ p}^J + M_{i\ \tau}^J) < 0$ since $\sum_{z=i,j,k} M_{z\ p}^J + M_{i\ \tau}^J < 0$ and $M_{k\ \tau}^J > 0$.
[11] $M_{i\ p}^J / (\sum_{z=i,j,k} M_{z\ p}^J + M_{i\ \tau}^J) > 0$ since $\sum_{z=i,j,k} M_{z\ p}^J + M_{i\ \tau}^J < 0$ and $M_{i\ p}^J < 0$.

with the the seminal paper by Markusen (1975b). Though researchers have raised their concerns about the effectiveness of the substitution between trade policy and environmental policy, recent empirical research shows that this substitution effect is statistically significant (Ederington and Minier, 2003). Second, international trade affects climate change cooperation by introducing the *leakage effect*. In autarky, there is no room to influence another country's emission by manipulating its own environmental policy as what happens with international trade.

Grand Coalition **Equilibrium**

Under *Grand Coalition*, countries cooperate to maximize the global welfare, but they don't necessarily implement same production tax. Each of them still has the right to implement their own value of the production tax.[12] Take policies for good J as an example. All derivations for the other four production taxes can be obtained in an analogous manner. Taking derivatives of global welfare $(\omega_i + \omega_j + \omega_k)$ with respect to τ_i^J and τ_k^J and solving the first order conditions yields

$$\tau_i^J(g) = \underbrace{\frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J} + \frac{\partial E_k}{\partial s_i^J}}_{\text{Pigouvian tax } (+)} \tag{4.3.2}$$

$$\tau_k^J(g) = \underbrace{\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J} + \frac{\partial E_k}{\partial s_k^J}}_{\text{Pigouvian tax } (+)} \tag{4.3.3}$$

Equation (4.3.2) and (4.3.3) are the optimal production taxes of good J in country i and j. When *Grand Coalition* is formed, environmental externality is fully internalized, therefore, production tax is the global efficient Pigouvian tax. Since there is no more distortion in the other supply country, the *leakage* term in equation (4.3.1) drops out. *Grand Coalition* with free trade regime eliminates incentives to manipulate *terms-of-trade* (the third term in (4.3.1) also drops out). It is only in *Grand Coalition* that equation (4.3.1) converges to the Pareto efficient production tax.

[12] Same framework applies to *the Pair* equilibrium. Please note that this framework is different from the one employed in Chapter 3, where countries under cooperation implement same policies.

The Pair Equilibrium

Under *the Pair*, signatories – country i and country j – form a coalition and choose production tax $\{\tau_i^J, \tau_j^I, \tau_i^K, \tau_j^K\}$ to maximize their joint welfare $(\omega_i + \omega_j)$, taking the production taxes of the non-signatory as given. For good I and J, *the Pair* is one of the exporters. Taking good J as an example, the optimal production tax is solved as

$$\tau_i^J(p) = \underbrace{\frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J}}_{\text{Pigouvian tax (+)}} + \underbrace{\frac{M_{k\ \tau}^J}{\sum_z M_{z\ p}^J + M_{i\ \tau}^J} \cdot (\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J})}_{\text{leakage effect (-)}} \underbrace{- \frac{M_{k\ p}^J}{\sum_z M_{z\ p}^J + M_{i\ \tau}^J} \cdot \epsilon_k^J}_{\text{terms-of-trade (-)}} \tag{4.3.4}$$

Since *the Pair* maximize their joint welfare, the Pigouvian tax (first term in (4.3.4)) internalizes the environmental negative externalities from production in country i to both of the signatories. Second, since the non-signatory, country k, is another emitter, $\tau_i^J(p)$ is also used to deal with *leakage* problem as what it did under *Stand-alone*.

What strikes me is how production tax works to affect trade pattern under *the Pair*. Country i and country j are exporting and importing countries of good J, respectively. Under *Stand-alone*, $\tau_i^J(s)$ is used by exporting country i to manipulate *terms-of-trade* gain from importing country j. There is no trade flow between country i and k as they are both exporting countries. However, when country i and j form a Pair, there is no need to manipulate *terms-of-trade* between themselves. Instead, $\tau_i^J(p)$ works as a tool by country i to manipulate *terms-of-trade* gain from country k for country j. The last term in (4.3.4) is negative, which indicates that country i tends to lower its production tax in order to export more to country j and decline the demand of its partner from country k. Thus, trade division effect predicts that country j will imports more from its partner i rather than country k, which is clearly an efficiency loss. When there is no climate change damage (the environmental related terms all drop out), the optimal production taxes $\tau_i^J(p)$ becomes subsidy to domestic producers in country i. The less elastic of export supply of country k, the lower the production tax in country i.

Even though *the Pair* is an environmental agreement, it also exhibits the nature of a regional trade agreement when environmental policies are used as second-best policies to affect trade patterns. The incentives to form *the Pair* stem not only from internalizing environmental externality to a larger degree, but also from exploiting a larger market power as a Pair. In this sense, due to the welfare gain for coalition members in trade, partial climate change cooperation might be more attractive than no cooperation, predicting that partial coalition might prevail when climate change damage is not severe (as shown later in formation section).

When it comes to the production tax of signatories for good K, there is no need to deal with the *leakage* problem since the two signatories are the only producers. Production tax $\tau_i^K(p)$ now is used to manipulate *terms-of-trade* gain from importing country k not only for country i but also for country j. The last term in (4.3.5) is positive, which indicates that signatories tend to implement a higher production tax to gain a even higher monopolistic surplus compared to the case without the last term. Thus, production tax for good K is inefficiently high due to the distortions for *terms-of-trade* purpose. This again shows that the benefits for country i and j by forming a Pair also stem from a larger market power in international trade.

$$\tau_i^K(p) = \underbrace{\frac{\partial E_i}{\partial s_i^K} + \frac{\partial E_j}{\partial s_i^K}}_{\text{Pigouvian tax (+)}} + \underbrace{\frac{M_{i\ p}^K}{\sum_z M_{z\ p}^K + M_{i\ \tau}^K + M_{j\ \tau}^K} \cdot \epsilon_i^K}_{\text{terms-of-trade for country i (+)}} + \underbrace{\frac{M_{j\ p}^K}{\sum_z M_{z\ p}^K + M_{i\ \tau}^K + M_{j\ \tau}^K} \cdot \epsilon_j^K}_{\text{terms-of-trade for country j (+)}} \tag{4.3.5}$$

Non-signatory maximizes its national welfare by choosing its own production taxes, taking signatories' policies as given. The optimal production taxes take the same structure as (4.3.1).[13]

[13] It must be remembered that optimal tax structure equations (4.3.1)-(4.3.5) are relationships, not values. We cannot compare the formulas under different coalition structures. Because the optimal taxes are solved by simultaneously solving a set of first order conditions. Once we move to a different policy regime, the values of the same term in these equations change. The aim of these equations is to show how trade makes a difference in the IEA formation (e.g., the use of environmental policy for terms-of-trade and the leakage effect).

Optimal Taxes with Specific Functions

In order to obtain more specific results for welfare calculations, the demand function, supply function and climate change damage function are taking the following functional forms throughout this chapter:

$$\begin{aligned} D_i^Z(p_i^Z) &= \alpha - p_i^Z && (4.3.6) \\ S_i^Z(q_i^Z) &= q_i^Z, \quad Z \neq I && (4.3.7) \\ E_i(\beta_i, S_w) &= \frac{\beta_i}{2}(S_w)^2 && (4.3.8) \end{aligned}$$

where $\alpha > 0$, p_i^Z and q_i^Z are local consumer and producer prices, respectively, of good Z in country i. $\beta_i \geq 0$ is a parameter that measures welfare loss level due to climate change in country i. A country with a higher β_i bears more welfare loss. Realistically, greenhouse gas is a pure public bad that adversely affect each country to a different degree, with the poorer countries in tropical regions being the biggest victims. This chapter shares similar reasons about symmetry as discussed in Chapter 3 and again assumes that countries are identical in every aspect, thus $\beta_i = \beta$ is a constant across countries.

The maximization problem should be subject to non-negative constraints of quantities and prices together with the constraints for non-prohibitive tariffs. A standard method to solve a maximization problem with inequality constraints is to apply KKT conditions (as what I did in Chapter 3). However, considering the tractability, I restrict myself to interior solutions. Because of symmetry, the optimal production taxes for each country under *Stand-alone* are the same and solved as[14]

$$\tau(s) = \frac{\alpha(1 + 54\beta)}{21 + 54\beta} \tag{4.3.9}$$

When there is no climate change damage ($\beta = 0$), the Pigouvian tax and *leakage* term in equation (4.3.1) drops out. $\tau(s) = \alpha/21$ is a second-best policy purely for *terms-of-trade*. $\partial\tau(s)/\partial\beta > 0$, the optimal production tax under *Stand-alone* is

[14] α is a parameter that affects the absolute value of optimal policies and welfare, but it has no effect in the process of determining the stable coalition. Hence, I will omit α in the following process of determining stable coalition.

increasing in β, which means that each country will tighten environmental policy if climate change damage from production is larger.

The optimal production taxes for three countries under *Grand Coalition* are the same and solved as

$$\tau(g) = \frac{54\alpha\beta}{5 + 54\beta} \tag{4.3.10}$$

Since it is the global efficient Pigouvian tax and there is no *terms-of-trade* term, $\tau(g) = 0$ when there is no climate change damage. $\partial\tau(g)/\partial\beta > 0$, as climate change damage increases, a more stringent environmental policy is needed to fully internalize the externalities.

The optimal production taxes under *the Pair* are solved as

$$\begin{aligned}
\tau_j^I(p) = \tau_i^J(p) &= \frac{2\alpha(-17 + 2079\beta)}{850 + 4095\beta}, \\
\tau_i^K(p) = \tau_j^K(p) &= \frac{2\alpha(10 + 567\beta)}{170 + 819\beta}, \\
\tau_k^I(p) = \tau_k^J(p) &= \frac{\alpha(34 + 2457\beta)}{850 + 4095\beta}
\end{aligned}$$

Unlike the previous two coalition structures where optimal production taxes always satisfy interior solution constraints, the optimal production taxes under *the Pair* should satisfy the following condition $0 \leq \beta \leq \bar{\beta}_f (= \frac{68}{231})$. The intuition behind this condition is that when the climate change damage is too severe ($\beta > \frac{68}{231}$), it is not beneficial for country i to export good J since the production tax $\tau_i^J(p)$ is relatively higher compared to that of the other producer, country k. This is shown in Figure 4.1 where p^J is much higher than np when β is big. Instead of being an exporter of good J, country i imports from country k, which contradicts my assumptions about trade pattern, therefore, this chapter focuses on the interval of $\beta \in [0, \bar{\beta}_f]$.

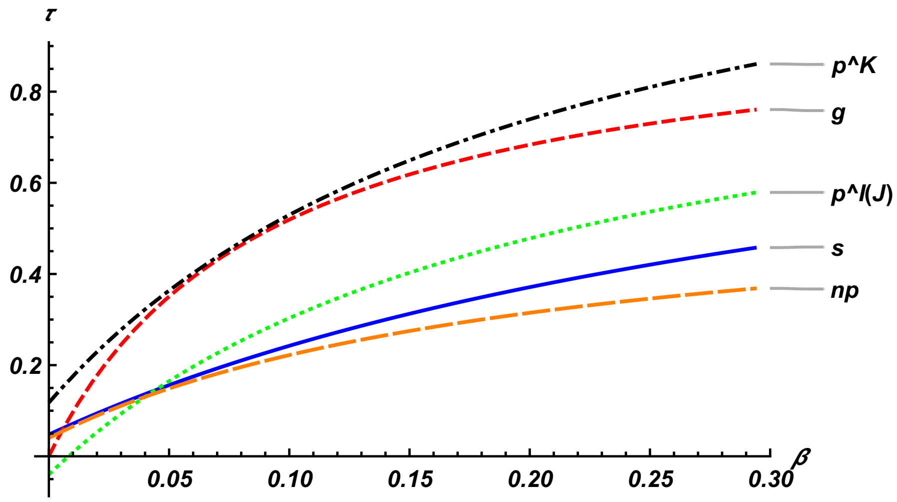

Figure 4.1: Optimal Production Taxes under Different Coalition Structures

[15]Note: s is production tax under *Stand-alone*; g is production tax under *Grand Coalition*, $p^I(J)$, p^K are production taxes of good $I(J)$, K in signatories under *the Pair*, respectively; np is production tax in free rider under *the Pair*.

Figure 4.1 plots optimal production taxes under different coalition structures. The horizontal axis is the climate change severity level, represented by β, while the vertical axis is the optimal production tax. There are some features that deserve special comments. First, $\tau_i^K(p)$ (p^K in the figure) is even higher than the global efficient Pigovian tax (g in the figure) because the *terms-of-trade* terms in $\tau_i^K(p)$ contributes to a higher production tax, which clearly is an efficiency loss. Except $\tau_i^K(p)$, production taxes are all below the global efficient level $\tau(g)$. Second, the figure also provides evidence for emission leakage. As β increases, non-signatory under *the Pair* imposes an even less stringent production tax (np in the figure) than that under *Stand-alone* (s in the figure) as a consequence of signatories reducing their emission sharply. The emission reduction efforts made by signatories are partly offset by higher emission in non-signatory. Third, the production tax of good K of the *Pair* (p^K) is much higher than that of each country under *Stand-alone*. This is partly because the Pair members internalize the environmental externalities to a larger degree, at the same time, it also indicates that the Pair members enjoy a greater market power than under *Stand-alone*.

4.3.2 Stable Coalition without Linkage

The maximized welfare for each country under different coalition structures can be obtained by substituting optimal production taxes calculated in the previous section into welfare functions. Let $\omega_i^*(r)$ be the welfare of country i with the relevant optimal policy under coalition structure r. Let $\Delta\omega_i^*(g-p)$ be the welfare difference for country i between *Grand Coalition* and *the Pair*. By applying Nash and strong Nash coalition conditions introduced in Chapter 3, I then investigate the equilibrium IEA with free trade regime.

Nash equilibrium conditions are firstly applied to exclude unilateral deviations. As is clear, *Stand-alone* is always a Nash equilibrium coalition. It is easy to show that any signatory of a Pair has no incentives to defect from *the Pair* since

$$\Delta\omega_i^*(p-s) = \Delta\omega_j^*(p-s) > 0, \forall\beta \in (0, \bar{\beta}_f) \tag{4.3.11}$$

It is interesting that even though signatories of *the Pair* face severe free riding of country k, cooperation between themselves still dominates non-cooperation. As discussed before, in addition to environmental benefits, members of *the Pair* also exploit more market power in trade compared to *Stand-alone*. Thus, each of them has no incentives to defect the agreement.

The IEA formation game resembles a Prisoners' Dilemma game: all countries are better off by implementing *Grand Coalition* tax than the tax under *Stand-alone*, since $\Delta\omega_i^*(g-s) > 0, \forall i$. There is welfare gain with any symmetric move to *Grand Coalition* from *Stand-alone*. *Grand Coalition* is a Nash equilibrium coalition only when $\beta_f^1(0.023) \leq \beta \leq \beta_f^2(0.121)$.[16] As climate change damage increases ($\beta > \beta_f^2$), the cost to fully internalize environmental externality is relatively high, which makes free riding more attractive for country k. By free riding, country k enjoys the efforts of emission reduction made by *the Pair*, but with no cost on its own side. Thus, country k will deviate to be the free rider of *the Pair* and (3.3.2) is violated. On the other hand, country i and j are strictly better off by forming a Pair other than *Grand Coalition* ((3.3.4) is violated) when climate change damage is relatively small

[16] The value of β_f^1 is obtained by solving (3.3.3). The value of β_f^2 is obtained by solving (3.3.2).

