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Global Warming and International Cooperation

Would negotiation of international environmental treaties be easier if the world only consisted of China, USA and EU?

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Abstract

The purpose of this master thesis is to use game theory to analyse global warming in a world consisting of three countries. The three countries are China, USA and EU, who currently accounts for more than 50% of carbon emissions. The first part models the countries' payoffs according to different levels of participation and abatement. The second part analyses the results and combines this with game theory under different scenarios. After discussing the Nash equilibrium and the efficient solution, both in a cooperative and a noncooperative environment, I move on to see how these results fit with what we observe in the real world.

Acknowledgements

This thesis is the last part of my master studies in Energy, Natural Resources and the Environment at the Norwegian School of Business Administration and Economics (NHH).

My interest of global warming has been increasing throughout my studies. Both courses at NHH and the increasing public interest have been very interesting to follow during the last couple of years. When I got the opportunity to write about international environmental agreements, just after the COP-15 negotiations in Copenhagen, I knew this was the perfect topic for me.

I would like to give a warm appreciation to Gunnar Eskeland who has helped me with valuable guidance and insights during my work with this thesis. In addition to this, I want to thank my parents who has listened to my views on global warming and helped me tremendously.

Oslo, June 2009

Joachim Emil Skjelbred

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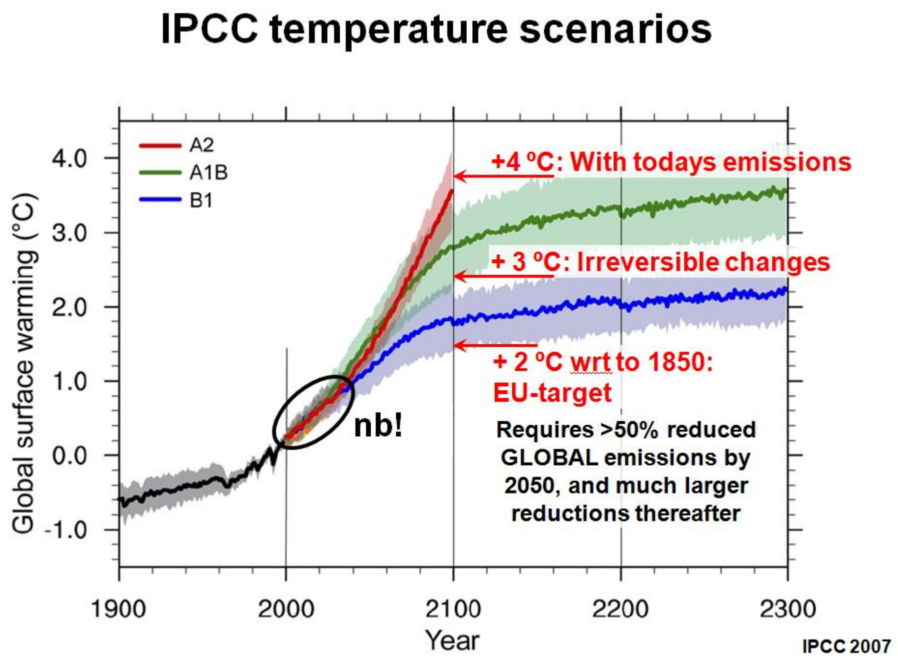
1. Introduction

To sustain an environment suitable for man, we must fight on a thousand battlegrounds. Despite all of our wealth and knowledge, we cannot create a redwood forest, a wild river, or a gleaming seashore. But we can keep these we have.

Lyndon B. Johnson

February 23, 1966

Global warming is one of our times largest challenges. The International Panel on Climate Change (IPCC) argues that we need to curb carbon emissions to avoid changing the climate in ways that may seriously harm the earth. This will have huge economic impacts that will affect people's lives tremendously. The figure below is a combination of the Intergovernmental Panel on Climate Change's (IPCC) scenario analysis and Helge Drange's comments on this matter.



IPCC temperature scenarios. Source: Helge Drange, lecture NHH, 14.09.09

We see that an increase in the average temperature of 3˚C or more by 2100 will lead to irreversible changes. These changes may impose effects such as rising sea level and more extreme weather such as drought and hurricanes. However, if we carry on with business as usual we may have an increase in the average temperature of more than 4˚C. This will result in even more dramatic economic consequences.

A different path, like the one suggested by EU, will hopefully result in an increased temperature of only 2˚C compared to the temperature in 1850. As Drange argues, this requires more than a “50% reduction of global emissions by 2050, and much larger reductions thereafter” (2009). In other words, this is a very optimistic scenario which will be difficult to reach.

The International Energy Agency (IEA) states in World Energy Outlook 2009: “The reductions in energy-related CO2 emissions required in the 450 Scenario (…) by 2020 – just a decade away – are formidable (2009:7).” Where the 450 scenario relates to reducing emissions so the long term concentration of CO2 in the atmosphere does not exceed 450 ppm. With a CO2 concentration lower than the limit, it is a 50% probability that the global temperature increase will be below 2˚C. From this we may conclude that it is urgent that we deviate from the current path.

Since the industrial revolution in the late 18th century, carbon emissions have been highly correlated with economic growth. The demand for energy production has been ever increasing and the most common energy source has been fossil fuels. The greenhouse effect was proposed as early as in 1824 by Joeph Fourier and later explained by Svante Arrhenius in 1896. But in the beginning, carbon emissions were not thought of as being especially dangerous for the environment. However, in the late 1980s global warming caught the scientists and environmentalists attention. Ultimately, the politicians’ concern about the environment grew as well.

In 1992 the United Nations Framework Convention for Climate Change was formed. This is an international climate treaty aimed at reducing global warming, but it does not specifically state *how* the reductions are to be reached. Therefore there have been several negotiations of additional protocols over the last two decades, aimed at solving the how-question.

Many saw it as a breakthrough when the Kyoto Protocol was presented in 1997. This Protocol is, as the UNFCC states on its homepage, “an international and legally binding agreement to reduce greenhouse gas emissions worldwide”. However, in many ways it turned out to be an agreement not reaching its ambitions. Both because USA, at the time the largest emitter of CO_2, did not ratify the agreement and because many of the developing countries, China included, did not have to do any large emission reductions on their own.

1.1 Topic

International Environmental Treaties so far have not been able to achieve large participation and emission reductions. Considering a world consisting of 200 countries, it is easy to understand as all countries have their own interests they want to protect. During the negotiations in Copenhagen 2009 we saw a new situation emerging where the plenum negotiations were partly abandoned for smaller group negotiations. In the beginning of the negotiations a text later called the “Danish text”, was leaked. The text proposed a climate treaty negotiated by, according to the Guardian (20.12.2009), “a few rich countries in secret”. The text received much critique and was later abandoned. However, towards the end of the negotiations a small group of 30 countries, consisting of most of the largest emitters, negotiated on their own and agreed on what was to become the Copenhagen Accord.

Considering this new situation, it is interesting to ask the question: If we have a smaller group of countries, is it easier to agree on a treaty with large participation and emission reductions? In this paper I will therefore address this question in detail. I will simplify by assuming that the world only consists of three countries, China, USA and EU. I will then develop a model that predicts the countries’ payoffs according to different levels of participation. Using game theory, I will then discuss why it is difficult to reach full participation and if it is possible at all.

There are three ways to deal with climate change, abatement, geoengineering and adaption. According to political discussions abatement is the most suggested solution to the challenge of global warming and this will be the focus of this paper. It should also be noticed that the IPCC’s research regarding climate change and whether mankind is responsible for these changes could be questioned. However, in the following I will assume that the IPCC is right, that climate change is manmade and that we can reduce global warming by investing in abatement. Before I move on to analysing why countries behave in the way they do, I will give a more detailed description of the climate problem and international environmental treaties.

1.2 Public goods

Public goods are characterized by being non-rivalrous and non-excludable. Non-rivalrous means that one individual's consumption of a good does not affect any other individual's ability to consume the good. Non-excludable meaning that it is impossible to exclude anyone from consumption of the good. In our case the current climate is a public good. It is not possible to exclude anyone from consumption of the climate and if I consume climate, that does not affect any other people's consumption of the same climate.

In lack of a world government, global public goods are especially difficult to handle. If climate change was a local problem, for instance domestic, the local government could have introduced measures to change current behaviour. Through taxation or legislation, costs may be imposed on different domestic players to significantly change their behaviour. This is unfortunately more difficult when we are addressing a global problem as we don't have a world government who can impose such measures on other free states. Countries maximize their own welfare which may lead to global inefficient solutions as externalities are not incorporated in the decision-making process. Each country has incentives to free ride on other countries' emission reductions. According to Asheim et al (2006:95) "there are two types of incentives for free riding: the incentive for a country to not sign the agreement (…) and the incentive for a signatory to not comply". Due to this volunteerism, corrections of the global problem must be introduced through voluntary measures. This fact suggests that it is much more difficult to achieve broad participation and significant changes in current behavior.

1.3 International environmental agreements

According to Barrett (2003: 133) a climate treaty may be defined as: "Cooperative arrangements for managing shared environmental resources". A treaty is legally binding on its participants, but it is of course voluntary to sign and ratify a treaty. What a treaty is trying to do is to restructure the game between nations, making it possible to reach the efficient solution and maximizing global welfare.

It is also worth mentioning that the treaty first is signed by a country, but this only signals a country's intentions, not their actual participation. A country is not a participant before the treaty is ratified. Often the signing is made on behalf of the government, while the ratification is done by the Parliament or similar institution. This introduces a new two-staged game between those who signs the treaty and those who ratify it. This is an interesting observation, but it will not be further explored in this paper.

2. Theory and presentation of model:

In this section, I will explain why different countries act the way they do when they address the question of global warming. I will use cooperative game theory to model how the different players behave under different scenarios. In the first section, I will present the theoretic framework, before I describe the model and assumptions. We then move on to parameterization and results. In the last section, I will look at the sensitivity analysis and discuss of how the results fit with reality.

2.1 Theoretic framework

Let us now turn to the theoretical framework applied in this paper. To describe countries' behaviour we will use classic game theory. A game is defined by Pindyck and Rubinfeld (2005:474) as a "situation in which players (participants) make strategic decisions that take into account other's actions and response". Every strategy has different outcomes, or payoffs, and the players seek to maximize their own payoffs. The outcome of the game is the result of the actual strategies chosen by the players. A dominant strategy is recognized as a player using one specific strategy no matter what the other players do. An equilibrium is defined by Barrett (2003:57) as "an outcome where no player would prefer to deviate, given the choices made by other players".

Information is an important aspect when it comes to game theory. In line with the assumptions made by Barrett (2003) I will look at the game as a game of imperfect information. This means that each player acts without knowing how the other players will act. On the other hand, what he does know is the payoffs the other players are facing under different outcomes. This is known as complete information and the player can make a qualified prediction about other players' strategies. In addition to this, let us assume that all players know that the other players know, or in other words, the information is common knowledge.

An equilibrium is a Nash equilibrium if all players are doing the best they can given what the other players are doing. The Nash equilibrium is then the expected solution of the game. However, the Nash equilibrium is not always the global optimum or what is also called the efficient solution. The global optimum is the outcome that maximizes the joint payoffs. Since every player is maximising their own payoffs we can have a situation where the behaviour leads to a non-efficient solution. This may be what we know as “tragedy of the commons”, or a situation where maximisation of self interest results in depletion of a shared resource, for instance the environment, even if this is not in the collective interest.

