# Diplomarbeit

Titel der Diplomarbeit

„Self Enforcing International Environmental Agreements (IEAs)“

Verfasser

Matthias Johannes Gruber

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| Betreuerin: | ao. Prof. Dr. Ana Begoña Ania Martínez |

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# Chapter 1

# General Issues

## 1.1 Introduction

After more than thirty years of fruitless discussions and denial, the topic of Global warming is on the global agenda nowadays. This year in spring, G8 leaders agreed on a reduction target of 20 per cent of their $CO_2$ emissions and in late autumn a United Nations conference in Bali shall find a way towards a follow up treaty to the Kyoto Protocol.
Generally the world climate is affected by many factors, but the biggest wedge is due to emission of so called greenhouse gases (GHGs). These are permeable for sunbeams on the one side and they avert that the heat is released from the atmosphere on the other side. As a result the world acts like a greenhouse, which gives the effect its snappy name. The problems that come along with global warming are manifold and the precise dimension of the damages to be feared are not yet clear. However it is common sense that these damages are going to be substantial and are basically caused by human behavior. Here is a short overview to the upcoming threats[1].

[1] Gabriel (2003): pp. 12 et seq.

**Rise of the Sealevel**

Rising sealevels are a result of the expansion of heating water and the melting of the glaciers. Estimates for the rise to be expected vary between 14 and 80 cm, but these are quite imprecise as many things have an effect on the sealevel. A rise is threatening both the habitat of men and animals. Feeding places of birds lie in coastal areas, breeding places of seals on the Greenland ice melt and whole ecological systems in river deltas and lagoons are flooded. On the other hand many countries of the world are in low lying areas, some even below sealevel. Bangladesh and the Netherlands are the most popular examples but many small groups of islands, that were on the news after the tsunami catastrophe in 2004, could simply disappear from earth's surface. The cost of coastal protection and lost land area are enormous and can be borne by economically developed countries but probably not by lesser developed states[2].

**Shifting of the Climate**

The increasing temperature changes the air humidity and hence the rainfall frequency. The question arises whether the ecosystems can adapt at the same speed. Generally, one assumes that the vegetation zones shift to the north. While Mid- and Northern Europe might even profit from global warming, other regions such as Southern Europe and many African states will suffer from a strong increase of droughts[3].

[2] Gabriel (2003): pp. 20-22
There is a lot more literature on the effects of global warming. Barrett (2003) or Nordhaus and Boyer (2000) for instance give an overview. The report, which gathered the most public attention, was published by former World Bank chief economist Nicholas Stern in 2006.

[3] Gabriel (2003): pp. 22-23

### Drinking Water Shortage

Similar to the point above, countries that have troubles with drinking water provision will have even greater problems in the future. This is due to the more widely spread aridity and to the rise of the sealevel. When the seas raise, the groundwater reserves get contaminated by salty water. The results are again manifold. As it was seen in Italy in spring this year, power plants could not operate anymore as the level of many rivers was to low. The biggest problem of course is the supply of the population and of the agriculture with clean drinking water[4].

### Natural Disasters

Extreme weather events, like hurricanes or aridity, occur more and more often. Thereby they do even bigger harm, caused by floods or droughts for instance[5].

The points mentioned above describe causes and their effects that are going to arrive sooner or later. The motivation to choose the topic of global warming for my thesis was to find out why, despite of all these threats, there were no changes towards a more sustainable world economy. I wanted to know how a framework must be built in order to sustain an ecologically bearable level of worldwide emissions. Therefore I start with describing the regime, that should regulate countries emissions nowadays, namely the Kyoto protocol. My aim is to identify the strengths and weaknesses of the Kyoto system. In the next chapter I list theoretical considerations about international environmental agreements. The problem is, that full cooperation of all states of the world would be desirable, but it does not appear in practice, as there are to many incentives to act unilaterally. To see why this is the case, I chose two models that describe symmetric games with external costs and limited participation. The main difference between those models are the

[4] Gabriel (2003): pp. 23-24

[5] Gabriel (2003): pp. 24-25

number of attending countries and that while the first one uses comparative statics the second one is a dynamic game. In the third chapter I establish a framework in which fully cooperation is possible, and in which the extent of cooperation, i.e. the decrease of GHG emissions, depends on more factors, such as technology or population that differ among the countries. In the last step I look at what happens when technology is improving and population is growing.

## 1.2 Why Kyoto?

A good example, out of the dozens of existing environmental treaties, for a successful international cooperation is the Montreal Agreement of 1989. It was an attempt to regulate the emission of CFC gases to conserve the ozone layer of the earth. Similar to the Kyoto Protocol it embodies exceptions as well as transfers of technology and money for developing countries. The crucial difference is that CFC is not a substantial production factor in the global economy. In contrast almost nothing can be produced or transported without the use of fossil resources[6].

In 1992 the United Nations Conference on Environment and Development (UNCED) took place in Rio de Janeiro. There, the United Nations Framework Convention on Climate Change (UNFCCC) was signed. It was the first time that goals to sustain the environment were binding by international law. A foresight principle was introduced, stating that even if the exact damages can not be evaluated yet, measures are taken to regulate global warming. On the World Climate Summit in Berlin in 1995 the parties agreed on the Berlin Mandate, which opened the door for the amendment protocol for concrete commitment for industrialized nations. These principles were then implemented in the Kyoto Protocol in 1997.[7]

[6]Barrett and Stavins (2003): pp. 365

[7]Barrett and Stavins (2003): pp. 351-353

### 1.2.1 Objectives and Coming into Force

The GHGs whose emission is regulated in the protocol are the following: Carbon-Dioxide ($CO_2$, which acts as a benchmark for the other gases in so called $CO_2$ equivalent metric tons), Methane ($CH_4$), Di-Nitrogen ($N_2O$), Hydroflourocarbons (HFCs), Perfluorocarbons (PFCs) and sulfur hexafluoride ($SF_6$). The industrialized countries, listed in Annex B of the treaty, appointed to reduce their annual emission of $CO_2$ equivalent tons by around five per cent on average in the period from 2008 to 2012 compared to their emissions in 1990. The respective countries have individual guidelines, that depend mainly on their economic standards. The European Union should reduce its emissions by eight per cent, Russia and Ukraine agreed on not exceeding their 1990 values while developing and emerging countries such as China have no binding goals to achieve.

The protocol should become effective as soon as 55 countries that represent 55 per cent of the world $CO_2$ emissions have ratified it. The number of 55 contracting states was reached rather soon, relative to the other criterion. Because the United States had first signed the treaty, but then did not ratify it, it seemed to have failed. But in 2005 Russia, which is responsible for about 18 per cent of worldwide emissions, agreed on the Kyoto targets and so the protocol finally came into effect. The critical point is, that Russia does not need to reduce its emissions at all. Because most of the Sowiet Union's production facilities broke down after 1990, in fact it could produce 32 per cent higher emissions and would still fulfill its obligations. The same is true for all other former communist countries in Eastern Europe and for Germany who bears (and in this case actually profits) the heritage of the old DDR industries. All in all the abatement supported by the Kyoto Protocol is too modest compared to the optimal results, stated in the literature[8]. This is one of the main points of criticism together with the fact that developing countries need not reduce their emissions at all. As it can be seen in the graph below, even these moderate targets will not be reached by most of the

[8]Nordhaus and Boyer (2000): pp. 152; Dutta and Radner (2005): pp. 11-15

countries, especially in the European Union. For instance, while the European Union agreed on reduction targets of eight per cent, it actually just cut its emissions by 0.6 per cent, Luxembourg agreed on a decrease of -28 but increased its emissions by 0.3 per cent, Denmark and Germany each with -21 per cent have the most ambitious targets, and both did not meet them. The biggest increase was allowed for Spain, Greece and Portugal with +15, +25 and +27 per cent, but in fact they raised their emissions by +49, +26.6 and +41 per cent.

**Table 1. Changes in GHG emissions for Annex I Parties**

| Party | Changes in emissions (%) | | |
|---|---|---|---|
| | 1990–2004 | 1990–2000 | 2000–2004 |
| Australia | 25.1 | 19.2 | 5.0 |
| Austria | 15.7 | 2.9 | 12.4 |
| Belarus | –41.6 | –45.2 | 6.6 |
| Belgium | 1.4 | 1.1 | 0.3 |
| Bulgaria | –49.0 | –51.4 | 5.1 |
| Canada | 26.6 | 21.1 | 4.6 |
| Croatia | –5.4 | –18.8 | 16.5 |
| Czech Republic | –25.0 | –24.0 | –1.4 |
| Denmark | –1.1 | –1.2 | 0.1 |
| Estonia | –51.0 | –54.8 | 8.4 |
| European Community | –0.6 | –2.9 | 2.4 |
| Finland | 14.5 | –1.6 | 16.4 |
| France | –0.8 | –1.0 | 0.2 |
| Germany | –17.2 | –16.6 | –0.7 |
| Greece | 26.6 | 21.2 | 4.5 |
| Hungary | –31.8 | –33.5 | 2.5 |
| Iceland | –5.0 | 8.2 | –12.2 |
| Ireland | 23.1 | 23.6 | –0.4 |
| Italy | 12.1 | 6.7 | 5.0 |
| Japan | 6.5 | 5.8 | 0.7 |
| Latvia | –58.5 | –61.7 | 8.2 |
| Liechtenstein | 18.5 | 11.8 | 6.0 |
| Lithuania | –60.4 | –59.1 | –3.1 |
| Luxembourg | 0.3 | –23.6 | 31.3 |
| Monaco | –3.1 | 8.9 | –11.0 |
| Netherlands | 2.4 | 0.7 | 1.7 |
| New Zealand | 21.3 | 13.6 | 6.8 |
| Norway | 10.3 | 7.4 | 2.7 |
| Poland | –31.2 | –31.6 | 0.5 |
| Portugal | 41.0 | 37.1 | 2.9 |
| Romania | –41.0 | –49.7 | 17.3 |
| Russian Federation | –32.0 | –34.6 | 4.1 |
| Slovakia | –30.4 | –32.7 | 3.3 |
| Slovenia | –0.8 | –6.9 | 6.6 |
| Spain | 49.0 | 33.8 | 11.4 |
| Sweden | –3.5 | –5.5 | 2.1 |
| Switzerland | 0.4 | –2.2 | 2.6 |
| Turkey | 72.6 | 63.9 | 5.3 |
| Ukraine | –55.3 | –57.3 | 4.6 |
| United Kingdom | –14.3 | –13.4 | –1.0 |
| United States | 15.8 | 14.3 | 1.3 |
| **Annex I EIT Parties** | –36.8 | –39.3 | 4.1 |
| **Annex I non-EIT Parties** | 11.0 | 8.8 | 2.0 |
| **All Annex I Parties together** | –3.3 | –5.6 | 2.4 |

Source: Highlights from Greenhouse Gas (GHG) Emissions Data for 1990-2004 for Annex I Parties, UNFCCC 2006

One reason for that might be that the protocol does not include real punishment. A country that exceeds its obligations by one ton emitted GHGs is punished by a reduction of its emission rights in the next period by one ton plus a 30 per cent 'fee'. That means that if for instance Germany emits one ton of $CO_2$ equivalents too much in 2007, its reduction targets for 2008 are automatically reduced by 1.3 tons. But if there is no institution that ensures that the fees are paid, no country has to fear the punishment and it will not work this way[9]. In the later chapters I will further explain the importance of the credibility of punishment in this topic.

