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Climate Agreements under Limited Participation, Asymmetric Information and Market Imperfections

- a summary of a Dr.polit. thesis -

by

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Contents

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List of the papers

Paper no. 1: Golombek, R., C. Hagem and M. Hoel (1995): "Efficient incomplete international climate agreements". *Resource and Energy Economics* 17, 25-46.

Paper no. 2: Hagem, C. (1994): "Cost-effective Climate Policy in a Small Country", *The Energy Journal* 15, 119-139. (With appendix).

Paper no. 3: Hagem, C. (1996): "Joint Implementation under Asymmetric Information and Strategic Behavior". *Environmental and Resource Economics*, forthcoming

Paper no. 4: Hagem, C. (1996): "The value of information and the design of a climate contract under asymmetric information both before and after the contract is signed". *CICERO Working paper* no. 1., 1996

Paper no. 5: Hagem, C. and H. Westskog (1996): "The Design of a Tradeable CO_2-quota System under Market Imperfections". *CICERO Working paper* no 2., 1996

Introduction and summary [*]

The greenhouse effect

The greenhouse effect is a natural phenomenon, whereby certain gases in the atmosphere (called greenhouse gases) and clouds keep the earth's temperature significantly higher than it otherwise would be. Solar radiation from the sun passes relatively unhindered through the atmosphere and is absorbed by the Earth's surface and warms it. This energy is then re-radiated to the space at longer infrared wavelengths. Some of the outgoing infrared radiation is trapped by the naturally occurring greenhouse gases, (principally water vapor, but also carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halocarbons and ozone) and clouds, which keeps the earth's surface and troposphere 33 $^{\circ}C$ warmer than it would otherwise be. This phenomenon is called the "natural greenhouse effect."

The natural greenhouse effect was first described by Baron Jean Baptiste Fourier (1827). In 1896 Svante Arrhenius (1896) calculated the climate effect of a doubling of the concentration of CO_2 in the atmosphere. Nearly fifty years later Callendar (1938) was the first to calculate the warming due to the increasing concentration of CO_2 following from the actual consumption fossil fuels. The added warming effect caused by the gases present in the atmosphere due to human activities such as burning of fossil fuels and land use changes is often referred to as the "enhanced greenhouse effect". The first economic articles on global warming came in the middle of the 1970's (see Nordhause (1976) and (1977)). The problem of a possible global warming due to man-made activities received increasingly attention through the 1980s and is now considered as one of the most important environmental threats to our future.

In 1988, the United Nations Environmental Programme and the World Meteorological Organization jointly established the Intergovernmental Panel on Climate Change (IPCC). The mandate of the IPCC was to provide assessments of (i) the science of climate change, (ii) impacts of climate change, and (iii) to formulate response strategies to climate change. The tasks were carried out by Working Groups I, II and III, respectively. The IPCC published their first comprehensive assessment report in 1990, with contributions of all of the working groups. A supplementary report was published in 1992.

Working Group I stated in their reports IPCC (1990) and IPCC (1992) that human activities had certainly lead to an increase in the atmospheric concentration of greenhouse gases and thereby contributed to an enhancement of the greenhouse effect.
The IPCC reports from 1990 and 1992 constituted the main scientific basis for the negotiation leading up to the United Nations Framework Convention on Climate Change (FCCC). A third report was published in 1994. This report was prepared in order to meet the needs of the first Conference of the Parties of the FCCC.

The IPCC was restructured in 1992 and is now organized into the following three working groups: Working Group I concentrates on the climate system, Working Group II on impacts and response options, and Working Group III on economic and social dimensions. The IPCC second comprehensive assessment report, with contributions of all Working Groups, was completed in 1995.[1]

The IPCC second comprehensive assessment report states that the atmospheric concentrations of greenhouse gases (GHGs) have grown significantly since pre-industrial times and thereby led to a

[*] Thanks to Jan S. Fuglestvedt, Michael Hoel, Jon Strand, and Asbjørn Aaheim for helpful comments.