Sometimes, we have games with more than one Nash equilibrium. In such a situation, it is interesting to observe how the players can agree on one particular equilibrium. In 1960, Thomas Schelling introduced the theory of focal points, or a solution that stands out among many and therefore is the natural solution. He describes focal points as “each person’s expectation of what the other expects him to expect to be expected to do” (1960:57). The illustrative example Schelling used is, if you were to meet at stranger in New York City the next day, where and when would you meet this person? Using Schelling’s definition of focal points, you would expect the other person to expect that you expect that meeting at Grand Central Station at noon is the best solution. This is because Grand Central Station is a common meeting place and noon is a time of day standing out from all others. In later sections we will have a closer look at how focal points may affect the expected equilibrium.

We also distinguish between cooperative and noncooperative games. Pindyck and Rubinfeld (2005:474) define a cooperative game as a “game in which participants can negotiate binding contracts that allow them to plan joint strategies”. This can for instance be achieved by an international environmental treaty. While in noncooperative games, the players are not allowed to negotiate at all. In the following we will look at both situations and we will see that a treaty may improve the equilibrium in some scenarios.

When discussing a cooperative game, profit sharing or side payments are important to determine if we can find a solution that is stable. Side payments are defined as a transfer of money from some members of the coalition to other members of the coalition. A stable solution is also known as the solution being a part of the core. Narahari (2009) has defined the core as “the set of payoff allocations that are individually rational, coalitionally rational, and collectively rational”. In other words, a solution which is the efficient solution and no single player or coalition wants to leave the grand coalition. The core can be empty and non-empty. An empty core means that there are no possible solutions in the core, while a non-empty core means that there are one or more possible solutions.

If the core is non-empty there are many ways to share the profits to find a solution that may be within the core. Here I will describe two interesting methods, the Shapley value and the Gamma core. The Shapley value is a fair way of sharing payoffs from cooperation because it assigns a payoff equal to their average marginal contribution to cooperation. The idea is that we look at all the coalitions that can be formed, and ask ourselves the question: If one particular player is included in the coalition, what is the marginal contribution to increased total payoffs? The answer is the profit that should be allocated to this country. Obviously, the marginal contribution depends on in which order countries are allowed into the coalition. Therefore, the Shapley Value takes the average marginal contributions over all orders and coalitions that can be formed. This provides us with a unique solution, but as Barrett (2003:344) points out “this value may not lie in the core of the game”.

Profit sharing based on the Gamma core was introduced by Chander and Tulkens (1994). It is an appealing method because the solution is in the core of the game, the solution is unique and it is easy to find. The Gamma core shares the profits from moving from the Nash equilibrium to the grand coalition. The profit sharing is a payment to each player that covers their increase in costs between the Nash equilibrium and the optimum. In addition to this, each player has to pay a share of the world’s total increase in costs equal to their share of marginal damages. In an extreme example, this means that a country with no marginal damages will be compensated for their increase in costs due to participation. This makes it individually rational for this country to participate, because the country can not do any better on its own. A country with high marginal damages on the other hand will receive an amount equal to their increased costs, but they will also have to pay a share of the total increased costs. In sum this may lead to a situation where the countries highly affected by climate change will transfer money to countries not harmed. Or in other words, the method exploits the high willingness to pay by the highly affected countries, in order to compensate the countries with low willingness to pay. The theory also assumes full knowledge of the damage- and abatement cost functions. Chander and Tulkens also comments that the results are obtained “under two alternative assumptions: either linearity of the damage cost functions (…) or identical abatement cost functions (…) for all countries” (1994:10). In the model presented here the damage cost functions are non-linear, but the abatement cost functions are similar for all countries. As we will see later, the Gamma core provides an efficient solution.

2.2 Modelling payoffs:

The payoff to country *i* is the net present value of the net consumption and it is calculated as follows:

$$\prod_i = \sum_{t=1}^{T} \left(\frac{C_i^t}{(1+k)^t}\right) + \frac{1}{(1+k)^T} \cdot \frac{C_i^T}{k - g_i^T}$$

This is in other words the sum of net consumption in every period until T. At this point we assume a normalisation and we calculate a terminal value using Gordon's growth model and discounted to today. k is the discount rate and g_i^t is the growth rate in country *i* in period t. The net consumption per capita equals the GDP minus capital investments, mitigation costs and the country's share of potential world damages, divided by the size of the population. This can be shown as:

$$C_i^t = \frac{GDP_i^t - I_i^t - q_i^t - s_i D_w^t}{P_i^t}$$

Here $GDP_i^t = GDP_i^{t-1}(1+g_i^t)$ is GDP in period t equal to last years GDP multiplied with the country's growth rate. The capital investments is calculated as following $I_i^t = r_i^t GDP_i^t$, where r_i^t is the share of GDP invested, also known as the savings rate in country *i* in period t. q_i^t is the abatement cost to country *i* in period t and this variable is assumed to be binary. In other words, a country can either invest the necessary amount in abatement or they do nothing. The last term is the country's share of the total damages from global warming. Where s_i is country's share and the damages is calculated as follows:

$$D_w^t = a^t GDP_w^t \cdot \left(\frac{u^t GDP_w^{t-1} - \sum_{i=1}^{I} q_i^{t-1}}{u^t GDP_w^{t-1}} \right)^{\alpha}$$

Here a^t is the rate of damages in period t. u^t is the rate of necessary investment to insure the world against climate damages. In other words, the damages to the world are equal to a share of GDP multiplied with factor depending on the investments made by the countries of the world. The factor is equal to the amount necessary to invest to prevent climate change less what is actual invested by the countries of the world, divided by the necessary investment amount, where $GDP_w^{t-1} = \sum_{i=1}^{I} GDP_i^{t-1}$ is last years world GDP . This factor is equal to zero if all countries participate and invests in mitigation and it is 1 if no countries participate. The damage function is also assumed to be non-linear, where α is the damage coefficient ($\alpha \geq 1$). The population size is calculated as $P_i^t = v_i^t P_i^{t-1}$, where v_i^t is the population growth rate in country *i* in period t multiplied with last years population size.

It is important to notice that I have modelled climate damages and mitigation costs as a reduction in consumption, not a reduction in GDP. This means that the growth path for output is not affected by any costs imposed by climate change or abatement.

The world’s total payoff is then equal to the sum of all countries’ payoff, or in other words:

$$\prod_w = \sum_{i=1}^{I} \prod_i$$

The model is summarized mathematically in Appendix 1.

The model described above differs from much of the other literature on the subject of global warming and international environmental agreements as it does not include the variables of temperature and CO2 emissions. However, in the discussion of parameters below I will use findings from different scientists who have used temperature in their models. It is also worth mentioning that during the financial turmoil in 2008-09 the International Energy Agency observed a drop in emissions in addition to a drop in GDP due to lower activity. We may therefore assume that GDP and emissions are highly correlated and that this relationship will hold in the model described above.

2.3 Parameterization

I have decided to model a world consisting of only three “countries”, China, USA and EU. These countries are the three largest emitters of CO2, with China being the largest emitter, USA second and EU third. According to numbers from the United Nations Statistics Division these three countries amounted to 55.5% of all carbon emissions in 2006. The behaviour of these three countries is therefore crucial when discussing climate policy because their actions have huge impact on the aggregated world emissions.

In the Stern Review released in 2006 by Sir Nicholas Stern, he argues for urgent and large mitigation to reduce the risk of climate change. His argument is based on a modelling of cost and benefits from climate change. He has found that if we invest up to 1% of GDP annually by 2050, we can with high certainty insure the world against non-reversible climate change (Stern, 2006: 13). If we, on the other hand, don’t invest in mitigation, and carry on with business as usual, “climate change will reduce welfare by an amount equivalent to a reduction in consumption per head of between 5 and 20%, now and into the future”(Stern, 2006: 10).

Another economist who has modelled the economic impacts of climate change, is William Nordhaus who has developed the model: Regional Integrated model of Climate and the Economy (RICE model). In his paper Economic Aspects of Global Warming in a Post-Copenhagen Environment (2010: 11) he states: “[under the Copenhagen Accord c]osts rise gradually over the coming decades and reach around 1 percent of national income for high-income countries in the late 21st century.” The Copenhagen Accord is believed to be a weak treaty that will not contribute to achieve the necessary emission reductions to prevent the world from significant damages. It is also interesting to note that Nordhaus suggests a ramp up of abatement costs over time.

Combining the results from Stern and Nordhaus I have decided on the following parameters for abatement costs:

Period	**2009-2055**	**2056-2075**	**2076-2105**	**2106-**
Abatement cost in % of GDP	0.5 %	1 %	1 %	0 %

The necessary investments in abatement are 0.5% of world GDP from now to 2055. From 2056 to 2105 it is 1% of GDP. After this period the necessary investments are zero. This is in line with the assumption above that the society will be transformed into a low-carbon society in 2105 (=T). As mentioned above, a country's investment in abatement is a binary variable equal to zero if it plays Pollute. If the country plays Abate the investment in abatement equals 0.5 % of GDP per year from 2009-2055 and 1% of GDP per year from 2056-2105. I also assume that any country can achieve efficient mitigation at the same prices anywhere in the world. In other words, it does not matter who invests in mitigation, only the aggregated amount invested is important.

When building a model of different scenarios with payoffs far into the future, the discount rate will have a deep impact on the results. Stern's report on climate change and the need of urgent actions has been highly discussed by Dasgupta (2006) and Nordhaus (2007). They have shown that Stern's results are different, for instance from Nordhaus' results, due to a significantly low discount rate. When using Nordhaus' discount rate combined with Stern's model, the results are more or less the same. I will therefore start out by using a discount rate of 4 % suggested by Nordhaus as an expected average for this century (2008:10). According to Kenneth Arrow: "Stern's fundamental conclusion is justified (…) even if, unlike Stern, one heavily discounts uncertainty and the future" (2007), the assumption of investments as an insurance from climate change and potential expensive damages therefore still holds. The discount rate is assumed to be equal to all countries. One could argue that the discount factor should reflect real return on capital in the different countries and that China therefore should have a higher discount rate compared to USA and EU. However, as we will see below, the growth rate of China will decline to the same level as the growth rate in USA and EU at approximately the same time as the costs of climate change occur. We may therefore believe that the same will happen to the real return on capital. The assumption of using the same discount rates will therefore not have any significant impacts on the results.

At what time costs occur, will significantly affect the results in the model. Using a high discount rate means that costs far into the future will have little impact on the net present value (NPV). Abatement costs are more uncertain and we cannot know for sure when they occur. They may be large from the middle of this century or from the end of it. For now, it is important to notice that the discount rate may affect the results significantly.

When it comes to growth rates for different countries I have used the same growth rates as Nordhaus has used in the RICE model for growth of net national income (2010:5). Nordhaus' estimates are until 2205 and I have assumed that the last period estimated, 2105-2205, will be relevant from 2106 and forever. The growth rates are summarized in the following table:

Growth of net national income	**2009-2055**	**2056-2075**	**2076-2105**	**2106-**
China	3.91 %	1.26 %	1.26 %	0.30 %
USA	2.04 %	1.08 %	1.08 %	0.29 %
EU	1.86 %	0.90 %	0.90 %	0.29 %

In the first period we have higher growth in China compared to USA and EU. From then, China's growth rate drops and becomes close to identical with the growth in the two other countries. This is expected since China is experiencing significant growth at the moment, but this growth will probably decline as GDP per capita becomes close to GDP per capita in other developed countries.