### 1.2.2 Flexible Mechanisms

The Kyoto Protocol includes some flexible marked based mechanisms, which shall help the signatory states to achieve their objectives. These mechanisms are voluntary:

- *Emissions Trading*
  The trade with emission entitlements is one of the main instruments of the protocol. The idea is, that emissions are reduced where it can be done in the most cost efficient way. Every Annex B country has a certain annual contingent of emissions. Every country distributes these entitlements to its domestic firms. But the firms get less certificates as they would need without improving their production technologies. So every company can decide if it wants to use cleaner technologies to reach the goal or buy certificates from other firms in order to be able to produce. So firms with lower abatement costs get supported by having emission certificates for sale, while those companies who cannot or are not willing to cut down emissions get punished. This is a market driven way to shift production to more efficient firms.
  The first period of emission trading did not bring the results wanted as too many entitlements where given to the firms. So the price for one

[9] Barrett and Stavins (2003): pp. 352

ton of $CO_2$ was to low to have any effect.

- *Joint Implementation*
  Joint Implementation (JI) stands for cooperative measures of two or more industrialized countries. The reduction resulting from that cooperation can be credited to the emission account of both countries. That makes it possible for countries with relatively high specific costs of emission reduction to follow their obligations by investing in countries that have relatively low abatement costs. For example, in Austria factories are obliged by law to use filtering systems to bind a certain percentage of $CO_2$ and sulfur of its exhausts. In eastern European countries the environmental standards for producers are lower, and hence the introduction of already developed filtering systems is cheaper then inventing new technologies in order to reduce the same amount of emissions in Austria.
  The JI-mechanism was introduced with regard to the Annex B countries in Eastern Europe. Additional to a decrease of $CO_2$ emission, the necessary technological progress for the former soviet countries should be supported.

- *Clean Development Mechanism*
  One speaks of Clean Development Mechanism (CDM), when an industrialized country takes action to reduce GHG emissions in an underdeveloped country. Because the harm done to the climate is independent of the place of emission of the pollutant, every reduction is an improvement to the current state. So on the one hand cost efficient actions give a chance for Annex B nations to achieve their aim and on the other hand it supports the transfer of technology to developing countries.
  Again the reduction of GHG emissions achieved will be credited to both countries.

- *Burden Sharing*
  It is possible for a group of contracting states to fulfill their obligations

together. For example, the European Union committed to cut down its emissions by eight per cent. Inside the union the burdens are allocated totally different. Luxembourg with -28 per cent, Denmark and Germany each with -21 per cent have the most ambitious targets.
The biggest increase was allowed for Spain, Greece and Portugal with +15, +25 and +27 per cent. This is a quite reasonable apportionment, as it refers mainly to the economically capability of the member states.

The other side of the coin is that a cut down on emissions is costly as well. New technologies have to be developed and reduction of energy use goes hand in hand with lower production and thus lower income.
Now that the general problem is defined, I want to turn to more theoretical points of view of the issue.

# Chapter 2

# Games with incomplete Participation

The literature on the subject of environmental agreements, is always concerned with two issues. First of all a country must be willing to participate in a treaty. And once a country has signed an agreement, it has to be clarified that compliance should be the only possible behavior of the signatory state. The problem is, that as soon as a country agreed on an environmental treaty it might be in its interest to produce more GHGs than it is allowed to in order to increase its national welfare. A situation like this can, of course, never be an equilibrium.

In the first section I have a look at the question, what makes an agreement efficient, fair and what possibilities are there to prohibit countries from breaking the rules. Then I present three models that compare fully cooperative outcomes with non cooperative results. The basic structure they use to improve the non cooperative situation is somewhat similar, but the models differ in the number of cooperating states.

The first model concludes that only a small group of countries can form a reasonable agreement, depending on how big the gains from cooperation are. The second model only considers two countries deciding whether to work together or not. The last system I am looking at is the most sophisticated one.

It includes efficient $CO_2$ reduction of all countries of the world and furthermore deals with issues such as population growth and technological progress, what the first two do not at all. What all the models have in common is that they allow for self enforcing mechanisms. So the result of the game is that it is in the own interest of any country to follow the rules.

## 2.1 Basic Considerations

Not participating would be the most obvious way of free riding. When a country decides to sign a contract, it must then be willing to comply the rules even if individual gains from a deviation were possible. This form of free riding has to be monitored by institutions.
Cost effectiveness of the emission reducing mechanisms seems to play an important role for compliance. On the other hand it is impossible to fulfill that demand, without full participation of all countries.
An efficient and cost effective climate treaty could sustain full cooperation of each state. There every country would reduce its emissions to the level where its own marginal abatement costs were equal to the sum of global marginal profits. In contrast to the situation where there is no treaty, every country would be better off or at least not worse off[1]. This might only be possible with transfers of money, technology or tradeable emission entitlements. This transfers might also be necessary in order to make a treaty 'fair' in the sense of richer countries bearing higher burdens than poorer ones. And furthermore, without transfers some countries will only be willing to cut down emissions up to that point, where their own marginal benefit equals its own costs[2].
The authors argue that it is a common mistake in theoretical literature, that participation and compliance are treated as one problem. For Barrett and Stavins it is a separated problem that has to be dealt with jointly. It can be

[1]Barrett and Stavins (2003): pp. 358
[2]see also Barrett and Stavins (2003): pp. 361 - 362

counterproductive if there are countries, who are not part of GHG reducing agreement. As the member countries will have costs to lower emissions, they make themselves worse off in terms of comparative advantages. It follows that countries, that did not sign the treaty, will attract emission intensive production but will carry it out with older and hence more polluting technology. This process is called emission leakage and if it is positive, i.e. that the stock of worldwide emissions grows, cooperation would need to be fully to avoid that.
Barrett and Stavins consider three possibilities of positive incentive setting[3]:

- *Side payment*
  A direct money transfer paid by one or more countries to another. Probably those countries who gain most from a emission reduction support those, who might even have higher cost than profits.

- *Issue linkage*
  A less pleasant word for this is horse trade. One country participates in an agreement and in return in another negotiation issue, it gets special conditions, for instance higher quotas in international trade.

- *Emission entitlements*
  To make a country participate it is granted more emission entitlements. As some countries have higher marginal costs of emission abatement, they will be willing to pay for other countries emission rights. This mechanism is assumed to be the most efficient and acts similar as side payments. Trading therefore promotes participation in the treaty.

And they also list three possibilities of negative incentives to make the parties comply. They argue that the threat of punishment must always be credible. This is very problematic in the case, where the punishing countries harm themselves. So all in all a nation must be better off, after punishing the deviant state. On the other side, a threat must be sufficiently severe.

[3]For more detailed proposals, see also Aldy, Orszag and Stiglitz (2001)

If a member of the treaty does not fear the threat it has low incentives to comply[4]:

- *Reciprocal measures*
  If one country brakes the rules and emits more than it agreed on, the other signatories of the contract will pollute more in return. According to the authors it is less credible that all nations take part in the punishing process, the more parties are involved in the punishment.

- *Financial penalties*
  A treatment could include the possibility of imposing a financial penalty on the deviant. For example, when a country exceeds its quota of emissions, it has to pay a certain amount of money per ton of additional $CO_2$. This alternative is more attractive as none of the cooperating states must sacrifice something in order to punish the non cooperating country. But the problem is, that what is the punishment if the country does not pay the fine? An even higher fine in the next period, that can not be collected won't produce the result we are looking for. And furthermore if the penalty is to high, a country will just decide not to participate at first.

- *Trade restrictions*
  For instance, if a country that does not participate in an emission reducing agreement wants to sell something to a country that participates. It is part of the treaty that in this case the participating country would be allowed to ask for a special tax that represents the marginal abatement costs of, say, one ton of $CO_2$ reduction. The idea is to shift production towards countries who do participate in such a treaty. The weakness of this approach is, that it might conflict with other contracts a country is obliged to. For instance in the WTO such conditions would be seen as discrimination of a member country and conflict with the equal treatment commitment.

[4]Barrett and Stavins (2003): pp. 362

A last possibility to cut down emissions would be to introduce technological standards, such as a catalyst for cars. But these standards tend to result only in short term reductions and not in abatement in the long run. Furthermore it seems that standards slow technological progress as they promote one solution for many users[5].