($\beta < \beta_f^1$). Because production taxes work more as a second-best policy to manipulate *terms-of-trade* gain, thus, signatories of *the Pair* can extract a larger monopolistic gain, which extinguishes *the Pair* as an attractive option for signatories when β is small. The above analysis about deviation incentives leads to the following Lemma.

Lemma 7. *Any two countries that can form a Pair only deviate from the Grand when $\beta < \beta_f^1$ to enjoy a larger monopolistic gain. For $\beta \geq \beta_f^1$, they are better off by being a member of Grand Coalition and thus have no incentives to deviate. However, country k, the non-signatory of the Pair, would choose to be a free rider as β increases to β_f^2.*

Given Lemma 7, the main results about Nash equilibrium coalition are summarized as Proposition 8.

Proposition 8. *Stand-alone and the Pair are each Nash equilibrium coalition regardless of the parameter values. Grand Coalition is a Nash equilibrium coalition if and only if $\beta_f^1 \leq \beta \leq \beta_f^2$.*

By applying Nash equilibrium concept, multiple Nash equilibrium coalitions arise. The question is that which coalition will be observed. To capture the realistic process of IEA formation, I apply strong Nash equilibrium conditions to exclude the coalitions that are not immune to group deviations. *Stand-alone* with free trade regime will not eventuate in equilibrium since

$$\Delta\omega_i^*(s-p) = \Delta\omega_j^*(s-p) < 0, \forall\beta \in (0, \bar{\beta}_f) \tag{4.3.12}$$

$$\Delta\omega_i^*(s-g) = \Delta\omega_j^*(s-g) = \Delta\omega_k^*(s-g) < 0, \forall\beta \in (0, \bar{\beta}_f) \tag{4.3.13}$$

Condition (4.3.12) states that country i and country j prefer to group deviate to form a Pair while condition (4.3.13) shows group deviation of all three countries to form *Grand Coalition*.

The Pair is strong Nash equilibrium only when $\beta \in (0, \beta_f^1) \cup (\beta_f^2, \bar{\beta}_f)$. It is beneficial for all three countries to cooperate to form Grand, therefore, *the Pair* is not immune to group deviation of all three countries to form *Grand Coalition* for that particular range (β_f^1, β_f^2). However, as β increases, being a free rider generates higher welfare for country k, therefore, a group deviation of all three countries is not possible any more. On the contrary, a group deviation of country i and country j to form *Grand Coalition* is impossible for $\beta \in (0, \beta_f^1)$ since (3.3.4) is violated. *Grand Coalition* is Nash and strong Nash for $\beta \in [\beta_f^1, \beta_f^2]$. The group deviation incentives are then summarized in Lemma 9 as follows.

Lemma 9. *Stand-alone is not immune to group deviations since all three countries have incentives to group deviate to form a Grand or any of two countries would deviate to form a Pair for all values of* β. *The Pair is not immune to group deviation of all three countries to form Grand for* (β_f^1, β_f^2).

Given Lemma 9, the main results about Strong Nash equilibrium coalition are summarized as Proposition 10.

Proposition 10. *Stand-alone is never a strong Nash equilibrium. The Pair is a strong Nash equilibrium for* $\beta \in (0, \beta_f^1) \cup (\beta_f^2, \bar{\beta}_f)$. *Cooperation, even partial cooperation, is better for each country than non-cooperation. Grand Coalition is a strong Nash equilibrium only when* $\beta \in [\beta_f^1, \beta_f^2]$.

As is shown from the above analysis, *Stand-alone* and *the Pair* are always a Nash equilibrium regardless of the climate damage level, which means that given the strategies of other parties, no player has incentives to unilaterally deviate. However, when the group deviations are allowed, a group deviation of all three countries or country i and j can group deviate to form *Grand coalition* or *the Pair*, respectively. Therefore, *Stand-alone* is never a stable equilibrium. Prior literature that employed *external & internal stability* concept failed to capture this important aspect of coalition formation game.

4.3.3 Welfare Gain from *Grand Coalition*

Let $W^*(r) = \sum_i \omega_i^*(r)$ be the global welfare under coalition structure r with relevant optimal policy. Let $\Delta W^*(r - v)$ be the global welfare difference between coalition structure r and v with relevant optimal policy. Figure 4.2 depicts the welfare gain from *Grand Coalition* compared to *Stand-alone* and *the Pair*, respectively, as a function of β, which is the climate change severity level.

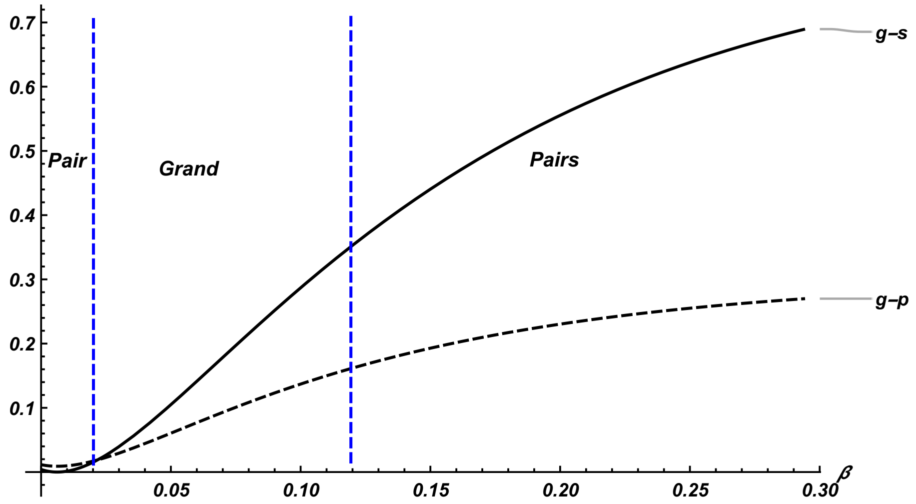

Figure 4.2: Welfare Gain from *Grand Coalition*

[17]Note: $g-s$, $g-p$ represent the welfare difference between *Grand Coalition* and *Stand-alone* and *the Pair*, respectively.

The global welfare gain from *Grand Coalition* compared to *the Pair* and *Stand-alone* becomes large as the climate change damage parameter β increases. *Grand Coalition* fully internalizes the externality caused by carbon emission to the whole world by setting the production tax to Pareto efficient level, while *the Pair* and *Stand-alone* only internalize the externality related to the welfare that the players are interested in. Thus, as climate change damage of carbon emission increases, a more stringent policy is needed to mitigate climate change, which results in a quite high cost for abating countries. Free riding becomes more attractive since the free rider can enjoy the benefit from abating efforts contributed by other countries without any cost on its side. The analysis again confirms the small coalition paradox.

Proposition 11. *Small Coalition Paradox: When climate change damage is small, the welfare gain from Grand Coalition is small even though Grand Coalition is a stable equilibrium. As climate change damage increases, welfare gain from Grand Coalition becomes larger. However, the incentives for the free rider to deviate increases at the same time, implying that the Grand Coalition is not a stable equilibrium any more.*

4.4 IEA Formation with Trade Linkage

According to my results and the existing literature, IEA seems to be small and vulnerable due to free-riding problems. The idea of linking public goods to club goods with exclusive benefit balances the gains from free riding against the loss from trade. This section aims to investigate IEA formation outcomes when members of an IEA are empowered to impose a tariff against free riders, whether this trade linkage sustains a wider cooperation in the IEA and what the global welfare gain/loss from linkage is.

4.4.1 Optimal Policies with Linkage Regime

Trade linkage empowers signatories of an IEA, if any is formed, to "punish" free riders of the IEA by excluding them from the free trade agreement. Since there are no free riders under *Grand Coalition*, trade linkage makes no difference when *Grand Coalition* is formed. There is no role for trade linkage to play since there is no existing IEA under *Stand-alone*. Trade linkage takes effect only when *the Pair* is formed. Once the free rider is excluded from free trade, the best choice for it is to retaliate by imposing a tariff against the signatories as well. The optimal policies under *the Pair* with linkage regime are to be resolved in this section.

An important aspect about how *the Pair* cooperate on trade policy deserves comments. Signatories can cooperate in a way that trade is free within the bloc, $t_{ij} = t_{ji}$, but members independently set tariffs on goods from non-signatory countries. An alternative is that signatories also select same external tariff on all imports. I use the former framework regarding trade policy in this study. However, it is noteworthy that there is no difference in outcomes between these two frameworks because of symmetry in this model.

With trade linkage regime, signatories of the IEA cooperate on production taxes and tariffs $\{t_{ik}, t_{ik}, \tau_i^J, \tau_j^I\}$ against country k to maximize the joint welfare $(\omega_i + \omega_j)$.

The reaction functions for policies regarding good J can be obtained as

$$t_{jk} = \epsilon_k^J - \frac{M_{i\ \tau}^J}{M_{i\ p}^J + M_{j\ p}^J}(\tau_i^J - (\frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J})) - \frac{M_{k\ \tau}^J}{M_{k\ p}^J}(\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J}) \tag{4.4.1}$$

$$\tau_i^J = \frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J} + \frac{M_{k\ \tau}^J}{\sum_z M_{z\ p}^J + M_{i\ \tau}^J}(\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J}) + \frac{M_{k\ p}^J}{\sum_z M_{z\ p}^J + M_{i\ \tau}^J}(t_{jk} - \epsilon_k^J) \tag{4.4.2}$$

The first order condition for tariff t_{jk} consists of three parts. The first term in (4.4.1) is the standard optimal tariff ϵ_k^J, extracting *terms-of-trade* gain from exporting country k. The second term is a second-best instrument to partially correct distortions caused by dirty production in one of the signatories, country i, provided that the first-best policy τ_i^J is not efficient. If production tax in country i is inefficiently high, $\tau_i^J > \partial E_i/\partial s_i^J + \partial E_j/\partial s_i^J$, tariff against country k will be relatively higher to reimburse the competitiveness loss of country i due to an inefficiently high production tax.[18] On the contrary, if the production tax is inefficiently low, $\tau_i^J < \partial E_i/\partial s_i^J + \partial E_j/\partial s_i^J$, tariff t_{jk} is then used to correct efficiency loss from trade diversion effect. The last term aims to partially internalize the environmental externality on signatories due to dirty production of good J in country k. It contributes to a higher tariff against country k, which in turn declines country j's import demand from country k.[19]

Production tax τ_i^J in equation (4.4.2) also consists of three parts: the first term is the well-known Pigovian tax that internalizes the externality on the Pair members. The second term is related to *leakage* problem while the last term is about *terms-of-trade* gain from non-signatory, which will be present if and only if the *terms-of-trade* gain is not fully extracted by tariff. If the tariff t_{jk} is inefficiently high, $t_{jk} > \epsilon_k^J$, the last term then contributes to a higher production tax (see footnote 11 for the sign of the coefficient) in country i to offset the trade diversion effect. By contrast, if the tariff is inefficiently low $t_{jk} < \epsilon_k^J$, the last term will result in a lower production tax in country i to correct the distortion caused by the inefficient tariff.

The optimal policies are the intersection of the two first order conditions and

[18] $M_{i\ \tau}^J/(M_{j\ p}^J + M_{i\ p}^J) < 0$ since $M_{i\ \tau}^J > 0, M_{j\ p}^J + M_{i\ p}^J < 0$.
[19] $M_{k\ \tau}^J/M_{k\ p}^J < 0$ since $M_{k\ \tau}^J > 0, M_{k\ p}^J < 0$.

solved as[20]

$$t_{jk} = \underbrace{\epsilon_k^J}_{\text{terms-of-trade } (+)} \underbrace{- \frac{M^J_{k\ \tau}}{M^J_{k\ p}}(\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J})}_{\text{leakage effect } (+)} \tag{4.4.3}$$

$$\tau_i^J(l) = \underbrace{\frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J}}_{\text{Pigouvian tax}(+)} \tag{4.4.4}$$

Production tax of signatories with linkage regime converges to the efficient Pigouvian tax with no other distortions, whereas the *terms-of-trade* gain and the *leakage* problem now are handled by tariff.

One can compare the optimal policies with and without trade linkage. Without trade linkage, the optimal policy (4.3.4) works as a Pigouvian tax, a second-best policy for *terms-of-trade* gain and also deals with *leakage* problem. With trade linkage, signatories of *the Pair* can use tariff which is a first-best policy to manipulate *terms-of-trade* gain. *The Pair* members are moving towards their trade Pareto frontier, which generates pure welfare gain in *terms of trade*. Moreover, tariff is more efficient to deal with *leakage* problem, as is shown by the two coefficients of the leakage term in (4.3.4) and (4.4.3). Policies for good K stay the same as *the Pair* members are exporting countries of good K with no access to tariffs. Thus, signatories of *the Pair* are strictly better off with linkage.

Once signatories punish the free rider by imposing a tariff, the best choice for the free rider is to retaliate by imposing tariff in its importing sector, good K. Here I will mainly focus on the derivation of the tariffs for good K since the policies for the other two exporting goods stay the same as under *Stand-alone*. The first order conditions for optimal tariffs of good K for signatories are given as follows:

$$t_{ki} = \epsilon_i^K + \frac{M^K_{j\ p}}{M^K_{j\ p} + M^K_{k\ p}}(t_{kj} - \epsilon_j^K) - \frac{M^K_{i\ \tau}}{M^K_{i\ p}}\frac{\partial E_i}{\partial s_i^K} + \frac{M^K_{j\ \tau}}{M^K_{j\ p} + M^K_{k\ p}}\frac{\partial E_i}{\partial s_j^K} \tag{4.4.5}$$

$$t_{kj} = \epsilon_j^K + \frac{M^K_{i\ p}}{M^K_{i\ p} + M^K_{k\ p}}(t_{ki} - \epsilon_i^K) - \frac{M^K_{j\ \tau}}{M^K_{j\ p}}\frac{\partial E_i}{\partial s_j^K} + \frac{M^K_{i\ \tau}}{M^K_{i\ p} + M^K_{k\ p}}\frac{\partial E_i}{\partial s_i^K} \tag{4.4.6}$$

The first order condition for t_{ki} in equation (4.4.5) reflects its four goals. The first

[20] $\tau_i^J(l)$ represents the optimal production tax of good J in signatory i with linkage.

term is the standard *terms-of-trade* effect. The less elastic of the export supply of country i, the higher the tariff against it. Since country k imports good K from two exporting countries, t_{ki} is also used to affect the import from the other trading partner, country j, due to the trade diversion effect in my model. If $t_{kj} < \epsilon_j^K$ (t_{kj} is inefficiently low) while t_{ki} is efficient in *terms-of-trade*, import demand from country j will be higher than that from country i. Country k switches part of its import from the efficient producer to a less efficient one because the latter enjoys a lower tariff, resulting in efficiency loss for country k. Therefore, when $t_{kj} < \epsilon_j^K$, the *terms-of-trade* related term in t_{ki} should be less than ϵ_i^K to avoid inefficiency caused by trade diversion. t_{ki} also works as a second-best policy to correct the distortions caused by environmental externalities in production countries. The third term reflects country k's incentives to impose a tariff that is higher than the standard optimal tariff in trade literature against country i to partially internalize the environmental externality by the production of good K in country i. Because of the trade diversion effect, t_{ki} also aims at correcting environmental distortions in the other trade partner. If the other trade partner is dirtier ($\frac{\partial E_i}{\partial s_j^K}$ is big), country k will set a lower tariff against county i. Then the domestic demand for good from country j decreases, which in turn decreases the dirtier production in country j.