Initial data for GDP, population and emissions are summarized in the following table:

	China	**USA**	**EU**	**Total/World/World average**
GDP PPP (billions) $ (2009 est.)	8791	14260	14510	37561
Population (millions) (2010 est.)	1338.6	307.2	491.6	2137.4
GDP/capita $ (2009 est.)	6500	46400	32700	
Emissions				
Thousand metric tons of CO2 (2006)	6103493	5752289	3914359	15770141
Share of real world total (2006)	21.5 %	20.2 %	13.8 %	55.5 %
Metric tons of carbon emissions per capita (2006)	4.6	19.0	8.1	4.4

The GDP numbers are gathered from the CIA Factbook and show that USA and EU are significantly larger economies compared to China. But remember that China has a higher growth rate and they will therefore catch up some time before 2050. China is much more populous compared to USA and EU and we therefore see that the GDP per capita is much lower than the two others.

China is the largest emitter of CO_2, closely followed by USA. EU is lagging somewhat behind and is only responsible for 13.8% of real world total. The three countries' emissions amounts to a share of 55.5% of world total and, as mentioned above, these countries actions will significantly affect total world emissions. China emits much less CO_2 per capita compared to USA. While EU is between the two, with 8.1 tons of CO2 per capita. The world average is only 4.4 tons of CO2 per capita and we see that China is close to this average, while EU and especially USA are high above the average.

Let's now turn to historic cumulative emissions. From Baumert et al. (2005) we have the following numbers:

Historic CO2 emissions (1850-2002)		
Country	**Cumulative emissions**	**Tripod-world**
China	7.6 %	12.0 %
USA	29.3 %	46.2 %
EU	26.5 %	41.8 %
ROW	36.6 %	
Sum	100.0 %	100.0 %

Baumert et al. have summarized all emissions since 1850 to 2002 and found that USA is responsible for 29.3% of total aggregated emissions in this period. Closely followed by EU, who has emitted 26.5%. China is only responsible for 7.6% of the total emissions in the period. Since we in this world, only have three players, we may recalculate the percentages. Now China is responsible for 12% of cumulative emissions, USA 46.2% and EU 41.8%.

As mentioned above, consumption equals GDP minus invested capital. Here the invested capital is the same as the savings rate times GDP. The savings rates for the different countries are collected from Nordhaus' RICE-model and they are summarized in the following table:

Savings rate	**2009 - 2015**	**2016 - 2025**	**2026 - 2035**	**2036 - 2045**	**2046 – 2055**	**2056 - 2065**
China	35.70 %	22.70 %	21.50 %	20.80 %	20.40 %	20.50 %
USA	17.80 %	20.40 %	20.10 %	19.80 %	19.70 %	19.80 %
EU	17.40 %	20.00 %	19.60 %	19.50 %	19.30 %	19.40 %
	2066 - 2075	**2076 - 2085**	**2086 - 2095**	**2096 - 2105**	**2106 -**	
China	20.40 %	20.50 %	20.50 %	21.10 %	21.70 %	
USA	20.00 %	20.30 %	20.50 %	20.80 %	22.10 %	
EU	19.50 %	19.70 %	19.90 %	20.60 %	22.00 %	

In the first period China's savings rate is higher compared to USA and EU, but over time it declines and at the end of the century, the savings rates are more or less equivalent.

Let us have a look at the population growth in the different countries. These numbers are also from Nordhaus' RICE-model and they are shown in the following table:

Population growth	**2009 - 2015**	**2016 - 2025**	**2026 - 2035**	**2036 - 2045**	**2046 - 2055**	**2056 - 2065**
China	0.6186 %	0.6186 %	0.4012 %	0.0632 %	-0.1520 %	-0.3289 %
USA	0.9328 %	0.9328 %	0.7646 %	0.5760 %	0.4318 %	0.2463 %
EU	0.4346 %	0.4346 %	0.2358 %	0.0966 %	-0.0001 %	-0.1551 %
	2066 - 2075	**2076 - 2085**	**2086 - 2095**	**2096 - 2105**	**2106 -**	
China	-0.3325 %	-0.3325 %	-0.3325 %	-0.3325 %	-0.1582 %	
USA	0.1346 %	0.1346 %	0.1346 %	0.1346 %	0.1035 %	
EU	-0.2382 %	-0.2382 %	-0.2382 %	-0.2382 %	-0.0971 %	

China's population growth is somewhat lower than the others. This is probably due to the effective politics aimed at reducing the birth rate. The population growth in USA is higher than in EU. For China and EU, the population growth is negative in the second part of the century.

Each country will have a share of the total costs in proportion to their share of marginal damages. Using Nordhaus' RICE model, Godal and Holtsmark have suggested marginal damages for the different countries in 2020 as follows (2010: 9). I have assumed that each country's share of world total is consistent from now and into the future. This is summarized in the following table:

Year 2020	**Marginal damage (US$/tC)**	**Share of world total (s_i)**
China	24.3	41.26 %
US	15.1	25.64 %
EU	19.5	33.11 %
Sum world	58.9	100.00 %

I have assumed the share of marginal damages to be constant for every time period. However, it is important to notice that the share of marginal damages may change over time, especially due to economic growth. Today China has the largest share of marginal damages and it is possible that this is due to lower GDP compared to the other countries. As we have seen above, China has a higher growth rate and they will catch up with the rest of the world within 2050. One could argue that China today is more affected by climate change because many people are rural workers. When they grow richer, more people will have other jobs, for instance to the service industry, and they will therefore be less affected by climate change. However, if we look at consumption per capita, it will take much longer time before China catches up with USA and EU. I have therefore assumed constant shares of marginal damages.

The damage coefficient ensures that the damage function is nonlinear. The coefficient is larger than one and in the following analysis I will assume it to be equal to 1.5. A coefficient larger than 1, indicates that some abatement is a lot better than no abatement and that there are diminishing marginal benefit of abatement. In the sensitivity analysis, I will also look at what happens if the coefficient is changed.

3. Scenarios and results

We have now looked at the theoretic framework, the model and its parameters. Let us now turn to the results considering different scenarios. As mentioned above, there are large uncertainties about many of the parameters in our model. Perhaps the most important parameter that we are highly uncertain about, is the damage costs. I have therefore decided to look at what happens if the damage costs change and especially which coalitions will form. Firstly, I will analyse damages of 5% of consumption from 2056 and then increase the damages to 12.5%. There are two 12.5%-scenarios with different discount rates. This illustrates the importance of the value of the discount rate and how it affects the results.

3.1 Scenario 1: Damages = 5% of consumption, discount rate = 4%

In the first scenario, the damages are 5% of consumption from 2056 and forever. The results and some important parameters are summarized in the following table:

Period	**2009-2055**	**2056-2075**	**2076-2105**	**2106-**		
World damages in % of GDP	0.0 %	5.0 %	5.0 %	5.0 %		
Damage coefficient	1.50					
Discount rate (k)	4.0 %					
Coalition	**Total payoff**	**V(u)-V(Ø)**	**China**	**USA**	**EU**	
V(CH, EU)	2 656 317	23 452	369 225	1 347 509	939 583	Efficient solution
V(CH, US)	2 654 404	21 539	369 413	1 338 101	946 891	
V(CH, US, EU)	2 652 928	20 062	370 469	1 340 173	942 286	
V(CH)	2 652 925	20 059	367 220	1 343 579	942 125	Nash equilibrium
V(US, EU)	2 644 340	11 475	371 191	1 335 772	937 378	
V(EU)	2 640 659	7 794	368 566	1 340 416	931 676	
V(US)	2 639 326	6 460	368 869	1 331 226	939 231	
V(Ø)	2 632 866	0	365 703	1 334 809	932 353	

The first column describes the different coalitions and they are ranked by their total payoffs. Total payoff refers to the payoff to the total utility to the world and it is the sum of all countries' payoff. The next column describes the respective coalitions' improvement compared to the business as usual path where no one abates. The next three columns show the individual payoffs to the countries under different coalitions. The largest individual payoff to each country is marked yellow.

The total payoff is maximized when China and EU are in a coalition investing in abatement. This is the efficient solution, also known as the global optimum or the solution that maximises the world's utility. The second best alternative for the world is a coalition of China and US, while the grand coalition is a third best option. It is also interesting to notice that all countries' individual payoffs are at their highest when they free ride and let a coalition of the two other countries abate. China abating alone has a higher total payoff compared to the coalition of US and EU. This is probably due to China's higher growth rates and marginal damages.

Next, we turn to the Nash equilibrium. Remember that the Nash equilibrium is defined as a situation where no player wants to change their behavior given the behavior of the other players. I have used the following matrix to illustrate how to find the Nash equilibrium when we have three players:

EU choose Abate		**US**	
		Abate	**Pollute**
China	**Abate**	(370, 1340, 942) ↓ →	(369, 1347, 936) ↑
	Pollute	(371, 1335, 937) →	(368, 1340, 931)
EU choose Pollute		**US**	
		Abate	**Pollute**
China	**Abate**	(369, 1338, 946) ↑ →	(367, 1343, 942) * ↑
	Pollute	(368, 1331, 939) →	(365, 1334, 932)

We exclude EU from the matrix, but include their payoffs. The different outcomes show the individual payoffs to each country in the following order (China, US, EU). The arrows show how each player acts to maximize their own payoffs. We see that China will play abate in all outcomes except when US and EU are in a coalition. US on the other hand has a dominant strategy to play pollute. The solution must therefore be in one of the upper right hand corners. Or in other words, EU must choose between abate or pollute given that USA will pollute and China will abate. To maximize their payoff EU will choose pollute. The Nash equilibrium (marked *) is then the solution where China abates alone, while the other two are free riders. If we check for the two other situations where China and US are excluded from the matrix we get the same result.

The Nash equilibrium is a relative improvement of 0.76% compared to the business as usual total payoffs and the efficient solution is a relative improvement of 0.89%. In other words, it is possible to improve total payoffs by moving from the Nash equilibrium to the efficient solution, but the additional gains are not very large. Meanwhile, it is interesting to have a closer look at whether it is possible to reach the efficient solution and maximize total payoffs at all. The solution described above is attained in the non-cooperative environment. But what if we let the players use side payments to improve the situation? The efficient solution is the coalition consisting of China and EU, but in this coalition EU will want to break out as they will receive higher payoffs by free riding. When including side payments China could be willing to pay EU for staying in the coalition, but is the increased payoffs large enough to sustain the efficient solution?

The following table summarizes the changes in payoffs for the different countries when moving from the Nash equilibrium to the efficient solution.

Coalition	Total payoff	China	USA	EU	
V(CH, EU)	2 656 317	369 225	1 347 509	939 583	Efficient solution
V(CH)	2 652 925	367 220	1 343 579	942 125	Nash equilibrium
Change in payoffs	3 393	2 005	3 930	2 542	

China is willing to pay EU up to $ 2005 billions. Paying more than this is not in the interest of China, as they can do better when abating alone. The coalition between EU and China will only be in the interest of EU if they are paid at least $ 2542 billions. Remember that side payments are defined as money transfers between countries in the coalition, the efficient solution is therefore not possible because the necessary payment to EU is larger than China’s total gain. Only if USA is willing to pay EU the efficient solution is possible. This is reflected in the positive change in total payoffs. However, this situation is much more difficult to achieve, as one country is free riding and at the same time paying another country to abate. This is probably politically controversial both in USA and EU and can be difficult to achieve when the additional gains are small.