## 2.2 A Static Game

The concept that was used by Scott Barrett (1994) in his article "*Self-Enforcing International Environmental Agreements*" is not new, but quite suitable for that kind of problem. In fact, it is so useful that most authors writing on the topic of global warming apply it. In short, there are two states of the world. One would be 'natural', considering economic rationalism, in the sense that all agents maximize their own profits subject to their own costs. Unfortunately in this framework we allow for external cost, which means that actions taken by one party affect all other parties in the game. So a possibility to make everyone better off would be to cooperate in order to regulate the global common in a way that is bearable for all agents involved. But as soon as some countries cooperate, it becomes profitable for others to free ride. So the basic problem can be taken as a simple '*Prisoners Dilemma*'. In the one shot game, where the cooperative outcome is compared with the deviating outcome, in which all players maximize their individual profits, the result will never be full cooperation. In the models, that will be introduced now, cooperation can have two meanings. In the first model the level of abatement of emissions is the decision variable where the total amount emitted is of interest in the models two and three. Comparing these models shows very well the evolution from static to dynamic modeling and from limited participation to a framework in which full participation can be achieved.
In this model countries have two possibilities when they have to decide on

[5] Barrett and Stavins (2003). pp. 368-369

what to do. They can set individual marginal cost of abatement either equal to individual marginal benefit of abatement, or equal to global marginal benefit of abatement. If marginal costs are small and marginal benefits are big, the international cooperation won't bear large gains as each country can profit a lot by acting unilaterally. When costs are large and benefits are small it is unlikely that the countries will cut down their pollution by high amounts, because low emissions are already a dominant strategy. Finally the gains to cooperation are larger if the ratio of marginal costs to global marginal benefits is close to one and the gap between cooperative and non cooperative emission abatement is big[6].
To make the agents cooperate in the prisoners dilemma, the game is repeated such that it is possible to punish one player for bad behavior. We have to write down two incentive constraints to ensure sustainability of the equilibrium. No signatory of the treaty should be able to attain additional profits from cheating and that the agreement is renegotiation proof. If the contract would be subject to further negotiations after the treaty is signed, nobody would be willing to comply as the result could be changed afterwards again. The crucial point in the repeated game is the value of the discount factor, i.e. the lower the better[7]. It means that the more patient the players are, the more they take into account future costs of environmental harm.

### 2.2.1 The Model

The framework contains $i = 1, ...I$ identical players, individual emission abatement $q_i$ and following abatement cost $C_i(q_i) = cq_i^2$ and abatement benefits $B_i(Q) = b(oQ - Q^2/2)I$, where $Q = \sum_{i=1}^{I} q_i$ is global GHG reduction. When the cooperating states manage to cut the emissions of the global pollutant by a total number of $Q$, every country benefits according to the benefit

[6]Barrett (1994): pp. 881 - 882

[7]Note that the discount rate $r$, that is applied in this and the following model, is different from the discount factor $\delta$, which is used in the models of Dutta and Radner. While $r$ close to zero means high patience, the opposite is true for $\delta$, where $\delta = \frac{1}{1-r}$

function $B_i(Q)$. The cost is only depending on national effort, and $c$ represents the slope of the marginal costs curve. Note that in this first of three models, the parameter of interest is abatement level and not the level of emissions, as it will be seen afterwards[8].

**Two Benchmarks**

In this section I describe two different states of the world. In the first one, no country is willing to sign a treaty so there is no coordinated way of emissions reduction. In the second state, at least some countries agree on joint abatement levels at which joint utility should be maximized. Individual net gains of abatement are denoted by $\pi_i = B_i(Q) - C_i(q_i)$, further more global net gains are $\Pi = \sum_i \pi_i$. If all countries would cooperate, their marginal abatement cost $C_i(q_i)$ would equal the global marginal benefit of emission reduction (MB). On the other side, countries set their level of abatement by maximizing their individual $\pi_i$, under the assumption that all others actions are given. This non cooperative behavior will be called '*Business as Usual*' (BAU). Comparing the outcomes, it follows that the cooperative GHG level $Q_c$ is lower than the BAU one $Q_n$. As countries are identical, optimal emission commitments are the same for all players. $Q_c$ and $q_c$ stand for cooperative emission abatement, while $Q_n$ and $q_n$ represent the non cooperative outcome:

$$q_n = \frac{o}{I(1+\frac{c}{b})} \quad < \quad q_c = \frac{o}{I+\frac{c}{b}}$$

$$Q_n = \frac{o}{1+\frac{c}{b}} \quad < \quad Q_c = \frac{oI}{I+\frac{c}{b}}$$

where $o$, $b$ and $c$ are constants. If there is no cooperation it makes sense to work together at some level, whilst if there is full cooperation it is individually rational to choose lower abatement than agreed on. Therefor a

[8] Barrett (1994), pp. 880

fraction $\epsilon$ of all countries will sign a treaty, while a proportion of $(1 - \epsilon)$ of all states will refuse to do so[9].

As this is a symmetric game, the payoffs are the same for all countries. Both benchmarks represent all future payoffs for player $i$ from the point in time, when the decision is made. So both players decide at the same time, say $t = 0$, on their expected future welfare. And both have expectations of what the other state might do in the future.

**How to sustain low emission levels?**

It is known that cooperation can be sustained when the game is played not only once but infinitely often. So when players do not act as they were supposed to do, the other players can punish the deviant after the next round. The severance depends amongst others on how long the punishment phase lasts. The punishment may only last for one repetition but as well until the end of the game, which would be infinity in this case. The crucial question is whether the possibility of punishing a country, which deviates from the agreement it signed, is a credible threat. When a country believes that it is really going to get punished after a deviation, it will cooperate when the costs of punishment are higher than the benefits of a single deviation.
Usually the punishment is carried out by the complying *I - 1* states by reducing the contribution to the public good. In the logic of the model, fewer abatement leads to lower benefits. Every country compares the sum of all future benefits resulting from cooperation with the one of not cooperating. When it can be assured that all cooperating countries contribute to the punishment of a single deviating state, the coalition is sustainable. The optimal number of the members of the coalition is reached, when a further cooperating state can not improve the joint utility of the coalition any more.

The model leads to the conclusion, that the smaller the number of participating parties is, the larger is the reduction of emissions, that will be agreed on by the signatories. The problem here is the credibility of punishment. As

[9] Barrett (1994), pp. 880-881

soon as there is only the slightest possibility that after a deviation the treaty would be renegotiated or some states might not punish, in order to avoid to harm themselves, there is no equilibrium. In other words if the punishment itself is not an equilibrium, there is no way to threat a country from deflection.

This result is not satisfactory, so I am looking for other conditions that might achieve better findings, in terms of international participation and substantial emission reduction.

## 2.3 A Dynamic Game

The paper of Dockner and Long (1992) "*International Pollution Control: Cooperative versus Noncooperative Strategies*" appeared two years earlier than the preceding one by Barrett, but contained already dynamic modeling. This bears in mind that the history of a country's actions may be influenced by any other country's behavior in the past. When a country realizes, that its own behavior, i.e. its own emissions, influences the behavior of an other state in the future, it might act according to another strategy[10].

The players act according to so called Markovian strategies. For these strategies the complete history of the game, say all emissions in former periods, are not of importance but only the state of the system, in this case aggregate emissions. One assumes that the stock of GHGs itself gives an information about past actions. The analysis focuses on so called Markov Perfect Equilibria (MPE), which are a subgame perfect equilibrium in Markov strategies. Dockner and Long see clear advantage for this dynamic modeling, because of its capability to show when and why negotiations about emission reductions fail, how they are accomplished and why the countries have an incentive to deviate after signing a treaty[11].

[10]Dockner and Long (1992): pp. 14

[11]Dockner and Long (1992): pp. 13-14

As I already mentioned at the beginning, only two identical countries are playing in this game. To be able to compare the results of the game, again two benchmarks are computed. The first one is the fully cooperative outcome, that itself is not sustainable in a one shot game, as it does not constitute an equilibrium. The second case is the one, where all countries maximize their national welfare, which bears the result that a global pollutant harms both countries. As in the previous paper and in contrast to the following the authors assume punishment as not fully credible[12].

### 2.3.1 The Model

Two neighboring countries produce a consumption good $X_i$. The good is produced using a technology $F_i$. As a side effect, during the production process an amount of pollutants $a_i$ per unit of good is generated, thus $X_i = F_i(a_i)$. Actual GHG emissions contribute to the global stock *g(t)*:

$$\dot{g}(t) = a_1(t) + a_2(t) - (1-\sigma)g(t), \qquad (1-\sigma) > 0$$

where $(1-\sigma)$ is the amount of $CO_2$, that is dissipated in one period. $N$ consumers in each country, derive utility $U_i(X_i)$ by consumption of good $X_i$. Overall pollution causes environmental costs $C_i(g)$ for country $i$, that have to be subtracted to calculate national net benefits of country $i$ $B_i$:

$$B_i(a_i(t), g(t)) = U_i\Big[F_i(a_i(t))\Big] - C_i(g(t))$$

The difference between the preceding and this model is, that here a dynamic modeling is utilized. Each player choses optimal behavior by maximizing a discounted[13] integral, representing its total net benefits[14]:

[12]Dockner and Long (1992): pp. 14-15
[13]Remember: $r \neq \delta$!
[14]Dockner and Long (1992): pp. 16

$$max_{a_i} \quad \int_0^\infty e^{-rt}\Big(B_i(a_i(t), g(t))\Big)dt, \qquad s.t. \ \ \dot{g}(t)$$

So every government aims to maximize the stream of collective welfare of its own country.

**Two Benchmarks**

Again I utilize the already known concept. In the first step I calculate the non cooperative state of the world in which every player only considers his own emissions. In the second step I calculate the joint welfare of the two players, in which the countries cooperate in order to attain higher welfare. For calculating any outcome, I firstly need to specify a profit function $\pi_i$ for country $i$. Preferences are denoted by $U_i[F_i(a_i(t))] = \gamma a_i(t) - \frac{1}{2}a_i^2(t)$ ($\gamma > 0$ being a constant), as well as the cost function $C_i(g(t)) = \frac{s}{2}g^2(t)$. Now I can write:

$$\pi_i(a_i(t)) = \gamma a_i(t) - \frac{1}{2}a_i^2(t) - \frac{s}{2}g^2(t)$$

When both players do not cooperate, they play according to linear Markovian strategies. That means that country $i$ decides on its emission strategy in period $t$ according to the following rule:

$$a_i(g(t)) = o_i - b_i g(t)$$

where $o_i$ and $b_i$ are constants. In equilibrium $b_i$ will be $> 0$, so when the stock of GHG is large, both countries will have an incentive to cut down their $CO_2$ emissions.