The optimal tariffs are the intersection of the above two first order conditions (4.4.5) and (4.4.6) and solved as

$$t_{ki} = \underbrace{\epsilon_i^K}_{\text{terms-of-trade}(+)} \underbrace{- \frac{M_i^K{}_\tau}{M_i^K{}_p} \frac{\partial E_k}{\partial s_i^K}}_{\text{leakage effect}(+)}, \quad t_{kj} = \underbrace{\epsilon_j^K}_{\text{terms-fo-trade}(+)} \underbrace{- \frac{M_j^K{}_\tau}{M_j^K{}_p} \frac{\partial E_k}{\partial s_j^K}}_{\text{leakage effect}(+)} \tag{4.4.7}$$

It is clear that if both of the tariffs are set efficiently, each of them is used to manipulate *terms-of-trade* gain and partially internalize the negative externality on country k due to dirty production in the related exporting country.

Given the specific function forms in (4.3.6)-(4.3.8), the optimal policies for both sides under *the Pair* are solved as

$$\tau_i^K(l) = \tau_j^K(l) = \frac{2\alpha(7+43\beta)}{140+785\beta} \tag{4.4.8}$$

$$\tau_i^J(l) = \tau_j^I(l) = \frac{190\alpha\beta}{28+157\beta}, \quad t_{ik} = t_{jk} = \frac{\alpha(16+809\beta)}{280+1570\beta} \tag{4.4.9}$$

$$\tau_k^I(l) = \tau_k^J(l) = \frac{\alpha(4+321\beta)}{140+785\beta}, \quad t_{ki} = t_{kj} = \frac{\alpha(21+379\beta)}{280+1570\beta} \tag{4.4.10}$$

β can only take values from the range $[0, \beta_l^*(=\frac{16}{141})]$ to satisfy the assumed trade pattern that country i imports good I from and exports good J, K to the other trading partners. Outside the above range, optimal policies will take different forms. When $\beta_l^* < \beta < \beta_l^{**}(=\frac{3}{13})$, the tariffs of signatories against country k become so high that country k will not export any good I or J to *the Pair* members. There are no *terms-of-trade* and *leakage* terms for country k. Then production taxes of good $I(J)$ in both signatories and non-signatory are Pigovian tax $\tau_k^I(l) = \partial E_k/\partial s_k^I$ and $\tau_j^I(l) = \partial E_i/\partial s_j^I + \partial E_j/\partial s_j^I$. When β is greater than $\beta_l^{**}(=\frac{3}{13})$, country k is better off by not consuming good K other than importing from *the Pair* members. Then there is no trade flow between *the Pair* members and the free rider. All policies are Pigovian taxes.

4.4.2 Does Linkage Sustain Wider Cooperation?

Now the stable coalition with trade linkage can be investigated. More importantly, I am able to determine whether or not trade linkage can sustain wider cooperation in IEA formation by contrasting the stable coalition under free trade with the ones achieved with linkage.

Let $\Omega_i^*(r)$ be the welfare of country i with the relevant optimal policy under coalition structure r when trade linkage is introduced. Since trade linkage only takes effect when *the Pair* is formed, the welfare for *Grand Coalition* and *Stand-alone* are the same with those under free trade, that is $\Omega_i^*(g) = \omega_i^*(g)$ and $\Omega_i^*(s) = \omega_i^*(s)$. Let $\Delta\Omega_i^*(g-p)$ be the welfare difference for country i between *Grand Coalition* and *the Pair* when trade linkage is introduced. By applying the Nash and strong Nash equilibrium conditions, I find that *Grand Coalition* is stable if and only if

$\beta_l^1(=0.0310) \leq \beta \leq \beta_l^2(=0.1516)$, since

$$\Delta\Omega_i^*(g-p) = \Delta\Omega_j^*(g-p) < 0, \forall\beta \in (0, \beta_l^1) \tag{4.4.11}$$

$$\Delta\Omega_k^*(g-p) < 0 \ \&\ \Delta\Omega_i^*(s-p) = \Delta\Omega_j^*(s-p) < 0, \forall\beta \in (\beta_l^2, \bar{\beta}_f) \tag{4.4.12}$$

Condition (4.4.11) states that for $\beta \in (0, \beta_l^1)$, a group deviation of country i and country j from *Grand Coalition* to form *the Pair* generates higher welfare for those two countries. Thereby, *Grand Coalition* is not immune to a group deviation of country i and j and will no longer be in equilibrium for $\beta \in (0, \beta_l^1)$. Condition (4.4.12) states that as β is beyond β_l^2, country k prefers to withdraw from *Grand Coalition* and be a free rider while the other two countries stick to form a Pair.

With trade linkage, *the Pair* is in equilibrium if and only if $\beta \in (0, \beta_l^1) \cup (\beta_l^2, \bar{\beta}_f)$. For $\beta \in (0, \beta_l^1)$, country i and j deviate from *Grand Coalition* according to (4.4.11). They have no incentives for further deviation since

$$\Delta\Omega_i^*(p-s) = \Delta\Omega_j^*(p-s) > 0, \forall\beta \in (0, \beta_l^1) \tag{4.4.13}$$

This is also true when country k deviates from *Grand Coalition* according to condition (4.4.12). It implicitly indicates that *Stand-alone* is again never in equilibrium.

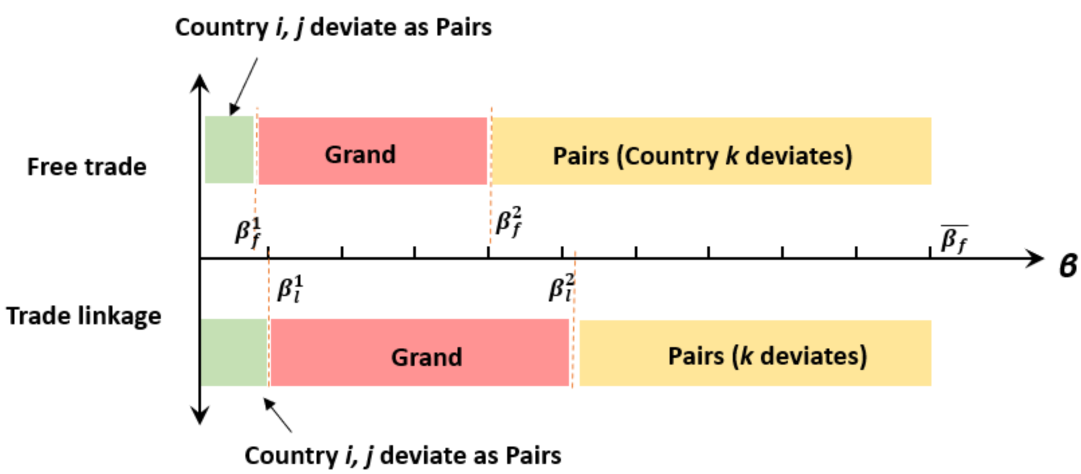

Figure 4.3: Free Trade Versus Trade Linkage: Stable Coalition

Figure 4.3 compares the stable coalition structures under free trade and those with trade linkage regime. Firstly, it is clear that trade linkage does sustain wider cooperation by eliminating free-riding incentives of country k for $\beta \in (\beta_f^2, \beta_l^2)$, which is otherwise impossible with free trade regime. This is shown in the figure that the yellow region is smaller with trade linkage than that under free trade. The intuition is that country k will be excluded from the free trade agreement if it free rides on the IEA. The benefit from free-riding on IEA is offset by the loss that country k bears from trade. Put differently, country k is threatened by trade sanction thus join the IEA. However, as β increases, the result is reversed that the benefit from free riding is higher than the loss from trade. Thus, country k again deviates from *Grand Coalition*, by that means trade linkage can't eliminate all free riding incentives.

Secondly, trade linkage induces participation in IEAs only for a relatively small interval of β. The reason is that production tax has been used as a second-best policy to extract *terms-of-trade* gain and deal with *leakage* problem under free trade. Trade linkage enables members of *the Pair* to move towards their Pareto frontier by using a first-best policy for *terms-of-trade* and a more efficient policy for *leakage* problem. However, this welfare gain, or the welfare loss of country k, is limited to fully eliminate all free riding incentives of country k. This result is consistent with Nordhaus (2015). By using his empirical C-DICE model, he found that for the lowest target carbon prices ($12.5 and $25 per ton), full participation and efficiency are achieved with relatively low tariffs (2 percent or more). However, as the target carbon price rises, it becomes increasingly difficult to attain the cooperative equilibrium.

Thirdly, I also find that for some specific values of β, trade linkage can be counter-productive. When $\beta \in (\beta_f^1, \beta_l^1)$, the stable *Grand Coalition* under free trade is no longer achieved with trade linkage because country i and j group deviate to a Pair. This is shown in the figure that the green region is bigger with linkage than that under free trade. The intuition is that when β is small, the climate change damage is negligible. Thus, the production tax is more used for trade purpose. Country i and j can extract more monopolistic surplus when they form a Pair rather than in *Grand Coalition*. With the introduction of trade linkage, *the Pair* members are able to extract more trade gain by imposing tariffs, thus, trade linkage is counter-productive for $\beta \in (\beta_f^1, \beta_l^1)$.

The above discussions can be summarized as the following proposition.

Proposition 12. *Trade linkage eliminates some free riding incentive of country k and stabilizes Grand Coalition for $\beta \in (\beta_f^2, \beta_l^2)$, which is otherwise a unstable with free trade regime. However, trade linkage is not effective for $\beta > \beta_l^2$ or counter-productive for $\beta \in (\beta_f^1, \beta_l^1)$ in terms of sustaining Grand Coalition.*

4.4.3 Global Welfare Gain/Loss from Trade Linkage

Trade linkage sustains wider cooperation in a sense that it eliminates some of the free riding incentives of country k. But it should be kept in mind that it is not effective or even counter-productive for some values of β. Hence, the questions that are addressed in this subsection are: is there global welfare gain or loss from trade linkage? If there is global welfare gain, where does it come from?

Let $V^*(r) = \sum_i \Omega_i^*(r)$ b global welfare under coalition structure r with trade linkage. Let $\Delta V^*(r - v)$ be the global welfare difference between stable coalition structure r with trade linkage and stable coalition v under free trade. Since $\Omega_i^*(g) = \omega_i^*(g)$ and $\Omega_i^*(s) = \omega_i^*(s)$, $V^*(g) = W^*(g)$ and $V^*(s) = W^*(s)$. The welfare difference between stable coalition with trade linkage and those achieved under free trade are then given as

$$\Delta V^*(p - p) = V^*(p) - W^*(p), \quad \forall \beta \in [0, \beta_f^1] \tag{4.4.14}$$

$$\Delta V^*(p - g) = V^*(p) - W^*(g), \quad \forall \beta \in (\beta_f^1, \beta_l^1] \tag{4.4.15}$$

$$\Delta V^*(g - g) = V^*(g) - W^*(g), \quad \forall \beta \in (\beta_l^1, \beta_f^2] \tag{4.4.16}$$

$$\Delta V^*(g - p) = V^*(g) - W^*(p), \quad \forall \beta \in (\beta_f^2, \beta_l^2] \tag{4.4.17}$$

$$\Delta V^*(p - p) = V^*(p) - W^*(p), \quad \forall \beta \in (\beta_l^2, \bar{\beta}_f] \tag{4.4.18}$$

Figure 4.4 plots global welfare difference (4.4.14)-(4.4.18) with and without linkage when β varies. First, there is welfare loss for $\beta \in [0, \beta_l^1)$. When β is small, policies with both regimes are used more to manipulate *terms-of-trade*. Trade linkage moves countries even far away from the globally Pareto efficient trade policy - free trade. For $\beta \in (\beta_l^1, \beta_f^2)$, *Grand Coalition* is in equilibrium with both policy regimes, $\Delta V^*(g-g) = 0$. For $\beta \in (\beta_f^2, \beta_l^2)$, trade linkage stabilizes the unstable *Grand Coalition* under free trade and generates large global welfare gain. This is because the free rider is threatened by trade sanctions and chooses to participate in IEA. Therefore, trade sanction is not taken place, resulting in no welfare loss from trade side. At the same time, cooperation in IEA is enhanced, which generates welfare gain from environmental side. For $\beta \in (\beta_l^2, \bar{\beta}_f)$, *the Pair* is in equilibrium in both policy regimes. However, there is still global welfare gain from trade linkage. Even tough country k still chooses to free ride but it has to reduce its production and not to export to *the Pair* due to the large tariff imposed by *the Pair*.

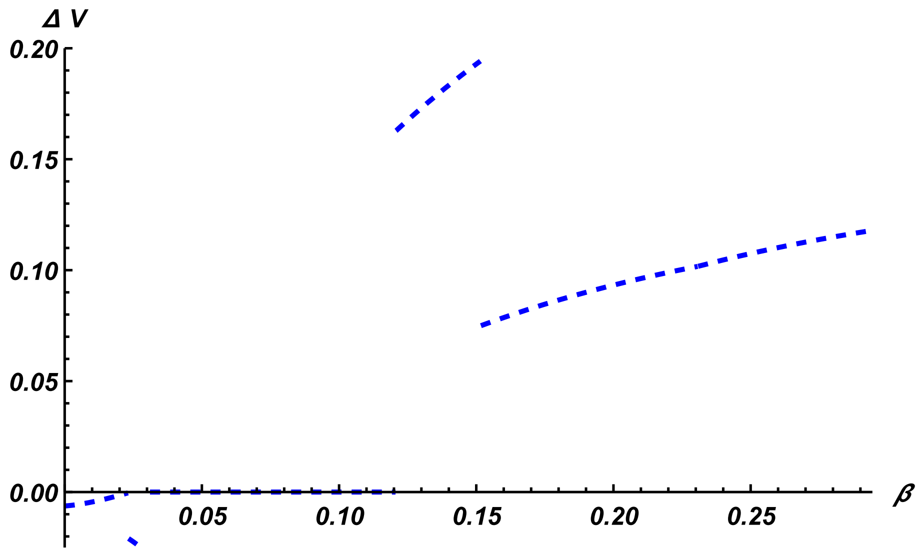

Figure 4.4: Global Welfare Gain/Loss from Trade Linkage

As is shown that trade linkage induces participation in IEA and generates large welfare gain for $\beta \in (\beta_f^2, \beta_l^2)$. If the welfare gain is from the environmental side, but at the cost of *non-climate welfare*, trade linkage might be opposed by some countries. This study assumes that countries are symmetric in β. However, some developing countries in the tropical region are harmed more by climate change while the others are not. If trade linkage incurs large welfare loss in *non-climate welfare*, those which are not largely affected by climate change might oppose trade linkage. Figure 4.5 depicts the decomposed global welfare under free trade and trade linkage for $\beta \in (\beta_f^2, \beta_l^2)$. The dashed line represents the global welfare (*non-climate* - climate welfare loss) while the solid line represents the *non-climate* welfare. Therefore, the climate change damage is the difference between solid line and dashed line. Figure

4.5 shows that *non-climate* welfare with trade linkage is lower than that under free trade. However, trade linkage helps to substantially reduce welfare loss from the environmental side.