3.2 Scenario 2: Damages = 12.5% of consumption, discount rate = 4%

Stern suggests that potential damages could reduce consumption by 5-20%. The first scenario was therefore a low damage costs estimate. What happens if the damages increase to 12.5% from 2056 and forever? The parameters and results are summarized in the following table:

Period	**2009-2055**	**2056-2075**	**2076-2105**	**2106-**		
World damages in % of GDP	0.0 %	12.5 %	12.5 %	12.5 %		
Damage coefficient	1.50					
Discount rate (k)	4.0 %					
Coalition	**Total payoff**	**V(u)-V(Ø)**	**China**	**USA**	**EU**	
V(CH, US, EU)	2 652 928	79 633	370 469	1 340 173	942 286	Efficient solution
V(CH, EU)	2 646 751	73 455	367 359	1 343 863	935 528	Nash equilibrium
V(CH, US)	2 646 267	72 971	367 829	1 334 993	943 445	Nash equilibrium
V(CH)	2 627 916	54 621	362 347	1 334 039	931 530	
V(US, EU)	2 626 986	53 691	367 800	1 329 171	930 015	
V(US)	2 604 097	30 802	361 995	1 317 806	924 297	
V(EU)	2 603 132	29 836	361 240	1 326 131	915 761	
V(Ø)	2 573 295	0	354 082	1 312 113	907 100	

When the costs are increased we see that the grand coalition becomes the efficient solution. This is to be expected because a larger problem usually needs more participants to be corrected. China's individual payoff is maximized in the grand coalition, while USA and EU maximize their individual payoffs when free riding. It is also interesting to observe that China abating alone gives a marginally higher total payoff compared to the coalition of USA and EU.

Finding the Nash equilibrium is shown in the following table:

China choose Abate		**EU**	
		Abate	**Pollute**
US	**Abate**	(370, 1340, 942)	(367, 1334, 943) *
	Pollute	(367, 1343, 935) *	(362, 1334, 931)
China choose Pollute		**EU**	
		Abate	**Pollute**
US	**Abate**	(367, 1329, 930)	(361,1317,924)
	Pollute	(361, 1326, 915)	(354, 1312, 907)

When China abates, USA's strategy is polluting if EU abates. And if EU pollutes USA will want to abate. The same is true for EU. If we exclude the two other countries in turn, China has a dominant strategy to abate. We are therefore in the upper half of the table above where we have two Nash equilibria, a coalition of China and USA and a coalition of China and EU. From basic game theory, it is hard to distinguish between the two and predict which equilibrium we will end up with.

As suggested in the theoretic framework, we may use the theory of focal points to select among several Nash equilibria. A focal point is a solution that stands out among others as more appealing. There are some differences between USA and EU that might suggest the most likely equilibrium. For instance, USA has much higher current emissions compared to EU. In a perspective of fairness, one could argue that USA should pay for abatement since they are a larger polluter compared to EU. However, there is little evidence that higher emissions lead to a higher sense of responsibility regarding climate change. Using these arguments, the coalition of China and USA is not very likely.

Another perspective is differences in marginal damages. EU has higher marginal damages compared to USA and they therefore have stronger incentives to prevent climate change. As a result, China and EU should form a coalition due to stronger incentives. Additionally, the total payoffs of the coalition of China and EU are marginally higher compared to the coalition of China and USA. Considering this, I believe it is more likely that the coalition between China and EU is formed. This is also in line with the results from the next scenario, where the coalition of China and EU is the only Nash equilibrium. This Nash equilibrium equals a total improvement of 2.85% compared to the business as usual case.

Looking closer at the grand coalition, we see that both USA and EU have individual incentives to break out. This is shown in the table above, where both USA and EU maximize their payoffs by free riding, in each case letting the two remaining countries abate. This might suggest that the core is small or even empty. To check if the core is empty we need to find out if it is any solution that is collectively, coalitionally and individually rational. From the table above we see that the grand coalition is collectively rational since it has the highest total payoffs. The coalitional and individual rationality is summarized in the table below:

Individual	**China**	**USA**	**EU**	**Sum**
Payoff grand coalition	370 469	1 340 173	942 286	
Maximum payoff alone	367 800	1 343 863	943 445	
	2 669	-3 690	-1 159	-2 180
Coalition	**China, US**	**China, EU**	**US, EU**	**Sum**
Payoff grand coalition	1 710 642	1 312 755	2 282 459	
Maximum payoff alone	1 702 821	1 302 888	2 265 569	
	7 820	9 868	16 890	34 578

For the individual rationality to be fulfilled the payoff each country gets after payoff sharing must be larger than what it can get on its own. The difference for China between their payoff from the grand coalition and the maximum payoff they can get when acting alone is $ 2669 billion. This means that China is willing to give up to $ 2669 billion and still be a part of the coalition. For US it is opposite, they can do much better if they act alone and so they must be compensated by at least $ 3690 billion, to want to stay in the grand coalition. The same is true fro EU, who needs a compensation of at least $ 1159 billion. The total sums of compensation and willingness to pay is negative, this means that the core is empty. There is, in other words, no possible solution that is individually rational for all countries at the same time.

Looking at coalitional rationality, the differences between the coalition's payoffs in the grand coalition compared to their best alternative on their own are obvious. For the coalition between China and USA, they are willing to give up $ 7820 billion before they will be interested in breaking out of the grand coalition. We see that the same is true for the coalition between China and EU as well as the coalition of USA and EU. If we only consider coalitional rationality, a core solution is possible. But, as mentioned above, the individual rationality is not possible to fulfil and we therefore have an empty core.

An empty core means that it is very difficult to find consensus for any agreement that provides full participation. It is not impossible, but an agreement providing full participation will need to be supported by other incentives than economic incentives alone. And it can be very difficult to ensure compliance when one or more parties have economic incentives to break out. For this scenario it is very difficult to improve on the Nash equilibrium and the efficient solution will probably not be reached. This is mostly due to the empty core. In the next scenario, the damage costs level is the same as here and I will analyse what happens if the discount rate is reduced.

3.3 Scenario 3: Damages = 12.5% of consumption, discount rate = 3%

In this scenario, the discount rate is reduced to 3%. This means that future damages have a larger impact on the net present value and cooperation is expected to be more profitable. The results are summarized in the following table:

Period	**2009-2055**	**2056-2075**	**2076-2105**	**2106-**		
World damages in % of GDP	0.0 %	12.5 %	12.5 %	12.5 %		
Damage coefficient	1.50					
Discount rate (k)	3.0 %					
Coalition	**Total payoff**	**V(u)-V(Ø)**	**China**	**USA**	**EU**	
V(CH, US, EU)	3 992 764	191 432	631 358	1 953 499	1 407 907	Efficient solution
V(CH, US)	3 973 295	171 963	625 513	1 942 290	1 405 492	
V(CH, EU)	3 971 619	170 288	624 385	1 954 400	1 392 835	Nash equilibrium
V(US, EU)	3 932 604	131 272	623 337	1 929 082	1 380 185	
V(CH)	3 925 326	123 994	613 255	1 933 078	1 378 992	
V(US)	3 877 170	75 839	610 401	1 904 328	1 362 441	
V(EU)	3 872 014	70 682	608 579	1 915 144	1 348 291	
V(Ø)	3 801 332	0	592 641	1 884 637	1 324 054	

We see that the grand coalition is the most efficient solution. For China and EU the individual payoffs are maximized in the grand coalition, while the best individual strategy for USA is to free ride and let the two others abate. We also find that the coalitions of any 2 countries of the 3 all provides higher total payoff than any single country's abatement.

The Nash equilibrium is found using the same method as before by excluding one country from the matrix at the time. Finding the Nash equilibrium is then shown in the following table:

China choose Abate		**EU**	
		Abate	**Pollute**
US	**Abate**	(631, 1953, 1407)	(625, 1942, 1405)
	Pollute	(624, 1954, 1392) *	(613, 1933, 1378)
China choose Pollute		**EU**	
		Abate	**Pollute**
US	**Abate**	(623, 1929, 1380)	(610, 1904, 1362)
	Pollute	(608, 1915, 1348)	(592, 1884, 1324)

We see that EU has a dominant strategy to abate. USA will have incentives to abate only if EU pollutes or if China pollutes. When excluding the two remaining countries in turn we find that China, like EU, has a dominant strategy to play abate. The result is that we have a Nash equilibrium where China and EU abates, while USA pollutes. The Nash equilibrium is a relative improvement of 4.48% compared to the business as usual path.

Let us now turn to the core of the game. As we can see from the table above, the grand coalition is collectively rational. The coalitional and individual rationality is summarized in the table below:

	China	**USA**	**EU**	**Sum**
Payoff grand coalition	631358	1953499	1407907	
Maximum payoff alone	623337	1954400	1405492	
	8020	-901	2415	9534
	China, US	**China, EU**	**EU, US**	**Sum**
Payoff grand coalition	2584856	2039265	3361406	
Maximum payoff alone	2567803	2017219	3312071	
	17054	22046	49336	88435

Individually, China will want to stay in the grand coalition as long as their payoff will not be reduced by more than $ 8020 billion. EU is also willing to give up some of their payoff to stay in the coalition and they are willing to give up $ 2415 billion at the most. USA, on the other hand, must be compensated for wanting to stay in the coalition. Their compensation must be at least $ 901 billion. In total we see that the individual rationality is possible to achieve since the total sum is positive.

Considering coalitional rationality, no coalition of two countries can do any better if acting on their own than in the grand coalition. In other words, the payoffs to all two-countries-coalitions are larger in the grand coalition than what they can get either by the two countries breaking out or forming their own two country coalition and excluding the third country.

It is now possible to find a solution that is both coalitionally and individually rational, the core is therefore non-empty. Even though the core is non-empty, we are not certain to find a reasonable profit sharing that is in the core. There are many ways of sharing profits and in the following, I will describe some possible solutions and check whether they comply with the core.

First, I will analyse the non-cooperative grand coalition suggested above.

Noncooperative grand coalition	**China**	**USA**	**EU**
V(CH, US, EU)	631 358	1 953 499	1 407 907

The non-cooperative grand coalition is not in the core. If it had been, this would have been the Nash equilibrium of the game, which it is not. The reason why this solution is not in the core, is because with current payoffs, USA will want to break out and let the two others abate on their own. However, if we let the game be a cooperative game where the players can agree on side payments, the results may change. There are numerous ways to share the profits according to different profit sharing alternatives. As mentioned in the theoretic framework, I will go into detail on the Shapley value and the Gamma core. In addition to this, I have looked at other profit sharing methods such as per GDP, per capita and per emissions. Here, I will only present the results, for a detailed analysis of the different methods for payoff sharing and to see if they are in the core, see appendix 2.