The second case is the one where countries cooperate, so this time joint utility is maximized instead of national utility. For computing global welfare, we only have to combine the individual utility functions to a joint one, including the law of motion of *g(t)*. As we use dynamic programming mechanisms, we have to utilize a so called Hamiltonian instead of the La Grange function[15]:

$$H(a_1, a_2, g, \lambda) \quad = \quad \gamma(a_1 + a_2) - \frac{1}{2}(a_1^2 + a_2^2) - sg^2 + \lambda[a_1 + a_2 - (1 - \sigma)g]$$

We have to take the first derivative of the Hamiltonian and set it equal to zero. The solution to this maximization problem is again a symmetric one[16].

**How to sustain low emission levels?**

The authors argue that in the case of no cooperation and a discount factor high enough, the loss of welfare to both neighbors exceeds the abatement costs, incurred in the case of cooperation. So both countries would gain more if they reduce their emissions. Furthermore they say that it is not necessary to monitor the opponents behavior, as it is in everyones self interest to cut down the pollutant, and - given a very low discount rate $r \approx 0$ - it is even possible to achieve the same reduction as in the fully cooperative setting. That means that it might not be necessary to threaten the other country in order to make it cooperate.

Despite the fine result of cooperation without punishment, the model does not satisfy the demand for a broader solution. Although the dynamic framework, in which goods production and interrelation between the acting parties are the clue variables, is already a very reasonable approach it covers only two players, which is barely enough considering a global problem. Furthermore, it does not at all take into account any other factor like population, technology, trade and different country sizes.

[15] $a_1 + a_2$ is the sum of the two players' emissions

[16] Dockner and Long (1992), pp. 17-18

# Chapter 3

# Games with complete Participation

## 3.1 A Dynamic Game

In 2002 Dutta and Radner published their first work on the topic of global warming. They wanted to show that it is possible to construct a game, in which more than 200 players could agree on cooperation for the purpose of reducing a global 'bad'. Step by step they upgraded the system towards more realistic assumptions and broader coverage of circumstances that influence the decision of every agent in every period.
The idea was the following: a solution for the problem of global warming must be as easy as possible. Otherwise it would be extremely difficult to convince the decision makers of the concept. And if the solution is relatively easy, compared to the situation we have nowadays (in the sense of complex internationl legal regulations) it would be easy to put it into practice. This is a global problem but there is no global administration, that is capable of enforcing international rules. So the only possibility for sustainable solutions are agreements that are incentive compatible for the signatories, in other words self enforcing[1]. The idea is the following. In order to sustain a low level

[1] Dutta and Radner (2006): pp. 252

of worldwide emissions at least close to the first best solution, we introduce two different types of punishment. The first one to be dealt with is a Third Best Solution, which will be improved to a Second Best Optimum in a second step.

### 3.1.1 The Model

Emissions are produced by production and consumption of energy and as well by production of goods. Thus higher emissions go along with higher production and, up to a point, with higher welfare. Every country contributes to a global stock of GHGs by producing emissions:

$$A(t) = \sum_{i=1}^{I} a_i(t)$$

The existing stock dissipates with a constant rate over time:

$$g(t+1) = A(t) + \sigma g(t)$$

*I* players, *i=1,...I*, participate in the game. In fact more then 200 countries of the world are the players. But the countries can differ in their population-size, their emission technology and their preferences[2]. Nevertheless there are regions of the world, such as Western and Eastern Europe, North America and Asia, that have maybe not the same but at least similar strategic interests. In the basic model there is no population growth and no possibility of changing the production technology. That means that there is no technological progress.

Every country has a utility function, that is represented by its national GDP minus the costs of the stock of GHG:

$$v_i(t) = h_i[a_i(t)] - c_i g(t)$$

[2] In contrast to the other models, where countries were homogeneous

where $a_i(t)$ are country *i's* emissions in period $t$[3]. An example of $h$ with three inputs could be:

$$h_i[a_i(t)] = \phi_i K_i^{\gamma_i} P_i^{1-\gamma_i-\beta_i} \left(\frac{a_i(t)}{f_i}\right)^{\beta_i} - p_i \left(\frac{a_i(t)}{f_i}\right)$$

where $K$ indicates capital use, $P$ stands for the population level and $\frac{a}{f}$ describes the energy use of the economy[4]. This function is based on the Sollow Model and thus it is concave. So we can assume that for a given population, there is an optimal level of emissions.
In the model the national discounted welfare is the decision variable:

$$\upsilon_i = \sum_{t=0}^{\infty} \delta^t \upsilon_i(t)$$

where discount factor $\delta$ is the same for all countries.
Every country has a set of strategies $\sigma_i \equiv [\sigma_{i0}, \sigma_{i1}, ...\sigma_{it}, ...]$, that maps the way from a certain history (past emission, stock of GHG) to a certain action (current emission). At a certain period $t$, the history of the game can be seen as the history of all GHG stocks until then. Moreover, the total discounted payoff is conditioned on each profile $\sigma$ and each initial stock of GHG, $g_0$:

$$\upsilon_i(\sigma, g_o) \equiv \sum_{t=0}^{\infty} \delta^t \upsilon_i(t; \sigma, g_0) \tag{3.1}$$

If player $i$ considers only last year's emissions the strategy is a so called *Markovian Strategy*. A Markov Perfect Equilibrium is a profile of Markovian strategies that constitutes a Nash Equilibrium in every subgame (Subgame

[3] $f_i$ tells us how clean a technology is and because $a_i(t) = e_i(t)f_i$, the lower $f_i$ the cleaner a technology is

[4] By now it is sufficient to let $h$ only depend on $a$, because the other factors $K$,$P$ and $f$ are constant here. In the following chapter we will see what happens, when population grows and technology improves

Perfect Nash Equilibrium in Markovian strategies)[5]. These strategies are functions that map the current state, $(g,\ P)$, into a current action, $a_i$, including the past states and emissions of all states. A stationary strategy for country $i$ is a function that maps the current stock of GHG into a current action, $a_i(t)$. A *Markov Nash Equilibrium* is a Nash Equilibrium in which the strategies of all countries are stationary[6].

### Two Benchmarks

### Business as Usual (BAU)

Again I define two benchmark levels of $CO_2$ emissions, to have a point of reference when looking at possible equilibria. This equilibrium corresponds to the '*Tragedy of the Commons*'. Each country plays a Markovian strategy, in which it maximizes its utility subject to its own emissions. As a result, the amount of GHGs emitted by all players exceeds a globally sustainable level. Therefore we need to introduce a new function $V_i$ that defines the total discounted utility of country $i$:

$$V_i(g) = \frac{\left(h_i(a_i) - \delta\left[\frac{c_i}{1-\delta\sigma}\right]A\right)}{1-\delta} - \left(\frac{c_i}{1-\delta\sigma}\right)g$$

The 'optimal level of emissions' is implicitly defined by setting the first derivative of $V_i$ equal zero. That gives the highest welfare attainable for country $i$ in the BAU (all results related to the BAU are marked with a*):

$$\begin{aligned} \frac{\partial V_i(g)}{\partial a_i} &= 0 \\ h_i^{'}(a_i^*) &= \delta w_i \end{aligned}$$

[5]Dutta and Radner (2002): pp. 7

A more precise definition of Markov perfect equilibrium can be seen in Sundaram (1999): pp. 271 et seq.

[6]Dutta and Radner (2006a): pp. 257

Introducing this emission level into the utility function gives the BAU values of the crucial variables of this model, namely the discounted cost of the stock of emissions $w$, the 'value' of an emission strategy $u$ and the sum of all players emissions $A$[7]:

$$
\begin{aligned}
V_i^*(g) &= u_i^* - w_i g, \\
w_i &= \frac{c_i}{1-\delta\sigma}, \\
u_i^* &= \frac{h_i(a_i^*) - \delta w_i A^*}{1-\delta}, \\
A^* &= \sum_j a_j^*
\end{aligned}
$$

**Global Pareto Optima (GPO)**

After defining the worst case scenario, it is good to know, what could be reached when nations cooperate. There are special weights given to every countries utility, that sum up to one. Using these weights, we form a weighted sum of all countries utility functions and call that global welfare[8]:

$$
v = \sum_i x_i v_i
$$

Considering this weighted sum, the utility function $V$ can be rewritten the following way:

$$
V_i(g) = \frac{\left(\sum x_i h_i(a_i) - \delta\left[\frac{\sum x_i c_i}{1-\delta\sigma}\right]A\right)}{1-\delta} - \left(\frac{\sum x_i c_i}{1-\delta\sigma}\right)g
$$

A GPO is a profile in which the discounted sum of all future payoffs $V_i$ of the function above is maximized over the amount of *worldwide* emitted gases:

[7] Dutta and Radner (2002): pp. 9-10

[8] One could criticise the point, that it would be difficult to negotiate these weights. But the weights are not the crucial factors, which will be shown soon

$$\begin{aligned}\frac{\partial V_i(g)}{a_i} &= 0\\ x_i h_i^{'}(\widehat{a}_i) = \delta w \quad &\Leftrightarrow \quad h_i^{'}(\widehat{a}_i) = \left(\frac{1}{x_i}\right)\delta w\end{aligned}$$

where $\widehat{a}$ is the GPO emission level. When implementing tis GPO value $\widehat{a}$ into $V$, we get the respective values for $\widehat{V}$, w and $\widehat{A}$:

$$\begin{aligned}\widehat{V}(g) &= \widehat{u} - wg,\\ w &= \frac{1}{1-\delta\sigma}\sum_i x_i c_i,\\ \widehat{u} &= \frac{\sum_i x_i h_i(\widehat{a}_i) - \delta w \widehat{A}}{1-\delta},\\ \widehat{A} &= \sum_i \widehat{a}_i\end{aligned}$$

And again we define implicitly the optimal emissions, but this time the sum of all $a_i$'s does not exceed the global sustainable level.