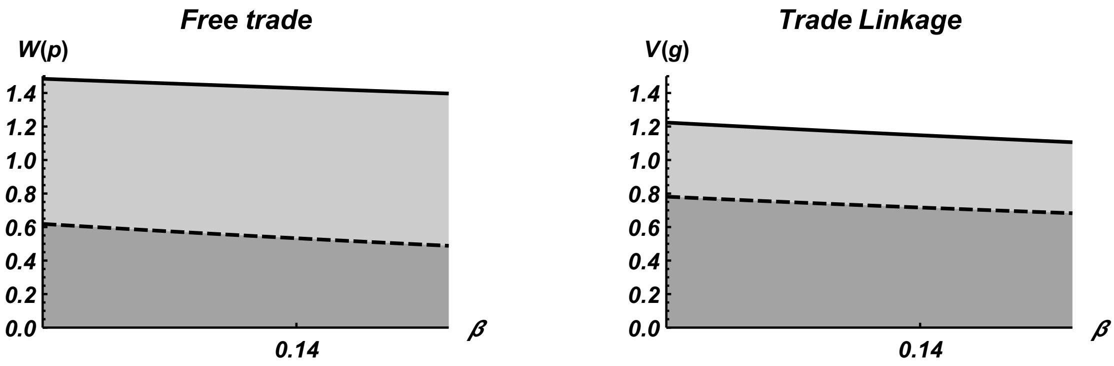

Figure 4.5: Welfare Decomposition: Free Trade VS Trade Linkage (β_f^2, β_l^2)

The above discussions lead to Proposition 13.

Proposition 13. *Trade linkage generates large welfare gain from global perspective for* $\beta \in (\beta_f^2, \beta_l^2)$ *and the gain comes from the decrease of welfare loss from climate change damage at the cost of lower non-climate welfare.*

4.5 Challenges of Introducing Trade Linkage

Proposals that link trade policy to international climate change cooperation have drawn a lot attention. This chapter shows that such trade linkage is an effective mechanism to overcome the free-riding problem in IEAs when climate change damage is moderate. However, there are challenges ahead of introducing trade linkage. This section investigates the possibility of such an linkage in my theoretical model and further discusses the practical issues under current WTO framework.[21]

[21] Trade linkage is not efficient in terms of global welfare gain when climate change damage is small. For those scenarios, it is not welfare-improving to introduce trade linkage. Thus the discussions about challenges of introducing trade linkage in this section are meaningful only when trade linkage generates welfare gains. However, I still compare welfare changes for each party under all damage levels.

4.5.1 Will All Countries Favour Linkage?

Despite the global welfare that trade linkage generates, players in this trade linkage game are individually rational, which means that a country will support such linkage if and only if it is weakly better off with trade linkage. Thus, in stage one when countries are in a position to agree or disagree to trade linkage, each of them will compare its welfare from stable coalition without trade linkage to the one with trade linkage.[22]

Let $\Omega_z(r)$ and $\omega_z(r)$ be the welfare for country z $(= i, j, k)$ under stable coalition structure r with and without trade linkage, respectively. It is noteworthy that the stable coalition structures are not necessarily the same with and without linkage. For example, when $\beta \in (\beta_f^2, \beta_l^2]$, trade linkage eliminates the free-riding incentive and stabilizes *Grand Coalition* whereas *the Pair* is the stable structure without linkage. Then the corresponding welfare for country z for this range of β would be $\Omega_z(g)$ (with linkage) and $\omega_z(p)$ (without linkage). Each country will support linkage if the following conditions are satisfied $(z = i, j, k)$

$$\Omega_z(p) - \omega_z(p) \geq 0, \qquad \forall \beta \in (0, \beta_f^1] \tag{4.5.1}$$

$$\Omega_z(p) - \omega_z(g) \geq 0, \qquad \forall \beta \in (\beta_f^1, \beta_l^1] \tag{4.5.2}$$

$$\Omega_z(g) - \omega_z(g) \geq 0, \qquad \forall \beta \in (\beta_l^1, \beta_f^2] \tag{4.5.3}$$

$$\Omega_z(g) - \omega_z(p) \geq 0, \qquad \forall \beta \in (\beta_f^2, \beta_l^2] \tag{4.5.4}$$

$$\Omega_z(p) - \omega_z(p) \geq 0, \qquad \forall \beta \in (\beta_l^2, \bar{\beta}_f] \tag{4.5.5}$$

Condition (4.5.1) means that country z is weakly better off with linkage than without linkage, because it enjoys a higher welfare with linkage. Same logic applies to the other four conditions.

I can then contrast the welfare with two policy regimes for each country. Countries that can form a Pair favour trade linkage since condition (4.5.1)-(4.5.5) are all satisfied for country i and j. In contrast , the free rider of *the Pair*, country k, is against trade linkage since it is weakly worse off with linkage ((4.5.1)-(4.5.5) are all

[22]Since it is assumed that the *status quo* in terms of trade cooperation is free trade agreement with complete participation, all three countries are eligible to make its own decision about linkage.

violated). This intuition is as follows. With trade linkage, country k can either keep free-riding but has to take trade sanctions, thus it will lose from trade side. Or the free-rider is threatened by trade sanction and chooses to join the IEA, then it can't free ride any more and losses welfare from environmental side. In either case, the free-rider is worse off with trade linkage, and thus will be against it. The members of *the Pair* are taking the opposite side and always better off with linkage. This partly explains why in real world non-linkage is much more prevalent than linkage, because free riders will always oppose it.

Whether trade linkage can be approved or not depends on the voting rule specified in the free trade agreement. If the trade agreement applies a unanimity voting rule, trade linkage is not possible in the first place despite the global welfare gain it generates, because country k is against linkage. If the trade agreement allows a majority voting rule, since country i and j favour trade linkage, linkage can take place.

The above discussions lead to Proposition 14.

Proposition 14. *If free trade is the status quo, any two countries that can form a Pair are weakly better off with linkage and will support linkage while free-rider of the Pair is weakly worse off with linkage and will be against linkage. Whether trade linkage can be approved or not depends on the voting rule specified in free trade agreement.*

Another possible explanation for the prevalence of non-linkage is that the welfare gain that trade linkage generates is at the cost of a lower *non-climate* welfare, as shown in Fig 4.5. This study assumes that countries are identical in climate change damage level (β is a constant across countries). In reality, there might be countries that have a very small value of β. In this case, a member of *the Pair* with a small β might be a loser from trade linkage since the welfare gain from a better environment is offset by the loss from *non-climate*. Therefore, this type of countries will be also against linkage. Future studies that relax the assumption of symmetry is needed to examine the welfare implication for countries with large β and small β.

4.5.2 WTO Rules and Trade Linkage

This study proposes a framework that links trade privileges of an existing free trade agreement to the formation of an IEA. Whether such linkage is compatible and possible under current WTO principles and rules is another concern of introducing trade linkage. This section discusses those relevant issues.

A linkage that punishes free riders of an IEA by imposing trade barriers might violate one of the fundamental principles of GATT (The General Agreement on Tariffs and Trade), non-discrimination, which is embodied by the National Treatment obligation and the Most Favoured Nation (MFN) treatment obligation.[23] The former obligation prohibits discriminatory treatment of foreign goods relative to domestic goods with respect to internal taxation or other government regulations, while the later obligation states that any special favour that is granted to one trading parter should be granted immediately and unconditionally to all WTO members.

If trade linkage of the form proposed in this chapter is introduced, free riders will be excluded from trade privileges of free trade and bear trade barriers imposed by IEA members while the others can still enjoy this privilege. In this sense, this discrimination is not compatible with current WTO rules. Such linkage is rare in practice, but the Montreal Protocol on Substances that Deplete the Ozone Layer (hereafter Montreal Protocol) is definitely one of them. Montreal Protocol bans trade between signatories and non-signatories in CFCs and other substances controlled by the treaty as well as imports from non-signatories of products containing these substances Montreal Protocol (1987). Interestingly, participation in the Montreal Protocol turned out to be almost global without the need of actually implementing the ban. However, Montreal Protocol has been criticized as "unnecessary and "inconsistent" with the non-discrimination principle of GATT.

On the other hand, there is still possibility of using trade restrictions to induce wider participation in IEAs under Article XX of GATT, as trade restrictions are allowed under this Article if they are "necessary to protect human, animal, or plant

[23]Since the main focus in this thesis is trade in goods, I will pay my particular attention to GATT rather than General Agreement on Trade in Services (GATS) and the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS).

life or health" and "relating to conservation or exhaustion of exhaustible natural resources if such measures are made effective in conjunction with restrictions on domestic production or consumption ..." Thus, there are still many legal and practical issues unsolved, which are beyond the scope of this study, under current WTO rules to introduce such a linkage.

4.6 Conclusion

This chapter first explicitly explored the role that trade plays in IEA formation. This study adopts a partial equilibrium competing exporters trade model of Bagwell and Staiger (1997), but allows a pure public bad "greenhouse gas emission" to be generated jointly with the production of goods. Consistent with prior literature (e.g., Markusen (1975b)), this study shows that production tax of a large exporter is not only used to internalize environmental externalities, but also to deal with *leakage* problem and to manipulate *terms-of-trade* gains. Such use of production tax in climate change cooperation leads to an interesting result, which has been not explored by prior literature. That is, in addition to the environmental benefits of a partial coalition, cooperating countries also enjoy a larger market power by forming a coalition and can exploit more surplus in international trade, which potentially prompts cooperation on climate. Hence, cooperation, even partial cooperation is better than non-cooperation. Consequently, *Stand-alone* is never a stable equilibrium.

This chapter then investigated the effectiveness and possibility of a trade linkage which aims to overcome free riding problems in climate change cooperation. Trade linkage in this study is defined as adding a clause to the existing free trade agreement, making the privileges of free trade contingent on participation of the IEA. More importantly, trade linkage is modelled as an endogenous choice for countries, which sharply contrasts the existing literature that has exogenously introduced trade linkage and only aims to uncover the effect of trade linkage.

Compared to the prior literature, this chapter also draws some interesting new results regarding trade linkage. Trade linkage can deter free riding incentives and stabilize the unstable *Grand Coalition* under free trade when climate change damage is moderate. This result is consistent with Nordhaus (2015). Nordhaus found that for the lowest target carbon prices ($12.5 and $25 per ton), full participation and efficiency are achieved with relatively low tariffs (2 percent or more). In addition to the effectiveness of trade linkage, this chapter also prevails that trade linkage generates large welfare gain globally, however, this gain mainly comes from the decrease of climate change damage but at the cost of *non-climate* welfare. Second, the presumption that trade linkage always induces participation in IEA is misleading. It can be ineffective when climate change damage is large, even though there is still global welfare gain. Nordhaus (2015) also found that as the target carbon price rises, it becomes increasingly difficult to attain the cooperative equilibrium. An interesting new finding in this study is that trade linkage is counter-productive in terms of sustaining full cooperation when climate change damage is small. Literature regarding the endogenicity of trade linkage is relatively missing. But this study shows that it matters. By contrasting the welfare of each country under trade linkage with those under free trade, I found that trade linkage can't be introduced in the first place if the voting rule requires consensus approval, since the free rider of *the Pair* is weakly worse off with linkage, and thus against linkage. Trade linkage is only possible if a majority voting rule is applied.

Appendix

A

Section A of the Appendix provides mathematical proofs for the derivations in Section 4.2.1.

A1: Derivation of $\partial p_i^I / \partial t_{ij}$ in (4.2.8)

Implicitly differentiating market clearing conditions (4.2.6) with respect to t_{ij} yields

$$\frac{dM_i^I}{dp_i^I}\frac{\partial p_i^I}{\partial t_{ij}} + \frac{\partial M_j^I}{\partial p_j^I}\frac{\partial p_j^I}{\partial t_{ij}} + \frac{\partial M_k^I}{\partial p_k^I}\frac{\partial p_k^I}{\partial t_{ij}} = 0 \tag{4.6.1}$$

From (4.2.2) - (4.2.3), one can obtain

$$\frac{\partial p_j^I}{\partial t_{ij}} = \frac{\partial \rho_{ij}}{\partial p_i^I}\frac{\partial p_i^I}{\partial t_{ij}} + \frac{\partial \rho_{ij}}{\partial t_{ij}} = \frac{\partial p_i^I}{\partial t_{ij}} - 1 \tag{4.6.2}$$

$$\frac{\partial p_k^I}{\partial t_{ij}} = \frac{\partial \rho_{ik}}{\partial p_i^I}\frac{\partial p_i^I}{\partial t_{ij}} + \frac{\partial \rho_{ik}}{\partial t_{ij}} = \frac{\partial p_i^I}{\partial t_{ij}} \tag{4.6.3}$$

By using (4.6.2) and (4.6.3), one can simplify (4.6.1) to obtain

$$\frac{dM_i^I}{dp_i^I}\frac{\partial p_i^I}{\partial t_{ij}} + \frac{\partial M_j^I}{\partial p_j^I}(\frac{\partial p_i^I}{\partial t_{ij}} - 1) + \frac{\partial M_k^I}{\partial p_i^I}\frac{\partial p_i^I}{\partial t_{ij}} = 0$$

$$(\frac{dM_i^I}{dp_i^I} + \frac{\partial M_j^I}{\partial p_j^I} + \frac{\partial M_k^I}{\partial p_k^I})\frac{\partial p_i^I}{\partial t_{ij}} = \frac{\partial M_j^I}{\partial p_j^I}$$

$$\frac{\partial p_i^I}{\partial t_{ij}} = \frac{\frac{\partial M_j^I}{\partial p_j^I}}{\frac{dM_i^I}{dp_i^I} + \frac{\partial M_j^I}{\partial p_j^I} + \frac{\partial M_k^I}{\partial p_k^I}}$$

$$\frac{\partial p_i^I}{\partial t_{ij}} = \frac{M_{j\,p}^I}{\sum_{z=i,j,k} M_{z\,p}^I} > 0 \tag{4.6.4}$$

where $M_{j\,p}^I$ is the partial derivative with respect to p_j^I. $\frac{\partial p_i^I}{\partial t_{ij}} > 0$ because $dM_i^I(p_i^I)/dp_i^I < 0$ and $\partial M_z^I(p_i^Z, \tau_i^Z)/\partial p_I^z < 0, z \neq i$.