The Shapley value is found as an average of marginal contributions to each coalition. In the table below we see all marginal contributions for each country:

Coalition	**V(u)**	**Marginal contribution China**	**Marginal contribution USA**	**Marginal contribution EU**	**Sum**
CH	3 925 326	123 994			
US	3 877 170		75 839		
EU	3 872 014			70 682	
Mean subgroup		**123 994**	**75 839**	**70 682**	
CH, US	3 973 295	96 124	47 969		
CH, EU	3 971 619	99 605		46 294	
US, EU	3 932 604		60 590	55 434	
Mean subgroup		**97 865**	**54 279**	**50 864**	
CH, US, EU	3 992 764	60 160	21 144	19 469	
Shapley value		94 006	50 421	47 005	191 432
New payoff		686647	1935058	1371059	3 992 764

The table describes all possible coalitions and the marginal contribution for each country when they are added into a coalition. For instance, let USA abate before China joins USA in a coalition to abate. Then the marginal contribution for China is equal to $ 96124 billion. After each subgroup of coalitions, the mean marginal cost for each country is calculated. The Shapley Value is the average of the subgroup means for each country. The Shapley value for China is then $ 94006 billion, USA $ 50421 billion and EU $ 47005 billion. This figure is then added to the business as usual payoffs and we get a new payoff for China equal to $ 686647, USA $ 1935058 billion and EU $ 1371059 billion. China has the largest Shapley value as they contribute the most when participating in the coalitions. It is also worth noticing that the sum of the Shapley values is equal to the total increase in payoff when moving from the business as usual path to the most efficient solution. This simple exercise gives a unique solution which is fair in the sense of profit sharing, but is the solution in the core? Unfortunately, the Shapley values of this game are far from the core. Coalitionally, two constraints are violated. First, the coalition of USA and EU receive larger payoffs if they break out of the grand coalition and form their own coalition, excluding China. Second, the coalition of USA and EU receive even larger payoffs if they together break out and free ride, while China abates alone. In addition to this, they both have incentives to break out of the coalition and let the two remaining parties abate. The profit sharing method using Shapley values does not qualify as a core solution.

The Gamma core method was introduced by Chander and Tulkens (1994). The Gamma core method is based on money transfers within the grand coalition. Each player gets compensation for the increase in costs when moving from the Nash equilibrium to the efficient solution. In addition to this, they have to make a payment equal to their share of marginal damages multiplied with the total increase in costs. The details for each country are summarized in the table below:

Abatement costs	**CH**	**US**	**EU**	**Total**
Nash equilibrium	6 944	0	5 356	12 300
Efficient solution	6 944	5 699	5 356	17 999
Share of total damages	41.26 %	25.64 %	33.11 %	100 %
Money transfer	2351	-4238	1887	0.0
Noncooperative	631358	1953499	1407907	3 992 764
New payoff	629 006	1 957 737	1 406 021	3 992 764

A money transfer that is positive means that this country has to pay, while a negative sign means that this country receives money. Using the Gamma core method, China and EU must pay, while USA receives money. China and EU must pay because they don't have any additional costs when moving from the Nash equilibrium to the efficient solution. In addition to this, they have a larger share of total damages compared to USA and therefore have to pay a larger share of the increase in total costs. In sum, this reduces the new payoffs for China and EU respectively to $ 629006 billion and $ 1406021 billion, while USA's new payoff equals $ 1957737 billion.

One of the benefits of using the Gamma core is that it exploits the players' willingness to pay. We know that players most harmed will have larger incentives to invest in abatement, while countries not affected by climate change, don't have the same incentives to participate. Given these characteristics, it is easier to find a solution in the core. And when we check whether the proposed payoffs here are in the core, we find that they are meeting all the necessary demands to be a core solution. In other words, using cooperative game theory combined with the Gamma core method, we find a solution that is efficient, unique and stable over time.

There are numerous different methods of profit sharing and I will now illustrate some of these. For most of the time, I will look at increased payoffs when moving from the Nash equilibrium to the grand coalition. The net gain is then $ 21144 billion which is to be divided between the different players according to a distribution formula.

One possible solution which is not very different from the Shapley value is to look at the marginal contribution when USA is included in the Nash equilibrium coalition. Due to USA’s participation, the total payoffs increase and USA therefore receive all of the additional gains by adding the marginal contribution to their Nash equilibrium payoff, which is shown in the table below:

Profit sharing based on marginal contribution	**China**	**US**	**EU**
Marginal contribution	0	21 144	0
New payoff	624385	1975544	1392835

The solution is not in the core because EU has incentives to free ride while the two remaining countries abate. EU’s strong incentives to free ride and the fact that many profit sharing agreements favour USA or China, results in many of the methods proposed here not being in the core.

The following table shows a summary of different profit sharing methods:

1. Profit sharing based on current emissions	**China**	**USA**	**EU**
Emissions	6103493	5752289	3914359
Share of total	38.70 %	36.48 %	24.82 %
Profit allocation	8183	7713	5248
New payoff	632 568	1 962 113	1 398 083
2. Profit sharing based on historic cumulative emissions			
Share of cumulative emissions	12.0 %	46.2 %	41.8 %
Profit allocation	2535	9772	8838
New payoff	626 919	1 964 172	1 401 673
3. Profit sharing based on population			
Population (millions)	1338.6	307.2	491.6
Share of total	62.63 %	14.37 %	23.00 %
Profit allocation	13242	3039	4863
New payoff	637 627	1 957 439	1 397 698
4. Profit sharing based on GDP			
GDP	8791	14260	14510
Share of total	23.40 %	37.96 %	38.63 %
Profit allocation	4949	8027	8168
New payoff	629 333	1 962 427	1 401 003
5. Profit sharing based on marginal damages			
Marginal damage	24.30	15.10	19.50
Share of total	41.26 %	25.64 %	33.11 %
Profit allocation	8723	5421	7000
New payoff	633 108	1 959 821	1 399 835
6. Profit sharing based on equal shares			
Share of total	33.33 %	33.33 %	33.33 %
Profit allocation	7048	7048	7048
New payoff	631 433	1 961 448	1 399 883

The first proposed profit sharing method is to use share of current emissions to allocate profits. An argument for using this alternative is that it compensates the large polluters, making it easier for these countries to implement emission reductions. This method favours China and USA since they have the largest emissions today.

The second alternative is to look at the historic cumulative emissions. The concentration of CO_2 in the atmosphere is a result of emissions over many years. Since USA and EU were industrialized much earlier than China, they are more responsible for the present situation. As we also know, these countries find it least attractive to participate in the grand coalition and we should therefore give them a large share of the gains to motivate participation. This is hardly fair, but it will give USA and EU an incentive in the right direction.

The third option is to divide the increased payoffs according to each country's share of total population, where a large country will get a larger share compared to smaller countries. This favours China greatly since they have a population that is more than 2.5 times larger than number two.

Alternative 4, is to look at GDP where each country receives a share of the gains according to their share of total GDP. This gives larger shares to USA and EU and could therefore lead to full cooperation.

From a fairness perspective, the most harmed countries should get a larger share of the gains. When looking at marginal damages, this favours China and EU, while USA gets the least. In this fifth alternative, the countries responsible for climate change get a smaller share compared to the more innocent China. This is in many ways more fair compared to for instance alternative 2.

In the last alternative the profit is divided in equal shares between the players. This can be reasonable when considering combination of current and historic emissions, size of population and GDP. For these factors, the countries shift between being first, second and third. To allocate one third of the total increase in payoff to each country therefore sounds reasonable.

One matter is to look at different alternatives in a perspective of fairness or what is believed to be reasonable. Another is to look at whether it is possible to implement and stable over time. All of the proposed alternatives are profit sharing methods that are possible to implement. However, they are not attractive solutions if they are not in the core. This turns out to be true for all alternatives. There is one particular problem, and that is to find a profit sharing method that ensures participation from EU. In neither alternative it is individually rational for EU to stay in the grand coalition as they can do better if they break out and free ride.

The reason why it is so difficult to find a solution where EU doesn't want to break out is due to their strong incentives for free riding. The payoff that they will receive from free riding is close to their initial noncooperative grand coalition payoff. Many of the methods above give a larger share of the payoffs to USA or China, which means that it is not individually rational for EU to stay in the grand coalition.

I will therefore suggest one profit sharing method that solves this problem. This method is based on giving all players their minimum payoff that makes it individually rational to stay in the grand coalition and the remaining profits to be shared among the players. This method is not dependent on the Nash equilibrium, only the minimum individual payoffs. The remaining profits can be shared according to any of the methods proposed above. Below, I have used equal shares of the remaining surplus, in the same way as alternative 6.

Profit sharing based on minimum individual payoff and equal share of surplus	**China**	**USA**	**EU**
Minimum payoff	623 337	1 954 400	1 405 492
Remaining profit	9534.21		
Share	33.33 %	33.33 %	33.33 %
Profit allocation	3178	3178	3178
New payoff	626 515	1 957 578	1 408 670

This is a core solution and therefore a possible method that will be stable over time. However, a possible problem is to figure out the exact minimum individual payoffs.

The last scenario, using a 12.5% damage cost and a discount rate of 3% shows that the Nash equilibrium is not the efficient solution. However, the efficient solution is attainable by profit sharing and the only two methods of profit sharing that have proven to be in the core, are the Gamma core and the method using minimum individual payoffs and share the remaining surplus.

3.4 Sensitivity analysis

Many of the parameters used in the model are highly uncertain, especially in the far future. This is true for parameters such as the discount rate, damage coefficient and the growth rate. An analysis of the different parameters and how they affect the results is therefore justified. In addition to this we have seen that China differs from the other countries both when it comes to growth rates and marginal damages. In light of this, it is interesting to examine what the important determinants for China's strategy are. In this section I will address the discount rate, damage coefficient, growth rate and marginal damages in detail.

We have already seen the importance of the discount rate. In scenario 2, where the discount rate equalled 4%, we had two Nash equilibria and an empty core. In scenario 3 the discount rate was reduced to 3% and all other parameters were kept equal. This resulted in one Nash equilibrium and a non-empty core. The future damages are more important when the discount rate is lower and this makes cooperation easier. The opposite is true if we increase the discount rate which makes it harder to reach full participation.

In the model we have assumed the damage coefficient to be 1.5, now we change it to be 2 and 1 and examine how the results change. A damage coefficient larger than 1 tells us that some abatement is a lot better than no abatement at all and that there are diminishing marginal benefit of abatement. While a coefficient equal to 1 suggests that the damage cost function is linear, or in other words, all abatement gives equal benefit. The table below summarizes the results given a damage coefficient of 2.

Period	**2009-2055**	**2056-2075**	**2076-2105**	**2106-**		
World damages in % of GDP	0.0 %	12.5 %	12.5 %	12.5 %		
Damage coefficient	2.00					
Discount rate (k)	3.0 %					
Coalition	**Total payoff**	**V(u)-V(Ø)**	**China**	**USA**	**EU**	
V(CH, US, EU)	3 992 764	191 432	631 358	1 953 499	1 407 907	Efficient solution
V(CH, EU)	3 987 775	186 443	627 571	1 960 483	1 399 721	Nash equilibrium
V(CH, US)	3 987 764	186 432	628 362	1 947 746	1 411 656	Nash equilibrium
V(US, EU)	3 954 340	153 008	627 627	1 937 260	1 389 453	
V(CH)	3 948 585	147 253	617 843	1 941 834	1 388 908	
V(US)	3 898 120	96 788	614 533	1 912 215	1 371 371	
V(EU)	3 891 742	90 411	612 467	1 922 578	1 356 698	
V(Ø)	3 801 332	0	592 641	1 884 637	1 324 054	

Comparing this table with the one from scenario 3, where the damage coefficient is 1.5, we get two Nash equilibria instead of one. However, the two Nash equilibria are as before not the efficient solution. The Nash equilibrium is found using the same method as before. In addition to this, EU no longer maximizes their individual payoff in the grand coalition, but they want to free ride while the two remaining countries abate. The benefit of some abatement, increase with the higher damage coefficient.