### Comparison of the Results

One can show that GPO emission levels are always lower than the BAU ones, by comparing the results above:

$$\begin{aligned}h_i^{'}(a_i^*) &= \frac{\delta c_i}{1-\delta\sigma}\\ h_i^{'}(\widehat{a}_i) &= \frac{\delta \sum_i x_i c_i}{x_i(1-\delta\sigma)}\end{aligned}$$

Now I want to show that the BAU level is higher than the GPO one. As the function $h$ is concave, it is logical that the slope of $h_i$ at the coordinate $\widehat{a}_i$ must be steeper the at $a_i^*$, if $\widehat{a}_i$ is smaller then $a_i^*$:

$$\begin{aligned} h_i^{'}(a_i^*) &< h_i^{'}(\widehat{a}_i) \\ \frac{\delta c_i}{1-\delta\sigma} &< \frac{\delta \sum_i x_i c_i}{x_i(1-\delta\sigma)} \\ c_i &< \frac{\sum_i x_i c_i}{x_i} \\ c_i x_i &< \sum_i x_i c_i \end{aligned}$$

which holds for all welfare weights $x_i$.

In a BAU all countries consider only their national marginal cost but not the cost occurring to other states due to its emissions. In a GPO the countries take these additional cost into account. Both results share the characteristic that the emission levels of the players, $a_i^*(t)$ and $\widehat{a}_i(t)$ respectively, are constant over time, which is part of the particular strategies GPO and BAU. Furthermore due to the linearity of the stock growth and cost of pollution, marginal cost is not depending on the current amount of GHG in the atmosphere[9].

### 3.1.2 Third Best Optimum (TBO)

Now that we know the two extreme position between whose borders the possible equilibria lie, we introduce a sanctioning mechanism, that should ensure that the countries do not emit to high levels of $CO_2$. The question is, whether this level coincides with the GPO level or is higher than that.

The idea is that if one country decides to emit more than it is entitled to, all other countries emit at the BAU level forever. This grim trigger strategy results in the *Third Best Optimum* (TBO). In equilibrium the weighted sum

[9] Dutta and Radner (2002): pp. 8-10

of all countries utility functions are maximized, as it was done before in the GPO case. But now the solution must fulfill an incentive constraint. Namely that country *i's* welfare is higher (at least not smaller) at the compliance level $\tilde{a}$ then at the BAU level $a_i^*$:

$$\Big[h_i(\tilde{a}_i) - c_i g + \delta[\tilde{u}_i - w_i(\sigma g + \tilde{A})]\Big] \quad \geq \quad \Big[h_i(a_i^*) - c_i g + \delta[u_i^* - w_i(\sigma g + \tilde{A}')]\Big]$$

$$where \qquad \tilde{A} = \sum_j \tilde{a}_j \qquad and \qquad \tilde{A}' = a_i^* + \sum_{j \neq i} \tilde{a}_j \qquad \forall a_i, i$$

$h_i(a_i) - c_i g$ is the direct nominal payoff minus country *i's* cost of pollution, and the following term $\delta[u_i - w_i(\sigma g + \sum_j a_j)]$ is the discounted utility minus the discounted national costs of $g$ in period $t$. On the left hand side (lhs) every country acts according to the treaty, while on the right hand side (rhs) country $i$ plays a deviating strategy[10]. The inequality shows that it does not pay to defect, as the punishment makes the deflector worse off. Because $a_i^* > \tilde{a}_i$, it follows that costs are higher and hence welfare is lower.
Because the emissions are constant over time and the term $u_i$ includes the sum of all countries emissions, it is not necessary to consider the steady state $g$ any more[11]. Hence we can rewrite the constraint in a shorter form:

$$\Big[h_i(\tilde{a}_i) - \delta w_i \tilde{a}_i + \delta \tilde{u}_i\Big] \geq \Big[h_i(a_i^*) - \delta w_i a_i^* + \delta u_i^*\Big], \qquad \forall a_i, i$$

This procedure bears many different findings. In the following I want to present numerical analysis that shows that when the discount factor exceeds a certain benchmark level $\overline{\delta}$ and the weights are equally distributed ($x_i = x_j$), the TBO solution can be equivalent with the GPO.
The next step is to have a look at all the equilibria, sustainable by BAU threat, and find the one that has the smallest overall emission level $A$ of the

[10]the authors write a instead of $a^*$ in their paper, but as the deviation profits are maximized at the BAU emission level I cut this step short

[11]Remember $u_i^* = \frac{h_i(a_i^*) - \delta w_i \sum a_i^*}{1-\delta}$, $\tilde{u}_i = \frac{h_i(\tilde{a}_i) - \delta w_i \sum \tilde{a}_i}{1-\delta}$

whole set. I call this result the *Minimum Emissions Solution* (Min) which is unique and of course the emission level is lower then the BAU one. It is possible that the minimum emission level can be even smaller than the GPO for most countries[12]. At first sight, this seems to be a pretty good solution to the problems discussed at the beginning. But in fact it could become problematic if the punishment is so strict. When the emission levels fall below the optimal level, it means that production is too low and thus resulting in welfare losses. When the gains of an healthier environment are lower than abatement costs, it is of course not an efficient system.

### 3.1.3 Second Best Optimum (SBO)

**The Set of Equilibrium Payoffs**

The modeling enables infinitely many equilibria, as there are infinitely many levels of emissions that can be produced by the countries. The functional frame is multivariable and is called a correspondence. Here a fixed point in the correspondence, is the amount of GHGs emitted at which no country has an incentive to act differently. The correspondence can have various fixed points[13].

In this chapter we have a closer look at these equilibria of the game which are subgame perfect (SPE). The set of equilibrium outcomes at a point in time $g = 0$ can be transformed linearly to another set of equilibrium outcomes at any other level of $g$[14]. So the possible set of equilibria can be independent of $g$, which means that the decision on the emission levels in period $t$ need not depend on the past emissions. But emissions $a$ can be varying with the stock $g$. The set of all solutions consists of all equilibrium payoff vectors, including all possible SPE starting at a special $g$.

[12] Dutta and Radner (2002): pp. 14-15

[13] Mas-Colell, Winston and Green (1995): pp. 949 et seq.

[14] Dutta and Radner (2002): pp. 17

**Extreme Equilibria**

The third approach now introduces another possibility to sanction a country, that deviates from the chosen emission level. Again it is the maximization of a weighted sum, but this time, out of the set of equilibrium payoffs (denoted here as $\Xi(g)$) and not out of the feasibility set of all possible allocations[15]:

$$max \sum_{i=1}^{I} x_i V_i(g), \qquad V(g) \in \Xi(g)$$

Again one result is that there is an optimal emission rate for each country. In the case that one country defects, all other nations will emit at a very high rate (in fact the sum of this punishment emissions is higher then the BAU emission level of the punishing countries) for one year. After the punishment phase they switch to an equilibrium, where the deviating nation has the lowest payoff of all possible outcomes. Here its weight in the maximization process is reduced to zero, $a(x_{-i}) = [a(x_1), ...a(x_{i-1}), a(x_{i+1}), ...a(x_I)]$, such that the punishing countries gain more than they loose in the period of punishment (to make it clear, in the period of very high emissions all countries in the world have higher cost but the new equilibrium bears enough gains to compensate).

One might think that a country which is thrown out of the international community does not have any incentive to emit at low rates of carbon dioxide any more. But the opposite is true. As all other countries maximize joint welfare excluding one nation, there is no more elbowroom for country $i$ to produce at a high level of $a_i$ because for any further emitted $a_i$ the cost due to pollution will be higher then the marginal profit of one further unit produced.

Again the punishment is itself an equilibrium, so it is credible for any country to get to pay the bill in case of deviation. Furthermore if one state deviates, the other countries can even increase their profits by punishing. This is very

[15]Do not confuse this with the results we gathered so far, see comparison of GPO, TBO and SBO at the end of the chapter

important, as it has been discussed, that the more the contracting countries would have to sacrifice to discipline the deviant, the less credible is the threat of punishment. The result is very easy to implement, because it carries with it an across the board cut of emission levels.

### Asymmetry

One critical aspect of the whole problem is that the different countries face different consequences. While some suffer substantial damage, some other might only have low costs. The question now is how this cost asymmetry affects the results concerning sustainability of cuts, optimality of cuts and welfare aspects.
For simplicity we consider only the case where the number of players is reduced to two. This can be interpreted as two regions such as the developed north in contrast to the economically underdeveloped south. If the marginal cost of another emitted giga ton of $CO_2$ (gtc) of country $i$ is high, the result is that it gets less interesting to brake the treaty as the profits to gain are low. Vice versa the threat of the sanction - the BAU emission level - gets less severe for the lower cost country. Estimates show that the first effect is stronger than the second one. That means that the country with the higher cost will be more willing to cut down emissions, and that the lower cost country will always agree on a cut that is supported by the higher cost country.
Looking at the extent of inequality of cost, overall welfare is at its maximum with GPO emissions, when costs are equal. If inequality increases, welfare strictly decreases[16].

### Greenhouse Trap

An interesting question arises, if one looks for convergence. Therefore we consider only Markov Perfect Equilibria, where the result is depending on current GHG levels. The so called '*Greenhouse Trap*' states that a country starting with an initial stock which is below a critical $g^*$ value will converge

[16]Dutta and Radner (2002): pp. 16-17

towards this value and then stay there. On the other side, a nation that starts above this critical value converges towards the unfortunate steady state of BAU emissions.

**Summary**

- Business as Usual - BAU
  Each Country maximizes its utility subject to its own emissions. The result is that the whole world emits to much $CO_2$, so the world climate heats up and thereby produces significant cost. This is an equilibrium in the one shot game.

- Global Pareto Optimum - GPO
  Here a weighted sum of all countries utility is maximized subject to emissions of GHG. The result is the maximum attainable global utility in terms of GDP minus cost of the GHG stock. This is not an equilibrium in the one shot game. Therefore we need some kind of agreement to get at least close to that result.

- Third Best Optimum - TBO
  Now we introduce a first possibility of sanctioning countries, that do not act according to what would be globally optimal. If one nation emits to much $CO_2$ all other countries start to emit on their BAU level of GHGs ever after. By repetition of the game, countries do not dare to deviate.

- Second Best Optimum - SBO
  After a deviation of country $i$ all other states emit at a very high rate for one year. After this year, global welfare is recalculated under exclusion of the deviant. Hence all countries can profit if they carry out the punishment, even if they harm themselves at first.