A2: Derivation of $\partial p_i^I/\partial \tau_j^I$ in (4.2.8)

noindent Implicitly differentiating market clearing conditions (4.2.6) with respect to τ_j^I yields

$$\frac{dM_i^I}{dp_i^I}\frac{\partial p_i^I}{\partial \tau_j^I} + \frac{\partial M_j^I}{\partial p_j^I}\frac{\partial p_j^I}{\partial \tau_j^I} + \frac{\partial M_j^I}{\partial \tau_j^I} + \frac{\partial M_k^I}{\partial p_k^I}\frac{\partial p_k^I}{\partial \tau_j^I} = 0 \tag{4.6.5}$$

From (4.2.2)-(4.2.3), one can obtain

$$\frac{\partial p_i^I}{\partial \tau_j^I} = \frac{\partial p_j^I}{\partial \tau_j^I} = \frac{\partial p_k^I}{\partial \tau_j^I} \tag{4.6.6}$$

By using (4.6.6), one can obtain

$$\begin{aligned}
&\frac{dM_i^I}{dp_i^I}\frac{\partial p_i^I}{\partial \tau_j^I}+\frac{\partial M_j^I}{\partial p_j^I}\frac{\partial p_i^I}{\partial \tau_j^I}+\frac{\partial M_j^I}{\partial \tau_j^I}+\frac{\partial M_k^I}{\partial p_k^I}\frac{\partial p_i^I}{\partial \tau_j^I}=0\\
&(\frac{\partial M_i^I}{\partial p_i^I}+\frac{\partial M_j^I}{\partial p_j^I}+\frac{\partial M_k^I}{\partial p_k^I})\frac{\partial p_i^I}{\partial \tau_j^I}=-\frac{\partial M_j^I}{\partial \tau_j^I}\\
&\frac{\partial p_i^I}{\partial \tau_j^I}=-\frac{M_{j\,\tau}^I}{\sum_{z=i,j,k} M_{z\,p}^I}>0
\end{aligned}\tag{4.6.7}$$

$\partial p_i^I/\partial \tau_j^I > 0$ because $dM_i^I(p_i^I)/dp_i^I < 0$ and $\partial M_z^I(p_i^Z,\tau_i^Z)/\partial p_I^z < 0, z \neq i$ and $\partial M_j^I(p_i^Z,\tau_i^Z)/\partial \tau_j^I > 0$.

A3: Sign of $\partial q_j^I/\partial \tau_j^I$ in (4.2.8)

$$\begin{aligned}
\frac{\partial q_j^I}{\partial \tau_j^I} &= \frac{\partial \mu}{\partial p_j^I}\frac{\partial p_j^I}{\partial \tau_j^I}+\frac{\partial \mu}{\partial \tau_j^I}\frac{\partial \tau_j^I}{\partial \tau_j^I}=\frac{\partial p_j^I}{\partial \tau_j^I}-1\\
&= -\frac{M_{j\,\tau}^I+\sum_{z=i,j,k} M_{z\,p}^I}{\sum_{z=i,j,k} M_{z\,p}^I}<0
\end{aligned}$$

It is negative since $M_{z\,p}^I < 0$ and

$$\begin{aligned}
\frac{dM_i^I}{dp_i^I}+\frac{\partial M_k^I}{\partial p_k^I}+\frac{\partial M_j^I}{\partial p_j^I}+\frac{\partial M_j^I}{\partial \tau_j^I} &= \frac{dM_i^I}{dp_i^I}+\frac{\partial M_k^I}{\partial p_k^I}+\frac{dD_j^I}{dp_j^I}-\frac{dS_j^I}{dq_j^I}\frac{\partial \mu_j^I}{\partial p_j^I}-\frac{dS_j^I}{dq_j^I}\frac{\partial \mu_j^I}{\partial \tau_j^I}\\
&= \frac{dM_i^I}{dp_i^I}+\frac{\partial M_k^I}{\partial p_k^I}+\frac{dD_j^I}{dp_j^I}-\frac{dS_j^I}{d\mu_j^I}(\frac{\partial \mu_j^I}{\partial p_j^I}+\frac{\partial \mu_j^I}{\partial \tau_j^I})\\
&= \frac{dM_i^I}{dp_i^I}+\frac{\partial M_k^I}{\partial p_k^I}+\frac{dD_j^I}{dp_j^I}-\frac{dS_j^I}{dq_j^I}(1-1)\\
&= \frac{dM_i^I}{dp_i^I}+\frac{\partial M_k^I}{\partial p_k^I}+\frac{dD_j^I}{dp_j^I}<0
\end{aligned}\tag{4.6.8}$$

B

Section B of the Appendix provides mathematical derivations of the optimal production taxes under all coalition structures without linkage in Section 4.3.1.

B1: Derivations under ***Stand-alone*** (4.3.1)

Taking derivatives of the welfare function ω_i with respect to τ_i^J yields

$$-D_i^J \frac{\partial p_i^J}{\partial \tau_i^J} + S_i^J \frac{\partial q_i^J}{\partial \tau_i^J} + S_i^J + \tau_i^J \frac{dS_i^J}{dq_i^J}\frac{\partial q_i^J}{\partial \tau_i^J} - \frac{\partial E_i}{\partial s_i^J}\frac{dS_i^J}{dq_i^J}\frac{\partial q_i^J}{\partial \tau_i^J} - \frac{\partial E_i}{\partial s_k^J}\frac{dS_k^J}{dq_k^J}\frac{\partial q_k^J}{\partial \tau_i^J} = 0$$

By using (4.2.1),one can show

$$\begin{aligned} \frac{\partial q_i^J}{\partial \tau_i^J} &= \frac{\partial \mu_i^J}{\partial p_i^J}\frac{\partial p_i^J}{\partial \tau_i^J} + \frac{\partial \mu_i^J}{\partial \tau_i^J} = \frac{\partial p_i^J}{\partial \tau_i^J} - 1 \\ \frac{\partial q_k^J}{\partial \tau_i^J} &= \frac{\partial \mu_k^J}{\partial p_k^J}\frac{\partial p_k^J}{\partial \tau_i^J} + \frac{\partial \mu_k^J}{\partial \tau_i^J} = \frac{\partial p_k^J}{\partial \tau_i^J} \end{aligned} \tag{4.6.9}$$

Given (4.2.1) and (4.2.6), one can also derive that

$$\frac{\partial M_z^Z}{\partial \tau_z^Z} = -\frac{dS_z^Z}{dq_z^z}\frac{\partial \mu_z^Z}{\partial \tau_z^Z} = \frac{dS_z^Z}{dq_z^z}, \quad z \neq Z \tag{4.6.10}$$

One can use excess demand function and (4.6.9)-(4.6.10) to simplify the above partial derivatives as

$$-M_i^J \frac{\partial p_i^J}{\partial \tau_i^J} + \tau_i^J M_{i\ \tau}^J (\frac{\partial p_i^J}{\partial \tau_i^J} - 1) - \frac{\partial E_i}{\partial s_i^J} M_{i\ \tau}^J (\frac{\partial p_i^J}{\partial \tau_i^J} - 1) - \frac{\partial E_i}{\partial s_k^J} M_{k\ \tau}^J \frac{\partial p_k^J}{\partial \tau_i^J} = 0$$

By substituting $\partial p_i^J / \partial \tau_i^J = \partial p_k^J / \partial \tau_i^J = -M_{i\ \tau}^J / \sum_{z=i,j,k} M_{z\ p}^J$, the above equation can be further simplified as

$$\begin{aligned} \tau_i^J M_{i\ \tau}^J \frac{-(\sum_{z=i,j,k} M_{z\ p}^J + M_{i\ \tau}^J)}{\sum_{z=i,j,k} M_{z\ p}^J} &= M_i^J \frac{-M_{i\ \tau}^J}{\sum_{z=i,j,k} M_{z\ p}^J} + \frac{\partial E_i}{\partial s_i^J} M_{i\ \tau}^J \frac{-(\sum_{z=i,j,k} M_{z\ p}^J + M_{i\ \tau}^J)}{\sum_{z=i,j,k} M_{z\ p}^J} \\ &\quad + \frac{\partial E_i}{\partial s_k^J} M_{k\ \tau}^J \frac{-M_{i\ \tau}^J}{\sum_{z=i,j,k} M_{z\ p}^J} \end{aligned}$$

One can further simplify to obtain

$$\begin{aligned} \tau_i^J(s) &= \frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_i}{\partial s_k^J} \frac{M_{k\ \tau}^J}{\sum_{z=i,j,k} M_{z\ p}^J + M_{i\ \tau}^J} + \frac{M_i^J}{\sum_{z=i,j,k} M_{z\ p}^J + M_{i\ \tau}^J} \\ \tau_i^J(s) &= \frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_i}{\partial s_k^J} \frac{M_{k\ \tau}^J}{\sum_{z=i,j,k} M_{z\ p}^J + M_{i\ \tau}^J} + \epsilon_i^J \frac{M_{i\ p}^J}{\sum_{z=i,j,k} M_{z\ p}^J + M_{i\ \tau}^J} \end{aligned}$$

where $\epsilon_i^J = M_i^J / M_{i\ p}^J > 0$ is inversely related to the elasticity of country i's export supply.

B2: Derivations under ***Grand*** (4.3.2)

Taking derivatives of the global welfare with respect to τ_i^J yields

$$-D_i^J \frac{\partial p_i^J}{\partial \tau_i^J} + S_i^J \frac{\partial q_i^J}{\partial \tau_i^J} + S_i^J + \tau_i^J \frac{dS_i^J}{dq_i^J} \frac{\partial q_i^J}{\partial \tau_i^J} - D_j^J \frac{\partial p_j^J}{\partial \tau_i^J} - D_k^J \frac{\partial p_k^J}{\partial \tau_i^J} + S_k^J \frac{\partial q_k^J}{\partial \tau_i^J} + \tau_k^J \frac{dS_k^J}{dq_k^J} \frac{\partial q_k^J}{\partial \tau_i^J}$$
$$-(\frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J} + \frac{\partial E_k}{\partial s_i^J}) \frac{dS_i^J}{dq_i^J} \frac{\partial q_i^J}{\partial \tau_i^J} - (\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J} + \frac{\partial E_k}{\partial s_k^J}) \frac{dS_k^J}{dq_k^J} \frac{\partial q_k^J}{\partial \tau_i^J} = 0$$

I again use (4.6.9)-(4.6.10) to simplify the above partial derivatives as

$$-D_i^J \frac{\partial p_i^J}{\partial \tau_i^J} + S_i^J (\frac{\partial p_i^J}{\partial \tau_i^J} - 1) + S_i^J + \tau_i^J M_{i\ \tau}^J (\frac{\partial p_i^J}{\partial \tau_i^J} - 1) - D_j^J \frac{\partial p_j^J}{\partial \tau_i^J} - D_k^J \frac{\partial p_k^J}{\partial \tau_i^J}$$
$$+S_k^J \frac{\partial p_k^J}{\partial \tau_i^J} + \tau_k^J M_{k\ \tau}^J \frac{\partial p_k^J}{\partial \tau_i^J} - (\frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J} + \frac{\partial E_k}{\partial s_i^J}) M_{i\ \tau}^J (\frac{\partial p_i^J}{\partial \tau_i^J} - 1) - (\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J} + \frac{\partial E_k}{\partial s_k^J}) M_{k\ \tau}^J \frac{\partial p_k^J}{\partial \tau_i^J} =$$

I use excess demand function to further simplify the above equation as

$$-M_i^J \frac{\partial p_i^J}{\partial \tau_i^J} + \tau_i^J M_{i\ \tau}^J (\frac{\partial p_i^J}{\partial \tau_i^J} - 1) - M_j^J \frac{\partial p_j^J}{\partial \tau_i^J} - M_k^J \frac{\partial p_k^J}{\partial \tau_i^J} + \tau_k^J M_{k\ \tau}^J \frac{\partial p_k^J}{\partial \tau_i^J}$$
$$-(\frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J} + \frac{\partial E_k}{\partial s_i^J}) M_{i\ \tau}^J (\frac{\partial p_i^J}{\partial \tau_i^J} - 1) - (\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J} + \frac{\partial E_k}{\partial s_k^J}) M_{k\ \tau}^J \frac{\partial p_k^J}{\partial \tau_i^J} = 0$$

By using the market clearing condition (4.2.6) and $\frac{\partial p_i^J}{\partial \tau_i^J} = \frac{\partial p_j^J}{\partial \tau_i^J} = \frac{\partial p_k^J}{\partial \tau_i^J}$, one obtain

$$\tau_i^J M_{i\ \tau}^J (\frac{\partial p_i^J}{\partial \tau_i^J} - 1) = -\tau_k^J M_{k\ \tau}^J \frac{\partial p_k^J}{\partial \tau_i^J} + (\frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J} + \frac{\partial E_k}{\partial s_i^J}) M_{i\ \tau}^J (\frac{\partial p_i^J}{\partial \tau_i^J} - 1) + (\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J} + \frac{\partial E_k}{\partial s_k^J}) M_{k\ \tau}^J \frac{\partial p}{\partial \tau}$$

I then substitute $\partial p_i^J / \partial \tau_i^J = \partial p_k^J / \partial \tau_i^J = -M_{i\ \tau}^J / \sum_{z=ij,k} M_{z\ p}^J$ to arrive

$$\tau_i^J = \frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J} + \frac{\partial E_k}{\partial s_i^J} - (\tau_k^J - (\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J} + \frac{\partial E_k}{\partial s_k^J})) \frac{M_{k\ \tau}^J}{\sum_{z=i,j,k} M_{z\ p}^J + M_{i\ \tau}^J} \quad (4.6.11)$$

Then τ_k^J can be derived analogously as

$$\tau_k^J = \frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J} + \frac{\partial E_k}{\partial s_k^J} - (\tau_i^J - (\frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J} + \frac{\partial E_k}{\partial s_i^J})) \frac{M_{i\ \tau}^J}{\sum_{z=i,j,k} M_{z\ p}^J + M_{k\ \tau}^J} \quad (4.6.12)$$

The optimal production taxes are the intersection of the above two first order conditions (4.6.11) and (4.6.12)

$$\begin{aligned}\tau_i^J(g) &= \frac{\partial E_i}{\partial s_i^J}+\frac{\partial E_j}{\partial s_i^J}+\frac{\partial E_k}{\partial s_i^J}\\ \tau_k^J(g) &= \frac{\partial E_i}{\partial s_k^J}+\frac{\partial E_j}{\partial s_k^J}+\frac{\partial E_k}{\partial s_k^J}\end{aligned}$$

B3: Derivations under *the Pair* (4.3.4) and (4.3.5)

For Equation (4.3.4):

Taking derivatives of the joint welfare $(\omega_i+\omega_j)$ with respect to τ_i^J yields

$$-D_i^J\frac{\partial p_i^J}{\partial \tau_i^J}+S_i^J\frac{\partial q_i^J}{\partial \tau_i^J}+S_i^J+\tau_i^J\frac{dS_i^J}{dq_i^J}\frac{\partial q_i^J}{\partial \tau_i^J}-D_j^J\frac{\partial p_j^J}{\partial \tau_i^J}-(\frac{\partial E_i}{\partial s_i^J}+\frac{\partial E_j}{\partial s_i^J})\frac{dS_i^J}{dq_i^J}\frac{\partial q_i^J}{\partial \tau_i^J}-(\frac{\partial E_i}{\partial s_k^J}+\frac{\partial E_j}{\partial s_k^J})\frac{dS_k^J}{dq_k^J}\frac{\partial q_k^J}{\partial \tau_i^J}=0$$

One can use excess demand function and (4.6.9)-(4.6.10) to simplify the above partial derivatives as

$$-M_i^J\frac{\partial p_i^J}{\partial \tau_i^J}+\tau_i^J M_{i\ \tau}^J(\frac{\partial p_i^J}{\partial \tau_i^J}-1)-M_j^J\frac{\partial p_j^J}{\partial \tau_i^J}-(\frac{\partial E_i}{\partial s_i^J}+\frac{\partial E_j}{\partial s_i^J})M_{i\ \tau}^J(\frac{\partial p_i^J}{\partial \tau_i^J}-1)-(\frac{\partial E_i}{\partial s_k^J}+\frac{\partial E_j}{\partial s_k^J})M_{k\ \tau}^J\frac{\partial p_k^J}{\partial \tau_i^J}=0$$