Reducing the damage coefficient to 1, gives the following results:

Period	**2009-2055**	**2056-2075**	**2076-2105**	**2106-**		
World damages in % of GDP	0.0 %	12.5 %	12.5 %	12.5 %		
Damage coefficient	1.00					
Discount rate (k)	3.0 %					
Coalition	**Total payoff**	**V(u)-V(Ø)**	**China**	**USA**	**EU**	
V(CH, US, EU)	3 992 764	191 432	631 358	1 953 499	1 407 907	Nash equilibrium
V(CH, US)	3 945 059	143 727	619 947	1 931 652	1 393 460	
V(CH, EU)	3 941 875	140 544	618 518	1 943 202	1 380 155	
V(US, EU)	3 899 925	98 594	616 891	1 916 781	1 366 253	
V(CH)	3 894 170	92 839	607 107	1 921 355	1 365 708	
V(US)	3 852 220	50 888	605 480	1 894 934	1 351 806	
V(EU)	3 849 037	47 705	604 052	1 906 484	1 338 501	
V(Ø)	3 801 332	0	592 641	1 884 637	1 324 054	

The Nash equilibrium is achieved by the grand coalition and this is also the efficient solution. Consequently, a lower coefficient makes it easier to ensure full participation. When abatement is only a fraction of full abatement, the damages are higher when the damage coefficient is low. A high damage coefficient makes it more difficult to reach full cooperation, while the opposite is true for a low coefficient.

Another important parameter is the different countries’ growth rates. I have used estimates from Nordhaus, but large uncertainties are attached to these numbers as they are so far into the future. To examine how the growth rate affects the results I have reduced all the countries growth rates to half.

Growth rate						
Period	**2009-2055**	**2056-2075**	**2076-2105**	**2106-**		
China	1.96 %	0.63 %	0.63 %	0.15 %		
USA	1.02 %	0.54 %	0.54 %	0.15 %		
EU	0.93 %	0.45 %	0.45 %	0.15 %		
Global warming impacts						
Period	**2009-2055**	**2056-2075**	**2076-2105**	**2106-**		
World damages in % of GDP	0.0 %	12.5 %	12.5 %	12.5 %		
Damage coefficient	1.50					
Discount rate (k)	3.0 %					
Coalition	**Total payoff**	**V(u)-V(Ø)**	**China**	**USA**	**EU**	
V(CH, US, EU)	2 700 782	81 025	293 781	1 390 917	1 016 084	Efficient solution
V(CH, EU)	2 690 586	70 829	289 824	1 393 256	1 007 506	Nash equilibrium
V(CH, US)	2 689 336	69 579	290 104	1 383 810	1 015 422	
V(US, EU)	2 683 887	64 130	292 271	1 383 679	1 007 938	
V(CH)	2 663 030	43 273	282 987	1 380 048	999 995	
V(EU)	2 657 414	37 658	285 118	1 379 860	992 436	
V(US)	2 656 748	36 991	285 515	1 370 632	1 000 602	
V(Ø)	2 619 757	0	276 299	1 362 828	980 629	

The results are little affected by the change in growth rates. The Nash equilibrium is the coalition of China and EU and the efficient solution is the grand coalition. It is worth noticing that the Nash equilibrium is second best alternative measures in total payoffs, compared to third from before.

The small differences suggest that the change in growth path has little impacts on the results. However, it may be interesting to examine what happens if we change the relative growth instead. Take for instance China, they have a dominant strategy which is different compared to the other two. China's parameters also differ from the other two, they have a higher growth path and a larger share of marginal damages. In the first scenario, China's growth path is equal to USA's growth path. The results are summarized below:

China						
Period	**2009-2055**	**2056-2075**	**2076-2105**	**2106-**		
Growth of net national income	2.04 %	1.08 %	1.08 %	0.29 %		
Period	**2009-2055**	**2056-2075**	**2076-2105**	**2106-**		
World damages in % of GDP	0.0 %	12.5 %	12.5 %	12.5 %		
Damage coefficient	1.50					
Discount rate (k)	3.0 %					
Coalition	**Total payoff**	**V(u)-V(Ø)**	**China**	**USA**	**EU**	
V(CH, US, EU)	3 684 587	136 262	323 181	1 953 499	1 407 907	Nash equilibrium
V(US, EU)	3 667 118	118 793	321 692	1 946 005	1 399 421	
V(CH, US)	3 660 297	111 972	316 391	1 940 472	1 403 434	
V(CH, EU)	3 657 688	109 363	315 078	1 952 235	1 390 375	
V(US)	3 621 234	72 909	310 651	1 924 839	1 385 744	
V(EU)	3 616 734	68 409	308 962	1 935 897	1 371 875	
V(CH)	3 602 214	53 889	302 149	1 927 453	1 372 611	
V(Ø)	3 548 325	0	293 487	1 906 239	1 348 599	

Reducing China's growth path leads to interesting differences. As we can see from the table above, the reduction leads to Nash equilibrium which is the grand coalition and this is also the efficient solution. Now, all of the countries maximize their individual payoffs by cooperating. The second best alternative measured in total payoff is the coalition of USA and EU. The results are very dependent on China's growth rate and this is probably due to the fact that abatement is calculated as a share of GDP. A lower growth in GDP leads to a reduction in abatement and this also reduces China's importance for total world abatement. This can also be seen from the changes in the net present value of abatement in the grand coalition which is summarized in the following table:

	China	**China (low growth)**	**USA**	**EU**
NPV abatement	6944	3513	5699	5356

China's net present value (NPV) of abatement has been reduced from $ 6994 billion to $ 3513 billion. The relative change means that China has moved from being the largest to the smallest country in terms of abatement. And this also suggests why the coalition of USA and EU now is a better alternative than any of the two-country coalitions including China.

China's marginal damages also differs from USA and EU. To look at the marginal damages' impact on the results, the shares of damages are now changed to being equal for all countries. This provides the following results:

Share of damages						
China's share of damages	33.33 %					
US' share of damages	33.33 %					
EU's share of damages	33.33 %					
Sum	100 %					
Global warming impacts						
Period	**2009-2055**	**2056-2075**	**2076-2105**	**2106-**		
World damages in % of GDP	0.0 %	12.5 %	12.5 %	12.5 %		
Damage coefficient	1.50					
Discount rate (k)	3 %					
Coalition	**Total payoff**	**V(u)-V(Ø)**	**China**	**USA**	**EU**	
V(CH, US, EU)	3 992 764	208 634	631 358	1 953 499	1 407 907	Nash equilibrium
V(CH, US)	3 970 969	186 839	626 636	1 938 926	1 405 407	
V(CH, EU)	3 968 861	184 731	625 724	1 950 404	1 392 733	
V(US, EU)	3 927 556	143 426	625 804	1 921 755	1 379 998	
V(CH)	3 918 145	134 015	616 733	1 922 684	1 378 729	
V(US)	3 866 991	82 861	615 353	1 889 572	1 362 066	
V(EU)	3 861 138	77 007	613 881	1 899 367	1 347 889	
V(Ø)	3 784 130	0	601 005	1 859 706	1 323 420	

The Nash equilibrium is also here the grand coalition and it is the efficient solution. China's strong incentive to invest in abatement is reduced because their marginal damages are lower. The opposite is true for USA, where the marginal damage has increased. They therefore have a stronger incentive to abate and the grand coalition is easier to obtain.

Another aspect worth mentioning is the relative improvements compared to the business as usual scenarios. In the table below the efficient solution and the Nash equilibrium from each scenario is compared to the business as usual results.

Scenario	**Efficient solution**	**Relative improvement compared to business as usual**	**Nash equilibrium**	**Relative improvement compared to business as usual**
Scenario 1	V(CH, EU)	0.89 %	V(CH)	0.76 %
Scenario 2	V(CH, US, EU)	3.09 %	V(CH, EU)	2.85 %
Scenario 3	V(CH, US, EU)	5.04 %	V(CH, EU)	4.48 %

From the first scenario we see that the gains are less than 1% compared to business as usual. The difference between the Nash equilibrium and the efficient solution is also marginal. Increasing the damages leads to a larger difference between business as usual and the Nash equilibrium and the efficient solution. From scenario 2 the payoffs increase by 2.85% in the Nash equilibrium and 3.09% in the efficient solution. The difference between the Nash equilibrium and the efficient solution is small. This is perhaps why it is difficult to reach the efficient solution for this scenario. In the last scenario the Nash equilibrium is an improvement of 4.48% and the efficient solution 5.04% compared to business as usual. The difference between the two is now more than 0.5%. This is a significant improvement. It also supports the results from the profit sharing where it was shown that full cooperation is possible.

The choice of parameters significantly affects the results. Both the damage coefficient, relative changes in growth rates and shares of marginal damages gives very different results compared to the scenarios discussed earlier. From the differences between scenario 2 and 3 it was clear that the choice of discount rate also is important for the results. A high discount rate means that future damages are less important for the net present value. This makes cooperation more difficult. Changing the growth rate equally for all countries will not affect the results significantly. Considering the different parameter’s impact on the results it is important to be critical to how they are used.

3.5 Discussion

We have now looked at the model and results according to different scenarios. In the first scenario the damages were low. This led to a Nash equilibrium where China abated alone. The efficient solution is the coalition between China and EU. This coalition, however, is quite unrealistic since it involves the free rider, USA, to pay EU to be a part of the coalition.

In the second scenario, the damages were increased. Now we had two Nash equilibria, the coalitions of China and USA and China and EU. Using the theory of focal points, the coalition of China and EU is viewed to be the most realistic solution, based on marginal damages. However, the efficient solution, in this case the grand coalition, proved to have an empty core. Reaching full participation will therefore be very difficult and must be supported by other means than economic perspectives alone.

In the third scenario the damages remained high, but the discount rate was lowered. The Nash equilibrium now consisted of the coalition between China and EU. The grand coalition is the efficient solution and the core is nonempty. Evaluating different methods of profit sharing proved few of them to be in the core. Two methods were proposed that were in the core, the Gamma core and the individual payoffs with sharing the remaining profits.

The results are quite clear when it comes to China's role, they prefer to abate, preferably in a coalition with one or two other players. EU wants to abate if the level of damages is high enough or the rate of discount is low enough. The player with largest incentives to free ride is USA, who in most cases wants to act alone and not be a part of any coalition. However, if we use a low discount rate and high damage costs they can be interested in participating if they receive a large share of the total profits. In this section, I will turn to a discussion of these results and how they fit with what we observe in the real world.

In the aftermath of the Copenhagen Accord, China, USA and EU submitted their targets for carbon emission reductions. These are summarized in the following table:

Country	**Emission reduction in 2020**	**Base year**
China	Lower its carbon dioxide emissions per unit of GDP by 40-45%	2005
USA	In the range of 17%, in conformity with anticipated U.S. energy and climate legislation, recognizing that the final target will be reported to the Secretariat in light of enacted legislation.	2005
EU	20/30%	1990

Source: UNFCCC.

China announced that they will reduce their carbon intensity by 40-45% compared to 2005. According to Bryony Worthington, director of Sandbag, a campaigning organisation focused on emissions trading, this “actually only amounts to a cut of between zero and 12% off business as usual emissions in 2020 (…). That is roughly a 40% increase in CO2 emissions on current levels” (The Guardian, 26.11.09). Even if the target sounds quite promising, the reductions are dismal due to large economic growth. The growth rate in GDP, which is expected to be substantially higher than the 3.9% used in the model above for the years until 2020, makes it easy to meet the carbon intensity goal as long as the growth comes without large increase in emissions.