## 3.2 Extensions to the Basic Model

Now that the basic model is defined, I want to turn towards some aspects that have not been covered so far.

### 3.2.1 Exogenous Population Change

The '*Global Warming Game*' is in general defined as in the section above. The difference here is that exogenous population growth is taken into account. That means that for a given population size there is an optimal level of energy use and thus an optimal level of emissions. The population of country $i$, $P_i(t)$, is growing linear towards a steady state, $S_i$, and stays at this level for ever:

$$P_i(t+1) = \ell_i P_i(t) + (1 - \ell_i) S_i,$$

where $\ell_i$ lies between zero and one. The solution of this difference equation is:

$$P_i(t) = \ell_i^t P_i(0) + (1 - \ell_i^t).$$

Now that we know the behavior of the new parameter, we can implement it into the utility function, which is already known from the basic model:

$$\upsilon_i(t) = h_i[a_i(t), P_i(t)] - c_i P_i(t) g(t) \tag{3.2}$$

$h_i(t)$ is now depending not only on $a_i(t)$ alone but also on $P_i(t)$, i.e. what the GDP of country $i$ would be, at a certain level of emissions and population size. For each value of $P_i$, $h_i$ is strictly concave in $a_i$. For a certain size of population there is an optimal level of emissions, if one does not take into account the cost of the stock of GHG[17]. And furthermore marginal costs are linked proportional to the population of nation $i$.

[17]Dutta and Radner (2006a): pp. 257

The decision variable is than the discounted sum of payoffs over the infinite future:

$$\upsilon_i = \sum_{t=0}^{\infty} \delta^t \upsilon_i(t)$$

**Two Benchmarks**

We now investigate, how the basic model changes after including the new variable.

**BAU**

The BAU emission level is linked to the current population of country $i$, and not to any other countries population level. Optimal emissions are than defined over the maximization of the welfare function, subject to the emission level:

$$\begin{aligned} h_{i1}(a_i^*, P_i) &= \delta w_i(P_i^{'}) \\ w_i(P_i) &= c_i\Big(\frac{S_i}{1-\delta\sigma} - \frac{S_i - P_i}{1-\delta\sigma\ell_i}\Big) \end{aligned}$$

where $h_{i1}$ is the first derivative of $h$, subject to $a$. Here player $i$ plays the Markovian strategy $a_i^* = \alpha_i^*(P_i)$ with the payoff:

$$V_i^*(g, P) = u_i^*(P) - w_i(P_i)g$$

where $g$ is the initial stock of GHG and $P = (P_1, \dots P_I)$ is the population vector. The function $u_i^*$ is bounded, continuous and separable in its arguments. That means that there exist the functions $u_i^{i*}(P_i)$ and $u_i^{j*}(P_i, P_j)$ that are also bounded and continuous. These functions solve the following equations:

$$
\begin{aligned}
u_i^{i*}(P_i) &= h_i[\alpha_i^*(P_i), P_i] + \delta[u_i^{i*}(P_i^{'}) - w_i(P_i^{'})a_i^*(P_i)] \\
u_i^{j*}(P_i, P_j) &= -\delta w_i(P_i^{'})a_j^*(P_j) + \delta u_i^{j*}(P_i^{'}, P_j^{'} \\
P^{'} &\equiv (P_i^{'}) \\
P_i^{'} &\equiv \ell_i P_i + (1-\ell_i)S_i
\end{aligned}
$$

$u_i^{i*}(P_i)$ is the utility of country $i$ derived from the population of its own country that enters the value function $V_i^{*}$[18]. While $u_i^{j*}(P_i, P_j)$ is the disutility of country $i$ that is caused by the population of country $j$[19]:

$$
\begin{aligned}
u_i^{i*}(P_i) + \sum_{j \neq i}^{I} u_i^{j*}(P_i, P_j) = \max_{a_i} \, [h_i(\alpha_i^*, P_i) + \delta[u_i^{i*}(P_i^{'}) - w_i(P_i^{'})a_i^*] \\
+\delta \sum_{j \neq i}^{I} [-w_i(P_i^{'})a_j^*(P_j) + u_i^{j*}(P_i^{'}, P_j^{'})]
\end{aligned}
$$

The space of bounded, continuous, separable functions is a complete, separable metric space. The *Bellman Equation*[20] is a contraction and therefore it has a fixed point which is the value function. BAU emissions result from the first order condition of the maximization of the utility function defined above[21]:

$$h_{i1}(a_i, P_i) - \delta w_i(P_i^{'}) = 0$$

[18]"*A value function is an estimate of expected cumulative future reward, usually as a function of state or state-action pair. The reward may be discounted, with lesser weight being given to delayed reward [...]*" (from http://rlai.cs.ualberta.ca/RLAI/valuefunctionhypothesis.html at 2007/11/03 - 15:00). It displays the present discounted value of the allocation denoted by its arguments.

[19]Dutta and Radner (2006a): pp. 258

[20]The Bellman Equation is a necessary condition for optimality when using dynamic programming, see also Sundaram (1999): pp. 285 et seq.

[21]Dutta and Radner (2006a): pp. 258
A correspondence is a multivalued function, a fixed point of a correspondence is a coordinate where there is no possible additional value added.

So the emission level is independent of the GHG stock and the BAU is a MPE. The value of $w_i(P_i)$ is determined by the cost equation[22]:

$$w_i(P_i)g = c_i P_i g + \delta w_i(P_i^{'})\sigma g$$

### GPO

A Global Pareto Optimum is a profile of strategies that maximizes the weighted sum of country payoffs:

$$v = \sum_i x_i v_i$$

where the weights sum up to one. The maximum achievable welfare is given by:

$$\begin{aligned} \widehat{V}(g) &= u(P) - w(P)g \\ u(P) &= \sum_j x_j u_j(P) \\ w(P) &= \sum_j x_j w_j(P_j) \end{aligned}$$

The technical properties are almost the same as in the BAU case, with the little difference that in this case a weighted sum is maximized instead of one countries utility:

$$u_i(P) = h_i[\alpha_i(P_i), P_i] + \delta[u_i(P_i^{'}) - w_i(P^{'}) \sum_j \alpha_j(P_j)]$$

where $\alpha_i$ is implicitly described by the first derivative of the welfare function[23]:

[22] Dutta and Radner (2006a): pp. 258

[23] Dutta and Radner (2006a): pp. 259

$$
\begin{aligned}
x_i h_{i1}[\alpha_i(P_i), P_i] &= \delta w(P^{'}) \\
or \qquad h_{i1}[\alpha_i(P_i), P_i] &= \delta\left(\frac{1}{x_i}\right)\sum_j x_j w_j(p_j)
\end{aligned}
$$

**Comparison of the Results**

Comparing those two benchmark emission levels it turns out that under any circumstances the GPO emissions are lower than the BAU ones:

$$
\begin{aligned}
h_{i1}[\alpha_i^*(P_i), P_i] &= \delta w_i(P_i) \\
h_{i1}[\widehat{\alpha}_i(P_i), P_i] &= \delta\left(\frac{1}{x_i}\right)\sum_j x_j w_j(P_j)
\end{aligned}
$$

The BAU emission level exceeds the GPO one, if:

$$
\begin{aligned}
h_{i1}[\alpha_i^*(P_i), P_i] &< h_{i1}[\widehat{\alpha}_i(P_i), P_i] \\
\delta w_i(P_i) &< \delta\left(\frac{1}{x_i}\right)\sum_j x_j w_j(P_j) \\
x_i w_i(P_i) &< \sum_j x_j w_j(P_j)
\end{aligned}
$$

which is true for all weights.

As the function $h$ is strictly concave, BAU value $\alpha_i^*(P_i)$ is strictly greater then GPO value $\widehat{\alpha}_i(P_i)$, which holds for all weights. This is not really surprising, but it had to be shown that it is still true in the new framework[24].

[24]Dutta and Radner (2006a): pp. 260

**Effects of population size on emission levels**

**Constant Population**

This would be the case for instant when the population has finally grown to the steady state. The theory is exactly the same as in the standard model, discussed at the previous section.

**Growing Population**

Now that we have adjusted the basic model for a growing population, we want to know what the effects of a growing society on a countries' emission level are. The central term is the cross partial derivative of the net welfare function:

$$h_{i12} - \frac{\delta c_i \ell_i}{1 - \delta \sigma \ell_i} > 0$$

If this term is positive it means that the marginal product of GDP with respect to emissions is augmenting in the population size. In other words, if the number of inhabitants of a country increases, the emitted amount of $CO_2$ is growing as well. This would be the case when the production function - representing the structure of GDP - takes the form which we already used as an example in the previous section[25]:

$$h_i(a_i, P_i) = \phi_i K_i^{\gamma_i} P_i^{1-\gamma_i-\beta_i} \left( \frac{a_i(t)}{f_i} \right)^{\beta_i} - p_i \left( \frac{a_i(t)}{f_i} \right)$$

### 3.2.2 A Change in the Emission Factor

**Exogenous Technological Change**

It is rather clear that to achieve a cut in GHG emissions, production technologies have to become more efficient. In this framework technological progress

[25]Dutta and Radner (2006a): pp. 261-262

enters the model over a reduction of the energy input by increasing the emission factor. This can only be reached by research and development efforts. If the reduction of GHGs can be met within the BAU, the threat of BAU and the corresponding SBO and TBO get less powerful.
In the article the authors presume that emission of $CO_2$ is only caused by production of energy. Furthermore energy is an input of the production function, just like capital and labor. The use of energy is then determined by the emissions and an emission factor that represents the effectiveness of energy production. So the question is, what is the resulting change of GHG emissions, if the emission factor changes?
The easier case is the one, where technological change is an exogenous factor in the model. The output is defined as $Y_i(e_i, P_i)$ and country *i's* emissions as $a_i = e_i f_i$. GDP in period $t$ is:

$$h_i(a_i, P_i; f_i) \equiv Y_i\left(\frac{a_i}{f_i}, P_i\right)$$

and welfare in period $t$ is:

$$v_i(a_i, P_i; f_i) = h_i(a_i, P_i; f_i) - c_i P_i g$$

where the emission factor $f_i$ remains constant.