By using the market clearing condition (4.2.6) and $\frac{\partial p_i^J}{\partial \tau_i^J}=\frac{\partial p_j^J}{\partial \tau_i^J}$, one can obtain

$$\tau_i^J M_{i\ \tau}^J(\frac{\partial p_i^J}{\partial \tau_i^J}-1)=-M_k^J\frac{\partial p_i^J}{\partial \tau_i^J}+(\frac{\partial E_i}{\partial s_i^J}+\frac{\partial E_j}{\partial s_i^J})M_{i\ \tau}^J(\frac{\partial p_i^J}{\partial \tau_i^J}-1)+(\frac{\partial E_i}{\partial s_k^J}+\frac{\partial E_j}{\partial s_k^J})M_{k\ \tau}^J\frac{\partial p_k^J}{\partial \tau_i^J}$$

I then substitute $\partial p_i^J/\partial \tau_i^J=\partial p_k^J/\partial \tau_i^J=-M_{i\ \tau}^J/\sum_{z=i,j,k}M_{z\ p}^J$ to arrive

$$\begin{aligned}\tau_i^J(p) &= \frac{-M_k^J}{\sum_{z=i,j,k}M_{z\ p}^J+M_{i\ \tau}^J}+\frac{\partial E_i}{\partial s_i^J}+\frac{\partial E_j}{\partial s_i^J}+(\frac{\partial E_i}{\partial s_k^J}+\frac{\partial E_j}{\partial s_k^J})\frac{M_{k\ \tau}^J}{\sum_{z=i,j,j}M_{z\ p}^J+M_{i\ \tau}^J}\\ \tau_i^J(p) &= \frac{\partial E_i}{\partial s_i^J}+\frac{\partial E_j}{\partial s_i^J}+(\frac{\partial E_i}{\partial s_k^J}+\frac{\partial E_j}{\partial s_k^J})\frac{M_{k\ \tau}^J}{\sum_{z=i,j,j}M_{z\ p}^J+M_{i\ \tau}^J}-\epsilon_k^J\frac{M_{k\ p}^J}{\sum_{z=i,j,k}M_{z\ p}^J+M_{i\ \tau}^J}\end{aligned}$$

where $\epsilon_k^J=M_k^J/M_{k\ p}^J>0$ is inversely related to the elasticity of country k's export supply.

For Equation (4.3.5):

Taking derivatives of the joint welfare $(\omega_i + \omega_j)$ with respect to τ_i^K yields

$$-D_i^K \frac{\partial p_i^K}{\partial \tau_i^K} + S_i^K \frac{\partial q_i^K}{\partial \tau_i^K} + S_i^K + \tau_i^K \frac{dS_i^K}{dq_i^K}\frac{\partial q_i^K}{\partial \tau_i^K} - D_j^K \frac{\partial p_j^K}{\partial \tau_i^K} + S_j^K \frac{\partial q_j^K}{\partial \tau_i^K} + \tau_j^K \frac{dS_j^K}{dq_j^K}\frac{\partial q_j^K}{\partial \tau_i^K}$$
$$-(\frac{\partial E_i}{\partial s_i^K} + \frac{\partial E_j}{\partial s_i^K})\frac{dS_i^K}{dq_i^K}\frac{\partial q_i^K}{\partial \tau_i^K} - (\frac{\partial E_i}{\partial s_j^K} + \frac{\partial E_j}{\partial s_j^K})\frac{dS_j^K}{dq_j^K}\frac{\partial q_j^K}{\partial \tau_i^K} = 0$$

I again use (4.6.9)-(4.6.10) to simplify the above partial derivatives as

$$-D_i^K \frac{\partial p_i^K}{\partial \tau_i^K} + S_i^K \frac{\partial p_i^K}{\partial \tau_i^K} + \tau_i^K M_{i\ \tau}^K(\frac{\partial p_i^K}{\partial \tau_i^K} - 1) - D_j^K \frac{\partial p_j^K}{\partial \tau_i^K} + S_j^K \frac{\partial p_j^K}{\partial \tau_i^K} + \tau_j^K M_{j\ \tau}^K \frac{\partial p_j^K}{\partial \tau_i^K}$$
$$-(\frac{\partial E_i}{\partial s_i^K} + \frac{\partial E_j}{\partial s_i^K})M_{i\ \tau}^K(\frac{\partial p_i^K}{\partial \tau_i^K} - 1) - (\frac{\partial E_i}{\partial s_j^K} + \frac{\partial E_j}{\partial s_j^K})M_{j\ \tau}^K\frac{\partial p_j^K}{\partial \tau_i^K} = 0$$

I further use excess demand function to arrive

$$-M_i^K \frac{\partial p_i^K}{\partial \tau_i^K} + \tau_i^K M_{i\ \tau}^K(\frac{\partial p_i^K}{\partial \tau_i^K} - 1) - M_j^K \frac{\partial p_j^K}{\partial \tau_i^K} + \tau_j^K M_{j\ \tau}^K \frac{\partial p_j^K}{\partial \tau_i^K}$$
$$-(\frac{\partial E_i}{\partial s_i^K} + \frac{\partial E_j}{\partial s_i^K})M_{i\ \tau}^K(\frac{\partial p_i^K}{\partial \tau_i^K} - 1) - (\frac{\partial E_i}{\partial s_j^K} + \frac{\partial E_j}{\partial s_j^K})M_{j\ \tau}^K\frac{\partial p_j^K}{\partial \tau_i^K} = 0$$

which can be written as

$$\begin{aligned}\tau_i^K M_{i\ \tau}^K(\frac{\partial p_i^K}{\partial \tau_i^K} - 1) \quad = \quad & M_i^K \frac{\partial p_i^K}{\partial \tau_i^K} + M_j^K \frac{\partial p_j^K}{\partial \tau_i^K} - \tau_j^K M_{j\ \tau}^K \frac{\partial p_j^K}{\partial \tau_i^K} + (\frac{\partial E_i}{\partial s_i^K} + \frac{\partial E_j}{\partial s_i^K})M_{i\ \tau}^K(\frac{\partial p_i^K}{\partial \tau_i^K} - 1) \\ & +(\frac{\partial E_i}{\partial s_j^K} + \frac{\partial E_j}{\partial s_j^K})M_{j\ \tau}^K\frac{\partial p_j^K}{\partial \tau_i^K}\end{aligned}$$

One can substitute $\partial p_i^K/\partial \tau_i^K = \partial p_j^K/\partial \tau_i^K = -M_{i\ \tau}^K / \sum_{z=i,j,k} M_{z\ p}^K$ to arrive

$$\begin{aligned}\tau_i^K \quad = \quad & \epsilon_i^K \frac{M_{i\ p}^K}{\sum_{z=i,j,k} M_{z\ p}^K + M_{i\ \tau}^K} + \epsilon_j^K \frac{M_{j\ p}^K}{\sum_{z=i,j,k} M_{z\ p}^K + M_{i\ \tau}^K} + \frac{\partial E_i}{\partial s_i^K} + \frac{\partial E_j}{\partial s_i^K} \\ & -(\tau_j^K - (\frac{\partial E_i}{\partial s_j^K} + \frac{\partial E_j}{\partial s_j^K}))\frac{M_{j\ \tau}^K}{\sum_{z=i,j,k} M_{z\ p}^K + M_{i\ \tau}^K}\end{aligned}$$

Applying same method to solve τ_j^K yields

$$\begin{aligned}\tau_j^K \quad = \quad & \epsilon_i^K \frac{M_{i\ p}^K}{\sum_{z=i,j,k} M_{z\ p}^K + M_{j\ \tau}^K} + \epsilon_j^K \frac{M_{j\ p}^K}{\sum_{z=i,j,k} M_{z\ p}^K + M_{j\ \tau}^K} + \frac{\partial E_i}{\partial s_j^K} + \frac{\partial E_j}{\partial s_j^K} \\ & -(\tau_i^K - (\frac{\partial E_i}{\partial s_i^K} + \frac{\partial E_j}{\partial s_i^K}))\frac{M_{i\ \tau}^K}{\sum_{z=i,j,k} M_{z\ p}^K + M_{j\ \tau}^K}\end{aligned}$$

Then τ_i^K and τ_j^K can be solved from the above two first order conditions

$$\tau_i^K = \frac{\partial E_i}{\partial s_i^K} + \frac{\partial E_j}{\partial s_i^K} + \epsilon_i^K \frac{M_{i\ p}^K}{\sum_{z=i,j,k} M_{z\ p}^K + M_{i\ \tau}^K + M_{j\ \tau}^K} + \epsilon_j^K \frac{M_{j\ p}^K}{\sum_{z=i,j,k} M_{z\ p}^K + M_{i\ \tau}^K + m_{j\ \tau}^K} \tag{4.6.13}$$

$$\tau_j^K = \frac{\partial E_i}{\partial s_j^K} + \frac{\partial E_j}{\partial s_j^K} + \epsilon_i^K \frac{M_{i\ p}^K}{\sum_{z=i,j,k} M_{z\ p}^K + M_{i\ \tau}^K + M_{j\ \tau}^K} + \epsilon_j^K \frac{M_{j\ p}^K}{\sum_{z=i,j,k} M_{z\ p}^K + M_{i\ \tau}^K + M_{j\ \tau}^K} \tag{4.6.14}$$

C

Section C of the Appendix provides derivations about the optimal policies under *the Pair* when trade linkage is introduced.

C1: Derivations for Pair members with Linkage Regime (4.4.1)-(4.4.4)

Taking derivatives of the welfare function $(\omega_i + \omega_j)$ with respect to t_{jk} yields

$$\begin{aligned}
&-D_j^J \frac{\partial p_j^J}{\partial t_{jk}} - M_k^J - t_{jk} \frac{\partial M_k^J}{\partial p_k^J} \frac{\partial p_k^J}{\partial t_{jk}} - D_i^J \frac{\partial p_i^J}{\partial t_{jk}} + S_i^J \frac{\partial q_i^J}{\partial p_i^J} \frac{\partial p_i^J}{\partial t_{jk}} + \tau_i^J \frac{dS_i^J}{dq_i^J} \frac{\partial q_i^J}{\partial p_i^J} \frac{\partial p_i^J}{\partial t_{jk}} \\
&-(\frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J}) \frac{dS_i^J}{dq_i^J} \frac{\partial q_i^J}{\partial p_i^J} \frac{\partial p_i^J}{\partial t_{jk}} - (\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J}) \frac{dS_k^J}{dq_k^J} \frac{\partial q_k^J}{\partial p_k^J} \frac{\partial p_k^J}{\partial t_{jk}} = 0
\end{aligned}$$

One can use excess demand function and (4.6.9)-(4.6.10) to simplify the above partial derivatives as

$$\begin{aligned}
&-M_j^J \frac{\partial p_j^J}{\partial t_{jk}} - M_k^J - t_{jk} M_{k\ p}^J \frac{\partial p_k^J}{\partial t_{jk}} - M_i^J \frac{\partial p_i^J}{\partial t_{jk}} + \tau_i^J M_{i\ \tau}^J \frac{\partial p_i^J}{\partial t_{jk}} - (\frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J}) M_{i\ \tau}^J \frac{\partial p_i^J}{\partial t_{jk}} \\
&-(\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J}) M_{k\ \tau}^J \frac{\partial p_k^J}{\partial t_{jk}} = 0
\end{aligned}$$

One can use market clearing condition (4.2.6) and $\frac{\partial p_i^J}{\partial t_{jk}} = \frac{\partial p_j^J}{\partial t_{jk}}$ to further simplify as

$$\begin{aligned}
t_{jk} M_{k\ p}^J \frac{\partial p_k^J}{\partial t_{jk}} &= M_k^J (\frac{\partial p_i^J}{\partial t_{jk}} - 1) + \tau_i^J M_{i\ \tau}^J \frac{\partial p_i^J}{\partial t_{jk}} - (\frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J}) M_{i\ \tau}^J \frac{\partial p_i^J}{\partial t_{jk}} \\
&\quad -(\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J}) M_{k\ \tau}^J \frac{\partial p_k^J}{\partial t_{jk}}
\end{aligned}$$

One can substitute $\partial p_j^J/\partial t_{jk} = M_{k\ p}^J/\sum_z M_{z\ p}^J$ and $\partial p_k^J/\partial t_{jk} = -(M_{i\ p}^J + M_{j\ p}^J)/\sum_z M_{z\ p}^J$ to arrive

$$t_{ik} = \epsilon_k^J - (\tau_i^J - (\frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J}))\frac{M_{i\ \tau}^J}{M_{i\ p}^J + M_{j\ p}^J} - (\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J})\frac{M_{k\ \tau}^J}{M_{k\ p}^J}$$

I then look at the production tax of good J. Taking derivatives of $(\omega_i + \omega_j)$ with respect to τ_i^J yields

$$\begin{aligned}
&-D_j^J\frac{\partial p_j^J}{\partial \tau_i^J} - t_{jk}\frac{\partial M_k^J}{\partial p_k^J}\frac{\partial p_k^J}{\partial \tau_i^J} - D_i^J\frac{\partial p_i^J}{\partial \tau_i^I} + S_i^J\frac{\partial q_i^J}{\partial \tau_i^J} + S_i^J + \tau_i^J\frac{dS_i^J}{dq_i^J}\frac{\partial q_i^J}{\partial \tau_i^J} \\
&-(\frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J})\frac{dS_i^J}{dq_i^J}\frac{\partial q_i^J}{\partial \tau_i^J} - (\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J})\frac{dS_k^J}{dq_k^J}\frac{\partial q_k^J}{\partial \tau_i^J} = 0
\end{aligned}$$

One can use excess demand function and (4.6.9)-(4.6.10) to simplify the above partial derivatives as

$$\begin{aligned}
&-M_j^J\frac{\partial p_j^J}{\partial \tau_i^J} - t_{jk}M_{k\ p}^J\frac{\partial p_k^J}{\partial \tau_i^J} - M_i^J\frac{\partial p_i^J}{\partial \tau_i^J} + \tau_i^J M_{i\ \tau}^J(\frac{\partial p_i^J}{\partial \tau_i^J} - 1) \\
&-(\frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J})M_{i\ \tau}^J(\frac{\partial p_i^J}{\partial \tau_i^J} - 1) - (\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J})M_{k\ \tau}^J\frac{\partial p_k^J}{\partial \tau_i^J} = 0
\end{aligned}$$

I then use market clearing condition (4.2.6) and $\frac{\partial p_j^J}{\partial \tau_i^J} = \frac{\partial p_i^J}{\partial \tau_i^J}$ to further simplify the above equation as

$$\begin{aligned}
\tau_i^J M_{i\ \tau}^J(\frac{\partial p_i^J}{\partial \tau_i^J} - 1) \quad = \quad & -M_k^J\frac{\partial p_i^J}{\partial \tau_i^J} + t_{jk}M_{k\ p}^J\frac{\partial p_k^J}{\partial \tau_i^J} + (\frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J})M_{i\ \tau}^J(\frac{\partial p_i^J}{\partial \tau_i^J} - 1) \\
& +(\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J})M_{k\ \tau}^J\frac{\partial p_k^J}{\partial \tau_i^J}
\end{aligned}$$