According to Climate Action Tracker the emission reduction targets introduced by China are inadequate to keep the global temperature rise to 2°C. Climate Action Tracker is a cooperation between Ecofys, Climate Analytics and Postdam Institute for Climate Impact Research and it is led by Dr. Niklas Höhne, one of the lead scientists at the IPCC. Climate Action Tracker has evaluated all countries participating in the Copenhagen Accord and their emission reduction targets, including China. In addition to the carbon intensity target, China has stated that they will increase the share of renewable energy consumption to 15%. According to Climate Action Tracker this does not include the “15% non-fossil fuel target by 2020 due to lack of information. Its inclusion could improve the rating”. The increased demand for renewable energy has spurred China to invest in renewables. And as The Economist explains it, this gives positive results, “[h]ydropower will expand by more than half (…). Wind power will see a big expansion, (…) as will nuclear (…). The rest will come from such niches as solar panels and incinerators” (29.04.2010).

China has been accused of being more concerned of economic growth than the environment. This may be a reasonable concern if they believe that becoming richer may lead to a lower marginal damage due to shifts in the industry. As mentioned above, when a country becomes richer, more people will be working in sectors that are less dependent on the climate. This is not reflected in the model above since the marginal damages are constant over time. In line with China's concern for their economic growth, they were accused of stalling the negotiations in Copenhagen 2009, or as Mark Lynas, an environmentalist and climate change author present during the final negotiations, argues "China wrecked the talks" (The Guardian, 22.12.2009). By postponing an international environmental agreement China can continue to grow its economy based on using coal.

The United States has announced that they will reduce their carbon emissions by 17% by 2020 based on 2005 level. However, this target is conditional on approval from the House of Representatives and the Senate. A climate bill that may lead to the necessary reductions to meet the 17% target was passed in the House of Representatives in June 2009. A similar bill is pending in the Senate but to the Economist (13.05.2010) one of the writers of the bill, "Mr Graham says [that] the bill does not have the votes". In other words, it seems difficult for USA to implement the necessary legislation to carry through significant emission reductions. The Climate Action Tracker rates USA's efforts as inadequate.

EU, on the other hand, has announced a target to reduce their emissions with 20% by 2020 based on 1990 level. In their application to be associated with the Copenhagen Accord, they have also said that they will increase their cuts to 30% "provided that other developed countries commit themselves to comparable emission reductions and that developing countries contribute adequately according to their responsibilities and respective capabilities" (2010). To implement the necessary cuts EU has among other measures introduced a cap and trade system for CO2 emissions. EU is often claimed to be one of the leading nations of significant size battling climate change.

But is the EU target really as ambitious as it might sound? The actual EU cuts compared to USA are, according to Worthington: "Europe – minus 11.7%; US – minus 17.3%" (The Guardian, 26.11.2009) compared to the 2007 emission levels. And if EU increase their emission reductions to 30% compared to the 1990 level this equals a "22% cut on 2007" (The Guardian, 26.11.2009). EU has not chosen 1990 as their base year without reason. In the beginning of the 1990s, the emissions decreased significantly in the Former Soviet Union due to lower activity. Many of these countries are today members of EU and their emissions figures are included in the total emission figures for EU. EU therefore have a base year with high emissions, which then dropped significantly in the early 1990s, making it easier to meet the proposed emission target. This is also reflected in the Climate Action Tracker's evaluation of EU's 20% emission reductions target which is rated inadequate. Also, the Climate Action Tracker argues that "if [EU] were to adopt the conditional commitment of -30%, it would reach the Medium category".

At the moment, it seems like none of the three countries, China, USA and EU, are doing what the IPCC believe is necessary. This may be due to three factors. Firstly, the countries may have concluded that the possible damages are small compared to the benefits and that they therefore find it difficult to implement strong measures. Second, there are other factors more important than economics that are being considered, for instance politics, trade and fairness. Third, the incentives to free ride are large, making it difficult to agree on any treaty that leads to higher participation and increased emission reductions.

The three arguments above may be the explanation to why we experience small carbon reductions and little willingness for cooperation. However, I believe it is worth mentioning that China's announced emission reductions target is only until 2020. What they will do after this period is still uncertain. At the moment, this target implies that China is not willing to do any large emission reductions that may affect their economic growth. At the same time, the Chinese renewable energy sector is booming and this may be helpful in the future. A large renewable sector may help China to a position where large cuts are more easily implemented. It can therefore not be excluded that China will do substantial emission reductions in the future.

4. Conclusion

In analysing the question of how the world would handle global warming if the world only consisted of China, USA and EU, there are some factors standing out. First, the choice of parameters is very important for what results we will have. Second, the model predicts that China will abate no matter what, that EU will be the second country to join the coalition and that USA will have to be paid to participate in the coalition. Is this reflected in what we see in today's real world? And third, can this simplified model be used to explain the behaviour of the three countries in a much more complex real world and are the results really significant?

The two most important parameters are the damage costs and the discount rate. The level of damage costs is highly uncertain. No one really knows for sure how large the damages will be, when they will occur or who will be the most affected. We have models that indicate the damage costs, such as the IPCC's models or Nordhaus' RICE-model, but also in these models there are high uncertainties as it is difficult to predict the damages 100 to 200 years from now.

By changing the discount rate from 4% to 3%, the core became non-empty and the efficient solution proved to be reachable. Considering the discount rate's impact on the results, it is important to be critical to what discount rate is used in various models, as illustrated in the scenarios.

Today, there are little or no signals from China that they will abate no matter what. They have been accused of stalling the climate negotiations. Furthermore, they have committed themselves to reduce their carbon intensity, which does not necessarily mean any emission reductions. Meanwhile, China plans to increase their share of renewable energy consumption. This may be motivated by other means than carbon emissions, but it may also make it easier for China to make substantial emission reductions in the future.

The model implies that EU will join China in a coalition and invest in abatement if the damages are high enough. EU definitely has some momentum in their climate policies, but their 20% target falls short of what the IPCC believes is needed. However, they already have some of the necessary measures in place, such as the European Trading Scheme (ETS) for carbon trading, and if they implement their 30% target this is very positive.

USA has signalled that they want to implement substantial emission reductions, but they are facing problems in getting the necessary legislation in place. Until this is obtained, there is no reason to believe that they will succeed in achieving significant emission reductions. This is in line with what the model predicts. Even though there are few signs that China and EU are willing to pay USA to be a part of a coalition, this does not mean that the solution is impossible. The results from the high damage and low discount rate scenario are therefore interesting to consider.

The model presented in this paper is a simplification of the real world based on many assumptions. The results must therefore be critically viewed and used with necessary caution. However, the model gives a clear indication about the issues the global society is facing when addressing global warming and possible solutions. This is shown by how the results may change according to different choices of scenarios and parameters.

If believing that the damages from global warming will be low, for instance equal to a reduction in consumption of 5% from 2056, this will not lead to any motivation for cooperation. In such a case, the differences in total payoffs between business as usual, the Nash equilibrium and the efficient solution are very small and probably not worth the effort. On the other hand, if the damages are believed to be large, the gains from cooperation will be significant and a coalition of two or three countries will be much easier to obtain.

In my opinion, the model gives valuable insight. Though, the international negotiations so far have not achieved much, the policy makers’ opinions may change quickly if we get a more certain picture of the possible damages. I therefore believe the model can explain some of both the current and possible future behaviour. In the coming decade, it will be especially interesting to see how the expected damages develop and observe the impact this may have on cooperation.

5. Appendix

5.1 Appendix 1

The payoff to country *i* is the net present value of the net consumption and it is calculated as follows:

$$\prod_i = \sum_{t=1}^{T} \left(\frac{C_i^t}{(1+k)^t}\right) + \frac{1}{(1+k)^T} \cdot \frac{C_i^T}{k - g_i^T}$$

Total world payoff is equal to the sum of all countries' payoff, calculated as follows:

$$\prod_w = \sum_{i=1}^{I} \prod_i$$

Where:

$D_w^t = a^t GDP_w^t \cdot \left(\frac{u^t GDP_w^{t-1} - \sum_{i=1}^{I} q_i^{t-1}}{u^t GDP_w^{t-1}} \right)^{\alpha}$	- Total world damages in period t
$I_i^t = r_i^t GDP_i^t$	- Capital investments by country in period t
$C_i^t = \frac{GDP_i^t - I_i^t - q_i^t - s_i D_w^t}{P_i^t}$	- Net consumption per capita in country i in period t
$GDP_i^t = GDP_i^{t-1}(1 + g_i^t)$	- GDP in country *i* in period t
GDP_i^{t-1}	- GDP in country *i* in period t-1
$GDP_w^t = \sum_{i=1}^{I} GDP_i^t$	- GDP of the world in period t, equal to the sum of all countries' GDP in period t
$P_i^t = v_i^t P_i^{t-1}$	- Population in country *i* in period t
g_i^t	- Growth rate in country *i* in period t
q_i^t	- Country *i*'s investment in abatement in period t.
s_i	- Country *i*'s share of world damages
a^t	- Rate of damages in period t

u^t	- Rate of necessary investment
k	- Discount rate
r_i^t	- Savings rate in country *i* in period t
α	- Damage coefficient
v_i^t	- Population growth rate in country *i* in period t

5.2 Appendix 2

Non-cooperative grand coalition	**China**	**USA**	**EU**
V(CH, US, EU)	631 358	1 953 499	1 407 907
Coalition	**Constraints**	**Payoff here**	**Stability? (1=Yes, 0=No**
V(CH, US, EU)	3 992 764	3 992 764	**1**
V(CH, US)	2 567 803	2 584 856	**1**
V(CH, EU)	2 017 219	2 039 265	**1**
V(US, EU)	3 309 267	3 361 406	**1**
V(CH)	613 255	631 358	**1**
V(US)	1 904 328	1 953 499	**1**
V(EU)	1 348 291	1 407 907	**1**
Payoff breaking out(CH)	623 337	631 358	**1**
Payoff breaking out(US)	1 954 400	1 953 499	**0**
Payoff breaking out(EU)	1 405 492	1 407 907	**1**
Payoff breaking out(US, EU)	3 312 071	3 361 406	**1**
Payoff breaking out(CH, EU)	1 972 842	2 039 265	**1**
Payoff breaking out(CH, US)	2 523 723	2 584 856	**1**
Sum			**Non-core solution**

The first part of the table describes the payoff received by each country. Here China receives $ 631 358 billion, USA $ 1 953 499 billion and EU $ 1 407 907 billion. In the next part of the table the different constraints that must be fulfilled for the solution to be in the core are summarized. These summarize the collective, coalitional and individual rationality. If the constraint is fulfilled, or in other words, payoff here is larger than the constraint, the solution is stable (marked 1). If the constraint is not fulfilled the solution is unstable (marked 0) and it is a non-core solution. All constraints must be fulfilled for the solution to be in the core. This is the same for all of the following tables.