### Effects of reducing emission factors

Until now the strategic variable in the maximization problem was $a_i$, the amount of emissions. As the emissions are defined now as the product of energy use and the efficiency of technology, the model changes as follows:

$$A(t) \equiv \sum_{i=1}^{I} f_i e_i(t)$$

The BAU energy input is then defined by the solution of these equations[26]:

[26]Dutta and Radner (2006a): pp. 266

$$
\begin{aligned}
h_{i1}(e_i^*, P_i) &= f_i \delta w_i(P_i^{'}) \\
w_i(P_i^{'}) &= c_i\Big(\frac{S_i}{1-\delta\sigma} - \frac{\ell_i(S_i - P_i)}{1-\delta\sigma\ell_i}\Big)
\end{aligned}
$$

where $e^*$ is the BAU energy consumption. Research and development that 'decarbonizes' energy inputs without increasing the price of energy would have the effect of decreasing the emission factors. The effect of an increasing emission factor on the emissions is:

$$\frac{\partial a_i^*}{\partial f_i} = e_i^* + f_i \frac{\partial e_i^*}{\partial f_i}$$

If the energy use was constant, then a lower emission factor would result in lower emissions. But as $h_{i1}$ is strictly concave and population does not change, when technology evolves, the only variable that changes is $e_i$. It is not intuitively clear but in this framework, a better technology can result in higher emissions[27], if:

$$\frac{\partial e_i^*}{\partial f_i} < 0 \qquad \textit{and hence} \qquad \frac{\partial a_i^*}{\partial f_i} > 0$$

which is true, if and only if:

$$\Big(\frac{\partial log e_i^*}{\partial log f_i}\Big) = \Big(\frac{\partial e_i^*}{\partial f_i}\Big)\Big(\frac{f_i}{e_i}\Big) > -1$$

The lhs gives the elasticity of energy use with respect to the emission factor[28]. A characterization of the BAU with emission factor as a parameter is sufficient, as the computation of the two benchmarks is rather similar, so there is no need to do it twice.

[27] For instance there are studies which find increasing energy use after houses got better temperature insulation. People tend to heat more rooms if they believe that fever energy is lost

[28] Dutta and Radner (2006a): pp. 267

### Endogenous Technological Change

In the article "*A game-theoretic approach to global warming*" previous results are summarized and some parts are getting more detailed. Especially the functional forms of the benchmarks (BAU and GPO) are enhanced, by a term for technological progress. A variable that measures the explicit cost of a new technology to reduce emissions is taken into account now:

$$k_i[f_i(t) - f_i(t+1)]$$

The costs are proportional to the reduction, which gets into force in the period after the effort is undertaken. Furthermore a constraint is introduced that restricts the physical borders of emission reduction by[29]:

$$m_i \leq f_i(t+1) \leq f_i(t).$$

It is essential for the sustainability of an equilibrium pareto superior to the BAU, that the emission factor is greater then zero. Imagine all countries of the world except one would set $m_i = 0$. Now that one country could defect, without having to fear any credible threat as all other countries had given up their ability to pollute[30]. Bringing this new factors together, the utility function changes as follows[31]:

$$v_i(t) = Y_i[e_i(t)] - c_i g(t) - k_i[f_i(t) - f_i(t+1)]$$

A countries strategy determines for each period its energy use and emission factor. A stationary strategy for country *i* is a strategy that is independent of the entire history of the play and only depends on the current state, *s(t) = [f(t),g(t)]*. One such strategy is again the Business as Usual.

[29]Dutta and Radner (2006b): pp. 139
[30]Dutta and Radner (2006): pp. 145
[31]Dutta and Radner (2006): pp. 139

**Choosing the optimal emission factor**

In this last step of modification of the basic model, energy use itself is now a function of the emission factor, i.e. $e_i(t) = E_i[f_i(t)]$ and next years emission factor is depending on the actual parameter value of f, $f_i(t+1) = F_i[f_i(t)]$[32]. As in the BAU players use a Markovian strategy, $f$ will be constant over time after period 0. Optimal energy consumption is defined implicitly over taking the first derivative of the production function:

$$Y_i^{'}[E_i(y)] = \delta w_i y$$

The next step is to compute the optimal emission factor, which is denoted by $y$. Therefore a new formula, namely $Z_i(y)$, is introduced. It does not make sense intuitively but the implications will make it pretty easy to see:

$$Z_i(y) = k_i y + \left(\frac{\delta}{1-\delta}\right) Y_i[E_i(y)] - \delta w_i y E_i(y)$$

Do not mix it up with the welfare function $\upsilon_i$. This function consists of the costs of reducing the emission factor by one unit times the optimal level of the individual $f_i$ - $h_i y$ - plus the discounted profits minus the environmental costs of energy use. Given that $Y_i$ is concave, $E_i(y)$ is decreasing with $y$, i.e. $\frac{\partial E_i(y)}{\partial y} < 0$, so $Z_i$ is convex.
The interesting thing about that can be seen when looking at the first derivative:

$$Z_i^{'}(y) = k - \left(\frac{\delta^2 w_i}{1-\delta}\right) E_i(y)$$

$y$ lies in the interval $[m_i, f_i]$, so the function reaches its maximum at one of the endpoints. There are two possibilities. When $Z_i^{'}(m_i) > 0$, then

[32] Dutta and Radner (2006a): pp. 140

$F_i(f_i) = f_i$[33], $\forall f_i > m_i$[34].
If $Z_i^{'}(m_i) < 0$, then there exists an $y_i^0 > m_i$ such that:

$$\begin{array}{lrcll} & F_i(f_i) & = & m_i & for \quad f_i < y_i^0 \\ or & F_i(f_i) & = & f_i & for \quad f_i > y_i^0 \end{array}$$

That means that if the slope of the function in the point $m_i$ is positive, the maximum lies above it. The second case is, that the slope is negative. Here it depends on the value of $y_i^0$, which states whether $Z_i$ reaches its maximum at $m_i$ or $f_i$[35].
The sign of $Z_i^{'}$ (either positive or negative) shows whether the cost of inventing cleaner technologies ($k$) is smaller or greater than the environmental costs of energy use ($\left(\frac{\delta^2 w_i}{1-\delta}\right) E_i(y)$). To see this, it is useful to rewrite the preceding equations:

$$\begin{array}{lcl} Z_i^{'}(y) < 0 & \Leftrightarrow & k < \left(\dfrac{\delta^2 w_i}{1-\delta}\right) E_i(y) \\ Z_i^{'}(y) > 0 & \Leftrightarrow & k > \left(\dfrac{\delta^2 w_i}{1-\delta}\right) E_i(y) \end{array}$$

**Effects of reducing emission factors**

The calculation of BAU and GPO emission levels, respectively energy inputs, is technically the same as shown in the previous chapters and therefore I will not repeat that again. In this point the question should be answered, whether the move from a BAU to a GPO reduces the emissions of all countries. Somewhat paradoxically, an improvement of the production technology, i.e. a lower emission factor, need not necessarily lead to lower emissions in GPO for that country[36].

[33] don't forget $f_i(t+1) = F_i(f_i)$
[34] Dutta and Radner (2006a): pp. 141
[35] Dutta and Radner (2006a): pp. 142
[36] Dutta and Radner (2006a): pp. 144

The proof has to be extended for the fact, that energy use itself is a function now, namely $e_i = E_i(f_i)$. Hence, emissions are now defined over $a_i = f_i E_i(f_i)$, and its reaction on a change in the emission factor is given by:

$$\frac{\partial a_i}{\partial f_i} = E_i(f_i) + f_i E_i^{'}(f_i)$$

We already know that $E_i^{'}(f_i) < 0$, so again, the following constraint has to be fulfilled, such that $\frac{\partial a_i}{\partial f_i} > 0$:

$$\Big(\frac{\partial log E_i(f_i)}{\partial log f_i}\Big) = E_i^{'}(f_i)\Big(\frac{f_i}{E_i(f_i)}\Big) > -1$$

The switch from BAU to GPO with the same initial state will not increase any country's emission factor. Furthermore a switch from a BAU to a GPO will decrease every countries emissions in every period and thereby increase global welfare[37].

How to sustain such a GPO, while every nation has incentives to deviate in order to gain higher profits, was already shown in the previous sections. The extensions to the basic model do not change the technical aspects.

[37]Dutta and Radner (2006a): pp. 144

# Chapter 4

# Final Remarks

## 4.1 Some ideas for further research

From my point of view there remain two questions, that are not answered by the models that I presented. First, how would the equilibria change if it was possible to invest in the technology of another country. That would reduce the global stock of the pollutant and at the same time enables additional production, and hence emission entitlements, for the investing country. And second, it has always been stated that the size of damage is not yet clear and so there remains some insecurity about the real cost of global warming.
I will only sketch my ideas, that could stand behind the mechanisms and try to enhance the Model of Dutta and Radner.

#### Fitting the Clean Development Mechanism into the Model

CDM was invented during the negotiations for the Kyoto Protocol. The idea was to promote investment in foreign technology such that global emissions would decrease. Parts of the cuts could then be accounted for the investor, hence she could produce a bit more. This should downsize the technological gap between higher and lower developed countries and make production cleaner.
From the chapter on endogenous technological change we know the term

$k_i[f_i(t) - f_i(t+1)]$ that represents costs of investing in cleaner technologies and hence a lower emission factor of country *i*. To enable country *i* to invest in other states technology as well, I denote its cost of foreign investment by $k_{ij}$, i.e. investment flows from nation *i* to *j*. Country *i's* own research effort is $k_{ii} = k_i[f_i(t) - f_i(t+1)]$ and $k_{ji}$ are FDIs from *j* to *i*. A function $k = \zeta_i(k_{ij}, k_{ji})$ sums up each $k$[1]:

$$k = k_{ii} + \sum_{j \neq i}^{I} k_{ij} - \sum_{j \neq i}^{I} k_{ji}$$

The new *k* does not change the calculations, already done in the preceding chapter. It is simply a further broadening of the framework, trying to make the model even more realistic. So utility of country *i* is still:

$$v_i(t) \quad = \quad Y_i[e_i(t)] - c_i g(t) - k$$

Note that $k_{ij}$ does not influence the emission factor of nation *i*, but the one of *j*.