One can substitute $\partial p_i^J/\partial \tau_i^J = \partial p_k^J/\partial \tau_i^J = -M_{i\ \tau}^J/\sum_z M_{z\ p}^J$ to arrive

$$\begin{aligned}
\tau_i^J &= -\frac{M_k^J}{\sum_z M_{z\ p}^J + M_{i\ \tau}^J} + t_{jk}\frac{M_{k\ p}^J}{\sum_z M_{z\ p}^J + M_{i\ \tau}^J} + \frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J} + (\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J})\frac{M_{k\ \tau}^J}{\sum_z M_{z\ p}^J + M_{i\ \tau}^J} \\
\tau_i^J &= (t_{jk} - \epsilon_k^J)\frac{M_{k\ p}^J}{\sum_z M_{z\ p}^J + M_{i\ \tau}^J} + \frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J} + (\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J})\frac{M_{k\ \tau}^J}{\sum_z M_{z\ p}^J + M_{i\ \tau}^J}
\end{aligned}$$

The optimal policies are the intersection of the above two first order conditions and solved as

$$t_{jk} = \epsilon_k^J - \frac{M_{k\ \tau}^J}{M_{k\ p}^J}\left(\frac{\partial E_i}{\partial s_k^J} + \frac{\partial E_j}{\partial s_k^J}\right) \tag{4.6.15}$$

$$\tau_i^J = \frac{\partial E_i}{\partial s_i^J} + \frac{\partial E_j}{\partial s_i^J} \tag{4.6.16}$$

Applying same method yields

$$t_{ik} = \epsilon_k^I - \frac{M_{k\ \tau}^I}{M_{k\ p}^I}\left(\frac{\partial E_i}{\partial s_k^I} + \frac{\partial E_j}{\partial s_k^I}\right) \tag{4.6.17}$$

$$\tau_j^I = \frac{\partial E_i}{\partial s_j^I} + \frac{\partial E_j}{\partial s_j^I} \tag{4.6.18}$$

C2: Derivations for the Free Rider with Linkage Regime (4.4.5)-(4.4.7)

Taking derivatives of the welfare function ω_k with respect to t_{ki} yields

$$-D_k^K \frac{\partial p_k^K}{\partial t_{ki}} - M_i^K - t_{ki}\frac{\partial M_i^K}{\partial p_i^K}\frac{\partial p_i^K}{\partial t_{ki}} - t_{kj}\frac{\partial M_j^K}{\partial p_j^K}\frac{\partial p_j^K}{\partial t_{ki}} - \left(\frac{\partial E_i}{\partial s_i^K}\frac{dS_i^K}{dq_i^K}\frac{\partial q_i^K}{\partial p_i^K}\frac{\partial p_i^K}{\partial t_{ki}} + \frac{\partial E_i}{\partial s_j^K}\frac{dS_j^K}{dq_j^K}\frac{\partial q_j^K}{\partial p_j^K}\frac{\partial p_j^K}{\partial t_{ki}}\right) = 0$$

One can use excess demand function and (4.6.9)-(4.6.10) to simplify the above partial derivatives as

$$-M_k^K \frac{\partial p_k^K}{\partial t_{ki}} - M_i^K - t_{ki}M_{i\ p}^K \frac{\partial p_i^K}{\partial t_{ki}} - t_{kj}M_{j\ p}^K \frac{\partial p_j^K}{\partial t_{ki}} - \frac{\partial E_i}{\partial s_i^K}M_{i\ \tau}^K \frac{\partial p_i^K}{\partial t_{ki}} - \frac{\partial E_i}{\partial s_j^K}M_{j\ \tau}^K \frac{\partial p_j^K}{\partial t_{ki}} = 0$$

$$t_{ki}M_{i\ p}^K \frac{\partial p_i^K}{\partial t_{ki}} = -M_k^K \frac{\partial p_k^K}{\partial t_{ki}} - M_i^K - t_{kj}M_{j\ p}^K \frac{\partial p_j^K}{\partial t_{ki}} - \frac{\partial E_i}{\partial s_i^K}M_{i\ \tau}^K \frac{\partial p_i^K}{\partial t_{ki}} - \frac{\partial E_i}{\partial s_j^K}M_{j\ \tau}^K \frac{\partial p_j^K}{\partial t_{ki}}$$

By substituting $\partial p_k^K/\partial t_{ki} = \partial p_j^K/\partial t_{ki} = M_{i\ p}^K/\sum_z M_{z\ p}^K$ and $\partial p_i^K/\partial t_{ki} = -(M_{j\ p}^K + M_{k\ p}^K)/\sum_z M_{z\ p}^K$, one can further simplify to obtain

$$
\begin{aligned}
t_{ki} &= \frac{M_k^K}{M_{j\ p}^K + M_{k\ p}^K} + \frac{M_i^K \sum_z M_{z\ p}^K}{M_{i\ p}^K (M_{j\ p}^K + M_{k\ p}^K)} + t_{kj} \frac{M_{j\ p}^K}{M_{j\ p}^K + M_{k\ p}^K} - \frac{\partial E_i}{\partial s_i^K} \frac{M_{i\ \tau}^K}{M_{i\ p}^K} \\
&\quad + \frac{\partial E_i}{\partial s_j^K} \frac{M_{j\ \tau}^K}{M_{j\ p}^K + M_{k\ p}^K} \\
t_{ki} &= \frac{M_k^K}{M_{j\ p}^K + M_{k\ p}^K} + \epsilon_i^K (1 + \frac{M_{i\ p}^K}{M_{j\ p}^K + M_{k\ p}^K}) + t_{kj} \frac{M_{j\ p}^K}{M_{j\ p}^K + M_{k\ p}^K} - \frac{\partial E_i}{\partial s_i^K} \frac{M_{i\ \tau}^K}{M_{i\ p}^K} \\
&\quad + \frac{\partial E_i}{\partial s_j^K} \frac{M_{j\ \tau}^K}{M_{j\ p}^K + M_{k\ p}^K} \\
t_{ki} &= \epsilon_i^K - \frac{M_j^K}{M_{j\ p}^K + M_{k\ p}^K} + t_{kj} \frac{M_{j\ p}^K}{M_{j\ p}^K + M_{k\ p}^K} - \frac{\partial E_i}{\partial s_i^K} \frac{M_{i\ \tau}^K}{M_{i\ p}^K} + \frac{\partial E_i}{\partial s_j^K} \frac{M_{j\ \tau}^K}{M_{j\ p}^K + M_{k\ p}^K} \\
t_{ki} &= \epsilon_i^K + (t_{kj} - \epsilon_j^K) \frac{M_{j\ p}^K}{M_{j\ p}^K + M_{k\ p}^K} - \frac{\partial E_i}{\partial s_i^K} \frac{M_{i\ \tau}^K}{M_{i\ p}^K} + \frac{\partial E_i}{\partial s_j^K} \frac{M_{j\ \tau}^K}{M_{j\ p}^K + M_{k\ p}^K}
\end{aligned}
$$

Applying same method to obtain

$$
t_{kj} = \epsilon_j^K + \frac{M_{i\ p}^K}{M_{i\ p}^K + M_{k\ p}^K} (t_{ki} - \epsilon_i^K) - \frac{M_{j\ \tau}^K}{M_{j\ p}^K} \frac{\partial E_i}{\partial s_j^K} + \frac{M_{i\ \tau}^K}{M_{i\ p}^K + M_{k\ p}^K} \frac{\partial E_i}{\partial s_i^K}
$$

Chapter 5

Discussion

The thesis explores the effects of trade and trade policy on climate change cooperation within a novel framework. Some of the model features are kept relatively simple to emphasize the role that trade plays in IEA formation. The model employed in this thesis has great potential to be extended in many different directions. Such extensions, which will be discussed in this chapter, can enhance its realism and at the same time, provide more policy insights to facilitate climate change cooperation.

5.1 Asymmetry

This theoretical study assumes that countries are *ex-ante* identical in every aspect. The assumption of symmetry determines a same strategy space and an equally sharing rule of payoff within a coalition for each country in IEA formation game. As a result, the game is simplified by a large extent, which ensures the tractability of the model. However, countries are heterogeneous in their contributions to climate change, in their vulnerability to climate change, and in their unique features such as developing stages, culture, lifestyles, etc. Such heterogeneity brings new challenges for climate change cooperation and should be addressed in future studies.

McGinty (2007) relaxed the symmetry assumption by letting the marginal benefit and marginal cost vary across nations. With a simulation method, he reached a promising conclusion that a much higher level of abatement can be sustained by an IEA for the asymmetric case compared to symmetric case. Fuentes-Albero and Rubio (2010) found that when countries differ in environmental damage and an income transfer is introduced, a larger coalition is possible. By allowing asymmetries in benefits and vulnerability to climate change simultaneously, Pavlova and De Zeeuw (2013) found that even without transfer, a large coalition is achievable if this coalition includes countries with high benefit but low cost. However, those countries would contribute less in coalition, resulting in a lower emission reduction than the case without those countries. With transfers, a large stable coalition performs better in emission reduction. As is evident, asymmetry matters in climate change cooperation. Thus, it is critical to analyse the formation outcomes when countries are asymmetric regarding climate change.[1]

The relaxation of symmetry might also provide new insights for trade linkage in IEAs. Trade linkage model predicts that welfare gains from trade linkage is at the cost of "non-climate" welfare. If asymmetry is allowed, countries with a lower preference over better environment (which has a relatively low β) might not favour trade linkage since they lose from trade side. For example, a member of *the Pair* with a small β might be a loser from trade linkage since the welfare gain from a better environment is offset by the loss from "non-climate" welfare. Therefore, these types of countries will be also against trade linkage. Future studies that relax the assumption of symmetry are needed to examine the welfare implication for countries with different βs from climate change cooperation as well as the introduction of trade linkage.

5.2 Large Import-competing Economy

This thesis employs a "three-country, three-good" trade model where each country imports one good, which it does not produce, from, and exports two goods to, the other two trading partners. Thus, two exporters of one good compete in the third country. As a large economy, each of them has incentives to impose a higher

[1]However, one should keep in mind that once symmetry is relaxed, the equally sharing rule of payoff within a coalition for each country can't hold any more. Thus, the rule of transfer within a coalition should be specified, which brings a new topic on the effects of different transfer rules on climate change cooperation.

environmental tax domestically in order to enjoy a monopolistic surplus from the *terms-of-trade* effect. When these two exporting countries form an IEA, their market power is enhanced, and they will enjoy an even higher monopolistic surplus by setting a tax higher than that under non-cooperation. In this sense, partial cooperation on climate change is preferred due to the gains in trade.

However, as showed in Markusen (1975b), if a country is an importer of a good and it produces this good at the same time, this country prefers a lower production tax for *terms-of-trade*. The study of Ludema and Wooton (1994) also confirmed the existence of such a similar mechanism. Thus, those importing countries might be reluctant to join an IEA due to the fact that an IEA usually requires a higher production tax since it internalizes the externality to a larger degree. In the import-competing context, some questions deserve further explorations: How the environmental policy works as a second-best policy for trade purpose for those importing countries? How will the optimal policies be different under different coalition structures? What is the outcome of climate change cooperation with the presence of trade?

5.3 Strategic Incentives

Governments have different motives to protect local firms. This thesis focuses on the *terms-of-trade* motive for large economies in a competitive market. This motive arises when large countries can affect world prices by manipulating its trade policy and further extracts gains from such manipulation in standard competitive trade models. When trade policies are unavailable due to a trade agreement, government might use environmental policy to achieve the purpose of protection. Apart from the *terms-of-trade* motive, governments might use environmental policy to give domestic firms a strategic advantage when firms compete in imperfectly competitive international market. Such strategic incentive of a government inevitably influences its decisions on climate change cooperation.

Most of the studies on environmental policy in an imperfectly competitive market are in the spirit of Brander and Spencer (1983), Brander and Spencer (1985) and

Eaton and Grossman (1986) in trade literature. Barrett (1994b) is one of the early studies that applied this framework to environmental policy. In his model, there are two governments and their respective industries, which both sell goods in the third market. It is a two-stage game where in the first stage governments set the environmental standards for their own firms, while in the second stage firms compete by choosing either prices or quantities, taking the environmental standards as given. Barrett (1994b) found that if firms compete by choosing quantities, a government has incentives to set a weak environmental standard, by which the domestic firm can commit to a higher output and earn a higher profit in turn. However, both governments have same strategic incentives and it ends up with weaker standards in both country as well as lower net benefits. In a similar framework, Conrad (1993) considered the Nash tax and cooperative tax set by two governments when firms compete imperfectly in a third market. He found that in Nash equilibrium, the environmental tax is set lower than the Pigouvian tax, implying that domestic industries can capture a greater market share. The other purpose of a lower tax is to indirectly reduce the output of foreign industries, which has a negative externality on Home (similar to the *leakage effect* in this thesis). When governments cooperate, those strategic incentives are eliminated, and so cooperation generates a higher welfare for both countries. Other related literature is Kennedy (1994) and Ulph (1996).

Instead of focusing on the competition between firms in a third market, Markusen et al. (1995) endogenized the plant location in a two-region model where an imperfectly competitive firm generates local pollution. The firm is facing the option to produce in both regions, only in one region or not produce at all. There exist increasing returns to scale and shipping costs. Each government sets environmental standards strategically to maximize its welfare. Markusen et al. (1995) showed that if the utility loss caused by pollution is high, the two governments would set the environmental standards very high to drive the polluting plant away. In contrast, if the disutility is not high, the two governments would undercut each other's environmental taxes(standards). In a similar model, Markusen et al. (1993) also endogenized market structure together with plant location by including two firms in a two-region model. The two firms have same options as in Markusen et al. (1995). The endogenous choices of the firms about plant location endogenously determined the market structure.

In a strategic game framework, some very interesting questions arise: when industries in each country internationally compete in an imperfectly competitive market, what is the incentive for each government to participate in climate change cooperation? What is the mechanism in such a market structure? I am not aware of such studies on IEA formation and it is left for future work.

5.4 Political Aspect of IEA Formation

When governments negotiate climate change cooperation in the international arena, their actions might be influenced by domestic pressures from different interest groups. On one hand, the environmentalists might form green lobbies which aim to exert pressure on the government and demand stringent actions on climate change mitigation. On the other hand, some industry lobby groups have incentives to lobby the government for a low level of environmental regulation when they compete internationally.[2] Rauscher (1997) argued that industry lobbing is one of the explanations for the lax environmental regulation. Such observations suggest that the concern with special-interest group by a government affects the outcomes of IEA formation.

This thesis assumes a benevolent government which is immune to political pressures and only aims to maximize the social welfare when taking actions on climate change cooperation. However, a small but growing body of literature on environmental issues has abandoned such welfare-maximization assumption and adopted political economy model, where governments care about social welfare as well as campaign contributions from special-interest groups.