Profit sharing based on the Shapley value	China	USA	EU
Shapley value	94 006	50 421	47 005
New payoff	686647	1935058	1371059
Coalition	**Constraints**	**Payoff here**	**Stability? (1=Yes, 0=No**
V(CH, US, EU)	3 992 764	3 992 764	**1**
V(CH, US)	2 567 803	2 621 705	**1**
V(CH, EU)	2 017 219	2 057 706	**1**
V(US, EU)	3 309 267	3 306 117	**0**
V(CH)	613 255	686 647	**1**
V(US)	1 904 328	1 935 058	**1**
V(EU)	1 348 291	1 371 059	**1**
Payoff breaking out(CH)	623 337	686 647	**1**
Payoff breaking out(US)	1 954 400	1 935 058	**0**
Payoff breaking out(EU)	1 405 492	1 371 059	**0**
Payoff breaking out(US, EU)	3 312 071	3 306 117	**0**
Payoff breaking out(CH, EU)	1 972 842	2 057 706	**1**
Payoff breaking out(CH, US)	2 523 723	2 621 705	**1**
Sum			**Non-core solution**

Profit sharing based on Gamma core	**China**	**USA**	**EU**
Money transfer	2 351	4 238	1 887
New payoff	**629 006**	**1 957 737**	**1 406 021**
Coalition	**Constraints**	**Payoff here**	**Stability? (1=Yes, 0=No**
V(CH, US, EU)	3 992 764	3 992 764	**1**
V(CH, US)	2 567 803	2 586 743	**1**
V(CH, EU)	2 017 219	2 035 027	**1**
V(US, EU)	3 309 267	3 363 757	**1**
V(CH)	613 255	629 006	**1**
V(US)	1 904 328	1 957 737	**1**
V(EU)	1 348 291	1 406 021	**1**
Payoff breaking out(CH)	623 337	629 006	**1**
Payoff breaking out(US)	1 954 400	1 957 737	**1**
Payoff breaking out(EU)	1 405 492	1 406 021	**1**
Payoff breaking out(US, EU)	3 312 071	3 363 757	**1**
Payoff breaking out(CH, EU)	1 972 842	2 035 027	**1**
Payoff breaking out(CH, US)	2 523 723	2 586 743	**1**
Sum			**Core solution**

Profit sharing based on marginal contribution	**China**	**US**	**EU**
Marginal contribution	0	21 144	0
New payoff	624385	1975544	1392835
Coalition	**Constraints**	**Payoff here**	**Stability? (1=Yes, 0=No**
V(CH, US, EU)	3 992 764	3 992 764	**1**
V(CH, US)	2 567 803	2 599 929	**1**
V(CH, EU)	2 017 219	2 017 219	**1**
V(US, EU)	3 309 267	3 368 379	**1**
V(CH)	613 255	624 385	**1**
V(US)	1 904 328	1 975 544	**1**
V(EU)	1 348 291	1 392 835	**1**
Payoff breaking out(CH)	623 337	624 385	**1**
Payoff breaking out(US)	1 954 400	1 975 544	**1**
Payoff breaking out(EU)	1 405 492	1 392 835	**0**
Payoff breaking out(US, EU)	3 312 071	3 368 379	**1**
Payoff breaking out(CH, EU)	1 972 842	2 017 219	**1**
Payoff breaking out(CH, US)	2 523 723	2 599 929	**1**
Sum			**Non-core solution**

Profit sharing based on current emissions	**China**	**USA**	**EU**
Emissions	6103493	5752289	3914359
Share of total	38,70 %	36,48 %	24,82 %
Profit allocation	8183	7713	5248
New payoff	**632 568**	**1 962 113**	**1 398 083**
Coalition	**Constraints**	**Payoff here**	**Stability? (1=Yes, 0=No**
V(CH, US, EU)	3 992 764	3 992 764	**1**
V(CH, US)	2 567 803	2 594 681	**1**
V(CH, EU)	2 017 219	2 030 651	**1**
V(US, EU)	3 309 267	3 360 196	**1**
V(CH)	613 255	632 568	**1**
V(US)	1 904 328	1 962 113	**1**
V(EU)	1 348 291	1 398 083	**1**
Payoff breaking out(CH)	623 337	632 568	**1**
Payoff breaking out(US)	1 954 400	1 962 113	**1**
Payoff breaking out(EU)	1 405 492	1 398 083	**0**
Payoff breaking out(US, EU)	3 312 071	3 360 196	**1**
Payoff breaking out(CH, EU)	1 972 842	2 030 651	**1**
Payoff breaking out(CH, US)	2 523 723	2 594 681	**1**
Sum			**Non-core solution**

Profit sharing based on historic cumulative emissions	**China**	**USA**	**EU**
Share of cumulative emissions	12,0 %	46,2 %	41,8 %
Profit allocation	2535	9772	8838
New payoff	**626 919**	**1 964 172**	**1 401 673**
Coalition	**Constraints**	**Payoff here**	**Stability? (1=Yes, 0=No**
V(CH, US, EU)	3 992 764	3 992 764	**1**
V(CH, US)	2 567 803	2 591 091	**1**
V(CH, EU)	2 017 219	2 028 592	**1**
V(US, EU)	3 309 267	3 365 845	**1**
V(CH)	613 255	626 919	**1**
V(US)	1 904 328	1 964 172	**1**
V(EU)	1 348 291	1 401 673	**1**
Payoff breaking out(CH)	623 337	626 919	**1**
Payoff breaking out(US)	1 954 400	1 964 172	**1**
Payoff breaking out(EU)	1 405 492	1 401 673	**0**
Payoff breaking out(US, EU)	3 312 071	3 365 845	**1**
Payoff breaking out(CH, EU)	1 972 842	2 028 592	**1**
Payoff breaking out(CH, US)	2 523 723	2 591 091	**1**
Sum			**Non-core solution**

Profit sharing based on population	**China**	**USA**	**EU**
Population (millions)	1338,6	307,2	491,6
Share of total	62,63 %	14,37 %	23,00 %
Profit allocation	13242	3039	4863
New payoff	**637 627**	**1 957 439**	**1 397 698**
Coalition	**Constraints**	**Payoff here**	**Stability? (1=Yes, 0=No**
V(CH, US, EU)	3 992 764	3 992 764	**1**
V(CH, US)	2 567 803	2 595 066	**1**
V(CH, EU)	2 017 219	2 035 325	**1**
V(US, EU)	3 309 267	3 355 137	**1**
V(CH)	613 255	637 627	**1**
V(US)	1 904 328	1 957 439	**1**
V(EU)	1 348 291	1 397 698	**1**
Payoff breaking out(CH)	623 337	637 627	**1**
Payoff breaking out(US)	1 954 400	1 957 439	**1**
Payoff breaking out(EU)	1 405 492	1 397 698	**0**
Payoff breaking out(US, EU)	3 312 071	3 355 137	**1**
Payoff breaking out(CH, EU)	1 972 842	2 035 325	**1**
Payoff breaking out(CH, US)	2 523 723	2 595 066	**1**
Sum			**Non-core solution**

Profit sharing based on GDP	**China**	**USA**	**EU**
GDP	8791	14260	14510
Share of total	23,40 %	37,96 %	38,63 %
Profit allocation	4949	8027	8168
New payoff	**629 333**	**1 962 427**	**1 401 003**
Coalition	**Constraints**	**Payoff here**	**Stability? (1=Yes, 0=No**
V(CH, US, EU)	3 992 764	3 992 764	**1**
V(CH, US)	2 567 803	2 591 761	**1**
V(CH, EU)	2 017 219	2 030 336	**1**
V(US, EU)	3 309 267	3 363 430	**1**
V(CH)	613 255	629 333	**1**
V(US)	1 904 328	1 962 427	**1**
V(EU)	1 348 291	1 401 003	**1**
Payoff breaking out(CH)	623 337	629 333	**1**
Payoff breaking out(US)	1 954 400	1 962 427	**1**
Payoff breaking out(EU)	1 405 492	1 401 003	**0**
Payoff breaking out(US, EU)	3 312 071	3 363 430	**1**
Payoff breaking out(CH, EU)	1 972 842	2 030 336	**1**
Payoff breaking out(CH, US)	2 523 723	2 591 761	**1**
Sum			**Non-core solution**

Profit sharing based on marginal damages	**China**	**USA**	**EU**
Marginal damage	24,30	15,10	19,50
Share of total	41,26 %	25,64 %	33,11 %
Profit allocation	8723	5421	7000
New payoff	**633 108**	**1 959 821**	**1 399 835**
Coalition	**Constraints**	**Payoff here**	**Stability? (1=Yes, 0=No**
V(CH, US, EU)	3 992 764	3 992 764	**1**
V(CH, US)	2 567 803	2 592 929	**1**
V(CH, EU)	2 017 219	2 032 943	**1**
V(US, EU)	3 309 267	3 359 656	**1**
V(CH)	613 255	633 108	**1**
V(US)	1 904 328	1 959 821	**1**
V(EU)	1 348 291	1 399 835	**1**
Payoff breaking out(CH)	623 337	633 108	**1**
Payoff breaking out(US)	1 954 400	1 959 821	**1**
Payoff breaking out(EU)	1 405 492	1 399 835	**0**
Payoff breaking out(US, EU)	3 312 071	3 359 656	**1**
Payoff breaking out(CH, EU)	1 972 842	2 032 943	**1**
Payoff breaking out(CH, US)	2 523 723	2 592 929	**1**
Sum			**Non-core solution**

Profit sharing based on equal shares	**China**	**USA**	**EU**
Share of total	33,33 %	33,33 %	33,33 %
Profit allocation	7048	7048	7048
New payoff	**631 433**	**1 961 448**	**1 399 883**
Coalition	**Constraints**	**Payoff here**	**Stability? (1=Yes, 0=No**
V(CH, US, EU)	3 992 764	3 992 764	**1**
V(CH, US)	2 567 803	2 592 881	**1**
V(CH, EU)	2 017 219	2 031 316	**1**
V(US, EU)	3 309 267	3 361 331	**1**
V(CH)	613 255	631 433	**1**
V(US)	1 904 328	1 961 448	**1**
V(EU)	1 348 291	1 399 883	**1**
Payoff breaking out(CH)	623 337	631 433	**1**
Payoff breaking out(US)	1 954 400	1 961 448	**1**
Payoff breaking out(EU)	1 405 492	1 399 883	**0**
Payoff breaking out(US, EU)	3 312 071	3 361 331	**1**
Payoff breaking out(CH, EU)	1 972 842	2 031 316	**1**
Payoff breaking out(CH, US)	2 523 723	2 592 881	**1**
Sum			**Non-core solution**

Profit sharing based on minimum individual payoff and equal share of surplus	**China**	**USA**	**EU**
Minimum payoff	623 337	1 954 400	1 405 492
Remaining profit	9534,21		
Share	33,33 %	33,33 %	33,33 %
Profit allocation	3178	3178	3178
New payoff	**626 515**	**1 957 578**	**1 408 670**
Coalition	**Constraints**	**Payoff here**	**Stability? (1=Yes, 0=No**
V(CH, US, EU)	3 992 764	3 992 764	**1**
V(CH, US)	2 567 803	2 584 093	**1**
V(CH, EU)	2 017 219	2 035 186	**1**
V(US, EU)	3 309 267	3 366 248	**1**
V(CH)	613 255	626 515	**1**
V(US)	1 904 328	1 957 578	**1**
V(EU)	1 348 291	1 408 670	**1**
Payoff breaking out(CH)	623 337	626 515	**1**
Payoff breaking out(US)	1 954 400	1 957 578	**1**
Payoff breaking out(EU)	1 405 492	1 408 670	**1**
Payoff breaking out(US, EU)	3 312 071	3 366 248	**1**
Payoff breaking out(CH, EU)	1 972 842	2 035 186	**1**
Payoff breaking out(CH, US)	2 523 723	2 584 093	**1**
Sum			**Core solution**

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