It is easy to see, that in this enhanced framework, all countries will foster technological progress where the effect is biggest, in relation to the arising capital requirements. For instance new low emission power plants in economically lower developed countries, replacing those burning fossil fuels to produce electricity, would reduce the global stock of GHGs substantially and thereby lower the investors cost of climate change. As a result production of goods could be undertaken at a higher level and hence welfare increases. The good thing about this result is, that the punishment mechanisms remain effective. Because better production technologies do not reduce the 'optimal' level of the GHG stock, but foster outcome and welfare. If one country decides to deviate from the cooperation strategy, the other nations can react the same way as described so far.

Unfortunately the Kyoto Protocol restricts the possibilities of reducing emissions abroad, as it aims to lower $CO_2$ production at the national level mainly.

[1] $k_{ii}$ must not be taken into account twice

#### Fitting Stochastic Cost into the Model

As it was already mentioned in the introduction, the real dimension of climate change is not yet foreseeable. So a major concern is to implement some degree of uncertainty about the possible cost into the model. This would influence the factor $c_i(g) = \pi(c_i^l g) + (1-\pi)(c_i^h g)$, where $l$ and $h$ denote whether the cost of country $i$ is low or high. Thereby the menace of joint higher emitting of $CO_2$ as a punishment in case of deviation of a player is decreased, if cost is low, or increased, if cost is high:

$$v_i(t) = Y_i[e_i(t)] - [\pi(c_i^l g) + (1-\pi)(c_i^h g)] - k_i(f_i)$$

As long as countries believe that $(1-\pi)$ (the chance that cost is high) is larger then some benchmark level $(1-\overline{\pi})$, they will rather cooperate because punishment is assumed to be substantially. As soon as $\pi$ exceeds the threshold $\overline{\pi}$ and thus environmental cost could be low, all countries would switch to the BAU strategy.

## 4.2 Conclusion

The main motivation to occupy myself with the matter of global warming was the question, why do all efforts in cutting down the emissions of anthropogenic gases have no observable effect on the behavior of some states of the world. At the beginning of my investigations I identified three different approaches. The first one is a more political one, that states that market driven mechanisms are not effective in international negotiations and it is a logic result that international environmental agreements do not work in reality. Other authors argue, that it is necessary to combine a bunch of actions, including both different kinds of transfers and punishments, to create the right positive and negative incentives for the countries involved. A third fraction holds the view, that the whole problem could be handled like a prisoners dilemma situation, in which the infinite repetition of the same game would bear the desired results. But the representatives of this approach are not homogeneous, as some believe that fully global cooperation could never be achieved and only the formation of coalitions can be successful. Unfortunately the gains of cooperation might not be high enough to reach this goal, as Barrett and Stavins as well as Dockner and Long argue. Only under certain circumstances and with some kind of communication agents act in an ecological reasonable way.

As I did not share any of these views completely, I tried to build my argumentation on a framework, that is applied by the game theorists Dutta and Radner. Their models bear the advantage that they try to cover much more factors then just emission abatement or production level respectively and hence enable to turn more then one cogwheel in the machinery of the world. A basic assumption is, that it is in every countries self interest to cooperate because the global common harms every country to some extent. So I do not look for reasons for participation but for possible ways to make all nations comply. It turns out that an agreement must include some form of punishment mechanism to be able to enforce the stipulated emission level, which is the crucial point. Many articles conclude that punishment is not realistic, because some countries would probably have to sacrifice national welfare in case of joint action against a deviant. The solution for that does not meet the eye intuitively. In the first two models, that I present, punishment in form of lower levels of cooperation does not always succeed. The punishment itself has to be an equilibrium, in order to be a credible threat to any player considering deviation. If that can be assured, it is easy to sustain cooperation, at least at some level. Therefore the crucial factors are how patient the countries are and that they behave rational.

Thence I conclude that it is possible to find ways to reduce international $CO_2$ emissions and save the worlds ecological equilibrium. Recent developments show that political and economic leaders get more and more aware of the threats of global warming.

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# Chapter 5

# Appendix


**Abstract**

By now all international efforts to cut down emissions of Green House Gases had no observable effect on countries behavior. When dealing with the theory behind the matter of global warming, one can identify various approaches for possible solutions. I apply models in which the problem is handled like a prisoners dilemma. That means that when the game is repeated only once, every agent can increase individual utility by not cooperating. But when the game is repeated infinitely often the other players can punish a country that is not willing to act according to an agreement. It is important that the threat of punishment is credible, because as soon as countries believe that they might not be punished they will try to free ride. Therefore the punishment must be an equilibrium itself.

In the models that I use, the threat is a situation in which every nation maximizes its own welfare, considering only its own harm due to environmental pollution. It is a subgame perfect equilibrium and hence it is always realistic, that countries fall back to that behavior when punishment gets necessary. As this result might not bear highest global welfare, I further describe a mechanism in which only the deviant is worse off, while all other nations can increase their utility. The level of abatement that can be achieved in a repeated game, is then depending on the patience of the players.

**Zusammenfassung**

Bisher hatten sämtliche internationalen Bemühungen den Ausstoß von Treibhausgasen zu begrenzen keinen Einfluss auf das Verhalten der Länder. Wenn man sich mit der Theorie beschäftigt, die es zur Problematik der globalen Erwärmung gibt, findet man verschiedenste Lösungsansätze. Ich verwende Modelle, in denen das Problem wie ein Gefangenen Dilemma behandelt wird. Das heißt, dass die Spieler ihren individuellen Nutzen maximieren können, indem sie nicht kooperieren, wenn das Spiel nur ein Mal durchgeführt wird. Aber wenn das Spiel unendlich oft wiederholt wird, haben die Staaten die Möglichkeit ein Land, das sich nicht gemäß der Vereinbarung verhält, zu bestrafen. Es ist sehr wichtig, dass dieses Drohpotential als glaubwürdig angesehen wird. Denn sobald die Länder glauben könnten, dass sie möglicherweise nicht mit einer Strafe zu rechnen haben, werden sie ein so genanntes Trittbrettfahrer-Verhalten an den Tag legen. Daher muss die Strafe selbst ein Gleichgewicht sein.

In den Modellen, die ich verwende, ist die Strafandrohung die Situation in der alle Länder ihre eigene Wohlfahrt maximieren, dabei aber nur ihre eigenen Kosten der Umweltverschmutzung in Betracht ziehen. Das ist ein Teilspiel perfektes Gleichgewicht und stellt damit eine realistische Bedrohung dar, in dem Sinn, dass alle anderen Länder in dieses Verhalten zurückfallen, wenn Bestrafung notwendig werden sollte. Dieses Resultat bringt allerdings nicht immer das höchste globale Nutzenniveau mit sich. Ich beschreibe im Anschluß noch einen weiteren Strafmechanismus, bei dem nur das abweichende Land schlechter gestellt wird, während alle anderen Staaten ihren Nutzen noch erhöhen können. Das konkrete Ausmaß der Emissions Reduktion, das in diesem wiederholten Spiel erreicht werden kann, hängt dann wesentlich von der Höhe der Geduld der Spieler ab.

## Lebenslauf

Person:

Gruber Matthias Johannes

geb. 20. Juni 1982 / Ried im Innkreis

Preysinggasse 46/14

1150 Wien

0664 / 280 26 99

Gruber_Matthias@gmx.net

abgeleisteter Zivildienst

Ausbildung:

| | |
|---|---|
| Sommersemester 2005 | Studium an der Universität Kopenhagen |
| von 2002 bis 2007 | Studium Volkswirtschaft an der Universität Wien |
| von 1996 bis 2001 | Bundes-Handels-Akademie Ried im Innkreis<br>- Ausbildungsschwerpunkt Marketing<br>- 1 Jahr Übungsfirma im Rahmen der Schule<br>- Schulsprecher 1999/2000 |
| von 1992 bis 1996 | Gymnasium Ried im Innkreis |
| von 1988 bis 1992 | Volksschule Ried im Innkreis |

Fremdsprachen:

Englisch und Französisch in Wort und Schrift

Grundkenntnisse in Dänisch

Kenntnisse:

MS Office

E-Views

Berufliche Praxis:

| | |
|---|---|
| 1998 | Kellerbrauerei, 4910 Ried i.I.<br>3 Wochen, Lagerverwaltung |
| 1999 | Hammerer Werbung-Druckerei, 4910 Ried i.I.<br>3 Wochen, Versand |
| 2001 | Fill Metallbau, 4921 Hohenzell, 4 Wochen, Fertigung |
| 2003 | Wochenzeitung Rieder Rundschau, 4910 Ried i.I.<br>2 Wochen, Redaktion |
| 2003 | Europäisches Parlament, Brüssel und Straßburg,<br>4 Wochen, Praktikum im Ausschuss für<br>Umweltfragen und Verbraucherpolitik |
| 2003/04 | Firma 2iAcadamy, 1040 Wien, Nachhilfe in Mathematik |
| 2005 | Hauptverband der Öster. Sozialversicherungsträger, 1030 Wien, 6 Wochen, Praktikum in der Abteilung für Gesundheitsökonomie |
| 2006 | Medizinisches Zentrum „Centre Médico Chirurgical Saint Damien“, Ambanja, Madagaskar,<br>2 Wochen, Volontariat in der Verwaltung |

Berufstätigkeit:

| | |
|---|---|
| seit 01.10.2006 | Investkredit Bank AG, 1010 Wien,<br>geringfügig angestellt in der Abteilung für Kommunikation |
| seit 18.06.2007 | Bundesministerium für Finanzen, 1030 Wien,<br>Abteilung für Wirtschaftspolitik, Referent für Strukturpolitik |

Diverse Erfahrungen:

- Maturaballorganisation
- Zivildienst beim Roten Kreuz, Ausbildung zum Sanitäter und Einsatzlenker
- Ehrenamtliche Mitarbeit beim Hilfswerk Wien – Altenbetreuung
- Verwaltungsarbeit im Flüchtlingslager Traiskirchen