One of the mostly influential theoretical political economy models is Grossman and Helpman (1994) on political lobbying for trade policy. In this model, the formation of lobby is assumed to be exogenous and lobbies maximize their welfare by choosing a contribution schedule to the government. The government then maximizes a weighted sum of social welfare and the contributions from special-interest

[2] Of course, lobbying trade policy is more efficient for those producers. However, if trade policy is binding due to an existing trade agreement, they have incentives to lobby the second-best policy.

groups. Fredriksson (1997) is the first study to apply this model to environmental issues. He considered a small open economy with presence of local production externality where both environmental and industrial lobby groups aim to influence the determination of pollution taxes. Different from Fredriksson (1997) where production tax is the only policy instrument, Schleich (1999) added trade taxes to the policy set and he compared the environmental quality in a situation where both policies are endogenously determined with a situation where one policy is unavailable. Rather than focusing on small economy, Conconi (2003) focused on two large economics with a trans-boundary pollution and examined how green lobbies influence the determination of environmental and trade policies. Persson (2012), Fünfgelt and Schulze (2016) are two recent work on environmental issues in a political economy model.

A recent study of Marchiori et al. (2017) explicitly focused on the formation of IEAs in a political framework. However, the model employed in their work is based on the benefit and cost functions of emission abatement as Barrett (1994a). The inclusion of more details about economic structure in the model developed in this thesis provides more potential to analyse the lobby behaviors in IEA formation. An easy way to extend the current work (chapter 4) is to have a weighted aggregate welfare with a higher weight on a particular group, similar to Limão (2005), which can be considered as a reduced form of Grossman and Helpman (1994).[3] By having different weights on consumers/producers, the model employed in chapter 4 should be able to answer the following questions: what is the outcome of IEA formation when government cares more about producers/consumers? How are the optimal policies in a political economy model different from the results in this thesis? What role does trade play in a political economy model of IEA formation?

[3] In this way, the government's preference on the special-interest group is assumed to be exogenous. While in Grossman and Helpman (1994), the effect of lobby on policies depends on the contribution transferred to the government. The model employed in this thesis can be extended to a richer framework in Grossman and Helpman (1994)'s fashion.

5.5 Integrated Assessment Models

Climate change is one of the most complex systems that involves a wide variety fields of science, economics, and politics. Greenhouse gas emission is a stock externality. Hence, a full analysis of climate change should depict how economic activities generate greenhouse gas emissions, which gradually concentrate in the atmosphere; how the temperature increases due to such concentration; and how the temperature increase affects the human and natural systems, which in turn contributes to the determination of the economic and climate policies. For the sake of tractability, this thesis together with other theoretical models that aim to uncover the theory of climate change cooperation, are incapable of depicting the complex climate and economic system in detail.

Countries are different in every aspect, and such heterogeneity should be assessed in detail to depict a country's incentive on climate change cooperation more realistically. More importantly, when the interactions between trade and the environment are considered, how trade might change a country's incentives for cooperation on climate change crucially depends on the trade pattern of that country (as discussed above). Therefore, the analysis of trade effects on IEA formation should take the trade pattern of each country into consideration. In summary, the complexities of the climate and economic system require an integrated model that captures all the above factors in a single framework to improve the understanding of real-world climate change cooperation.

As the mainstream platform in climate change research, integrated assessment modelling (IAM) combines scientific and socio-economic aspects of climate change into a single framework to assess the impact of climate change in every aspect, to determine climate change policy or to evaluate the effectiveness of relevant policies. The modelling is integrated because it usually is coupled with different modules, e.g., climate modules, biogeochemistry modules, energy-use modules, economic modules. Each of the models relies on the knowledge from related disciplines and their underlying interactions connected to climate change. Based on the knowledge in climate change system and economic system, IAMs use empirical data to calibrate their models, produce numerical simulation results for various scenario designs or provide useful insights about the optimal climate policies.

The development of an integrated model that aims at analysing the role that trade plays in climate change cooperation can benefit from some of the existing integrated assessment models. Nordhaus and Yang (1996)'s Regional Integrated Climate-Economy model (RICE) is a perfect candidate.[4] The RICE model is based on the neoclassical growth theory but extends this Ramsey type model to an IAM by considering GHGs as a negative natural capital, which reduces the output of the economy via a damage function. Therefore, economies use part of the output to abate emissions, thereby reducing the consumption today but protecting the economy from harmful climate thus increasing the output in the future. Each region optimizes the welfare by endogenously determining its saving behaviour and abatement in a long term, perfectly foresight, dynamic framework.

With the RICE model, Nordhaus and Yang (1996) firstly analysed three national strategies of climate change mitigation of 10 different regions: pure market solution where there is no correction for climate change externality, the efficient cooperative solution, and Nash equilibria. They assessed the effectiveness of these three climate policies and also evaluated the welfare gain/loss of different countries/regions under the three policy regimes. This can be considered as the first step towards climate change cooperation study. However, they didn't analyse other possibilities of cooperation and didn't further predict which coalition is more likely to be observed based on game-theoretic framework. Later, a noteble work by Yang (2008) bridged the RICE model (or IAM modelling) and game-theoretic modelling approach in a comprehensive way. The main interest in Yang's research is whether the grand coalition is stable, or put differently, whether there is a nonempty core in the cooperative game. Considering the computation needs, Yang only compared the welfare of each country under the cooperative game and Nash equilibria and concluded that given the penalty rule, no region can gain by deviating from the grand.[5] Two similar works by Yang are Yang (2003) and Yang (2017).

[4] A global level version of RICE which enjoys more fame is DICE (Dynamic Integrated model of Climate and the Economy).

[5] Yang applied the traditional assumption in the cooperative game literature that if one agent or a group of agents deviate from the grand, the grand will collapse and the remaining players turn

Due to the powerfulness of the RICE model, other scholars also studied climate coalition by using modified IAM models of RICE.[6] Eyckmans and Tulkens (2006) constructed the CLIMNEG World Simulation (CWS) model based on RICE to simulate the global climate negotiation in a cooperative game theoretic framework. Unlike the RICE model, the CWS model assumed a linear utility function to allow transferability between countries/regions and abandoned international trade. It also adopted a different mechanism of feedback on abatement cost and climate damage on net output (from multiplicative to additive formulation). Eyckmans and Finus (2006) simulated IEA formations in different game framework within same CWS model framework, e.g., from single coalition to multiple coalitions, from open membership to exclusive membership. Carraro et al. (2006) paid particular attention to the role that transfers play in the formation of IEAs by using the CWS model. Bréchet et al. (2011) evaluated the two competing coalition stability concepts - the core in a cooperative game and the external & internal stability in a non-cooperative game - by numerical simulations using the CWS model. Another extension of RICE is the WITCH model (Bosetti et al. (2006), Bosetti et al. (2014)), which paid particular attentions to the energy sector with endogenous technology change.

The main shortcoming of the above IAMs that study climate change cooperation is that in most IAMs countries only interact with each other via climate change. As studied in this thesis, the economic gains and losses from trade matter and should be taken into consideration in climate change cooperation. International trade was originally included in the seminal paper of RICE in Nordhaus and Yang (1996). However, this paper didn't explicitly analyse the role that trade plays and the strategic interactions between trade and climate change cooperation. The updated version in Yang (2008) is a simplified version of RICE2007, which completely ignores international trade between countries. This is also true for Eyckmans and Tulkens (2006)'s CWS model.

The Model of International Climate Agreements (MICA), which was first intro-

into singletons.

[6] Lessmann et al. (2015) did a comprehensive comparative assessment about the climate change cooperation results obtained from these models.

duced by Lessmann et al. (2009), contributes to the literature by including international trade. They followed a similar economic framework to RICE but abandoned the assumption that countries produce identical goods. Instead in MICA, each country produces a distinct good that is imperfect substitute of each other and consumed by all countries (Armington assumption Armington (1969)). It is noteworthy that this paper assumed that there are nine identical players rather than empirically calibrated to real lworld. However, as discussed before, heterogeneity should be taken into consideration and more policy insights can be obtained if the model is calibrated to real world regions. In a recent work, Kornek et al. (2017) calibrated the MICA model into 11 different regions. However, international trade in this work is mainly on a macro-level. There is no public information about the calibration of the Armington model introduced in Lessmann et al. (2009) and the role that trade plays in climate change cooperation has not been explicitly analysed in any IAMs.

The Armington assumption provides an effective method to model international trade in computational works in the past four decades. However, its inconsistency with micro-level data and counterfactural implications has been criticized by Brown (1987) and Melitz and Redding (2015). More importantly, the Armington model might lead to unrealistically strong *terms-of-trade* effects (De Melo and Robinson, 1989). Recent advances in trade theory, especially the firm-heterogeneity trade model under monopolistic competition developed by Melitz (2003), brings an alternative to the commonly used Armington model. Balistreri and Rutherford (2013) explicitly compared the Armington structure, Krugman structure and Melitz structure in Computable General Equilibrium (CGE) models. They did find that the assumption of trade structure matters. Balistreri and Rutherford (2012) used a CGE model to study the efficacy of sub-global carbon policy under different trade structures. They found that with heterogeneous firms, the competitive effects and leakage effects are both larger. Even though Balistreri and Rutherford (2012) used a different coalition formation framework with the one employed in this thesis, the authors concluded that a grand coalition is not favoured since the larger the coalition is, the higher the advantages for the non-coalition members. Another similar study is Balistreri et al. (2018).[7]

[7]Many researchers (e.g., Rutherford and his various co-authors) have done a great deal of

Therefore, a calibrated IAM with an appropriate trade structure in the RICE framework can investigate how trade affects each country's incentives in climate change cooperation. Such a quantitative work will benefit from the theoretical analysis in this thesis and more importantly, it can provide a great detail about how trade patterns of each country affect its participation decision in climate change cooperation. All these results will provide valuable and practical insights for policy-makers.

5.6 Conclusion

This chapter discussed some of the assumptions in the model employed in this thesis and how those aspects in climate change cooperation can be captured if those assumptions were to be relaxed. Those discussions can be considered as starting points for future research.

computational works about climate change policies. The main model used in those works is the Computable General Equilibrium model, which is not exactly the same as the Integrated Assessment Models discussed in this section. Thus, I will not emphasize on those CGE model studies. Interested readers can refer to Bernstein et al. (1999), Böhringer and Rutherford (2002), Böhringer et al. (2014) in addition to the above mentioned references.

Chapter 6

Conclusion

Climate change has become one of the most challenging issues. The challenges to tackle climate change stem from its nature of a pure public good (bad) and the sovereignty of nations. On the other hand, the close interactions between international trade and the environment compound the challenge in climate change cooperation. Countries are connected not only via climate change but also via international trade. The gains and losses in trade are taken into consideration for each country when it is strategically choosing environmental policies. However, the role that trade plays in IEA formation has been relatively neglected in the literature. The aim of this thesis has been to study how IEAs are formed in a globalized economy and how trade and trade policy affect the formation of such an IEA.

Chapter 2 firstly conducted a comprehensive and in-depth literature review regarding the interactions between trade and the environment, the state-of-art in IEA formation, and trade linkage in IEAs. This review chapter set the context for the following chapters. The literature review implied that international trade does affect international cooperation on climate change, therefore, its effects should be considered in IEA formation studies. However, how trade might affect a country's incentives to participate in climate change cooperation really depends on the characteristics of this country.

A small economy has stronger incentives to free ride due to the *pollution haven effect* in the presence of trade compared to the case in autarky. For large economies, the use of environmental policy as a second-best instrument to manipulate gains from trade affect their participation incentives in IEAs. A large import-competing country tends to loosen domestic environmental regulation, so it is reluctant to join an IEA. By contrast, a large export-competing country prefers a higher environmental tax, which generates a monopolistic gain. By acceding to an IEA, its market power is enhanced, and an even higher *terms-of-trade* gain is obtained. This potential benefit partly offsets the free riding incentives, thus, will facilitate cooperation on climate change. In addition to the *terms-of-trade* effect, large economies also manipulate environmental policy for *leakage* effect. A large economy always prefers a lower environmental tax to indirectly reduce the emission in other emitting countries, irrespective of its trade pattern.

The other implication of Chapter 2 is that there is great potential to tackle climate change by using trade policy. Given the close interactions between trade and the environment, linking IEA formation to trade policy, which aims to induce wider participation in IEA, is a natural idea with great potential. This implication motives Chapter 4, which studies trade linkage in IEA formation.

Based on the literature review, Chapter 3 has developed a "three-country, three-good" general equilibrium model in an open economy and defined an endogenous IEA formation game accordingly. It is found that countries implement relatively lax policy under *Stand-alone* than that of *Grand Coalition*. The non-signatory of *the Pair* free rides on the emission reduction efforts contributed by signatories of *the Pair*. As the climate change problem becomes severe, the environmental policy is tightened no matter what coalition structure is in place. Environmental policy is used both for emission reduction and *terms-of-trade* gains in international trade under *Stand-alone* and *the Pair*.

By applying Nash equilibrium and strong Nash equilibrium coalition conditions, Chapter 3 has predicted that when climate change problem is not severe, welfare gain and emission reduction from *Grand Coalition* is small even though *Grand Coalition* is in equilibrium. As climate change problem becomes severe, welfare gain and emission reduction from *Grand Coalition* becomes large. However, the incentives for the free rider to deviate increases at the same time, and *Grand Coalition* can't be achieved any more.

Chapter 3 also has discussed how trade affects the formation outcomes of an IEA. A stringent environmental policy generates a monopolistic gain from international trade for an export-competing country when they form a partial coalition on climate change and their market power is enhanced. When climate change severity level is low, the use of environmental policy to exploit terms-of-trade from the free rider eliminates the free riding incentives of country k. In this sense, international trade facilitates climate change cooperation.

It is shown that trade affects climate change cooperation in Chapter 3. A natural idea is linking trade policy with IEA formation to induce wider participation. Chapter 4 then constructed a theoretical model to explore how trade policy can be used to induce wider cooperation on climate change, and the feasibility of such policy linkage in IEA formation.

It has firstly derived the optimal policy structures under different coalition structures in IEA formation. It is shown that production tax of a large exporter is not only used to internalize environmental externalities, but also to deal with *leakage* problem and to manipulate *terms-of-trade* gains. Thus, in addition to the environmental benefits of a partial coalition, cooperating countries also enjoy a larger market power by forming a coalition and can exploit more surplus in international trade, which potentially prompts cooperation on climate. Hence, cooperation, even partial cooperation is better than non-cooperation. Consequently, *Stand-alone* is never in equilibrium.

Chapter 4 then investigated the possibility of a trade linkage which aims to overcome free riding problems in climate change cooperation. Some important findings are as follows. Trade linkage can deter free riding incentives and stabilize the otherwise unstable *Grand Coalition* under free trade when climate change damage is moderate. It also generates large welfare gain globally, however, this gain mainly comes from the decrease of climate change damage but at the cost of *non-climate* welfare. Second, the presumption that trade linkage always induces participation in IEA is misleading. It can be ineffective when climate change damage is large or even counter-productive when climate change damage is small. But there is still global welfare gain in the former case. Third, by contrasting the welfare of each country under trade linkage with those under free trade, it is found that trade linkage can't be introduced in the first place if the voting rule requires consensus approval, since the free rider of *the Pair* is weakly worse off with linkage, and thus against linkage. Trade linkage is only possible if a majority voting rule is applied.

While the thesis has explored the effects of trade and trade policy on climate change cooperation within a novel framework, some of the model features are kept relatively simple to emphasize the role that trade plays in IEA formation. Chapter 5 has discussed possible extensions to the current framework, which can enhance its realism and provide more policy insights to facilitate climate change cooperation.

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