[1] See IPCC (1996a), IPCC (1996b) and IPCC (1996c) for the contribution of Working Group I, Working Group II and Working Group III, respectively.

positive radiative forcing. Radiative forcing is the perturbation to the energy balance of the earth-atmosphere system measured in Watts per square meter (Wm^{-2}).[2]

The direct radiative forcing of the long-lived GHGs (2.45Wm^{-2}) is due primarily to increases in the concentrations of CO_2 (1.56 Wm^{-2}), CH_4 (0.47 Wm^{-2}) and N_2O (0.14Wm^{-2}) (values for 1992).

The atmospheric concentrations of CO_2, CH_4 and N_2O have increased by about respectively 30%, 145% and 15% since pre-industrial times (i.e. since about 1750). This development can be attributed largely to human activities. The increased concentration of CO_2 in the atmosphere is primarily affected by the burning of fossil fuels and land use changes. Important sources for increased concentration of CH_4 in the atmosphere are rice paddies, animal husbandry, landfills, biomass burning and fossil fuel production. The main antropoghenic sources of N_2O are agriculture, biomass burning and various industrial processes.

The IPCC second comprehensive assessment report states that the global mean surface temperature has increased by between 0.3°C and 0.6°C over the past 100 years. The sea level has risen by between 10 and 25 cm over the same period and much of the rise may be related to the increase in global mean temperature. Variations in climate can have both natural and antropoghenic causes. According to IPCC (1996a) considerable progress has been made in attempts to distinguish between natural and anthropogenic influence on climate. IPCC (1996a) concludes that the balance of evidence suggest that there is a discernible human influence on global climate.

The IPCC has developed six emission scenarios based on assumptions concerning population and economic growth, land use, technological changes, energy availability and fuel mix over the period 1990 to 2100.[3] All except one of the scenarios are non-intervention scenarios ("business as usual" scenarios) which means that the scenarios do not assume any climate policies to reduce GHGs emissions. The mid-range of the emission scenarios cause an estimated increase in global mean surface temperature before the end of the next century of 2°C above the present level, assuming the "best estimate" for climate sensitivity.[4,5] Combining the lowest IPCC emission scenario with a low value for climate sensitivity gives a warming of about 1°C by 2100. The corresponding projection for the highest IPCC emission scenario, combined with a high value of climate sensitivity, gives a warming of about 3.5°C. Regional temperature changes could differ substantially from the global mean value.

The IPCC anticipates that the sea level will rise due to the melting of glaciers and to the fact that water expands when it is heated. The best estimate for the sea level rise in the mid-range of the emissions scenarios is 50 cm by the end of the next century. There will probably be regional variations in sea level changes.

Warmer temperatures will lead to a more vigorous hydrological cycle. This gives prospects for more severe droughts and floods in some regions and less severe droughts and floods in other regions. Several models indicate a possibility for more extreme rainfall events. The current knowledge is, however, insufficient to predict whether there will be any changes in the occurrence or geographical

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[2] Gases emitted to the atmosphere may affect the radiative balance both directly and/or indirectly by their influence on the concentration of other greenhouse gases. Emissions of CO_2 have only a direct effect on the radiative balance, while emissions of CH_4 and N_2O have both direct and indirect effects. Emissions of some other gases have only indirect effects on climate. Emissions of nitrogen oxides (NO_x), for instance, affect the radiative balance indirectly by their impact on the tropospheric concentrations of the GHGs ozone and methane.

[3] See Pepper *et al.* (1992) or IPCC (1995b) for a description of the emission scenarios.

[4] These calculations include the direct radiative forcing effects of all greenhouse gases and the effect of future increases in aerosols.

[5] Climate sensitivity refers to the long term change in global mean surface temperature following a doubling of atmospheric CO_2 concentration. The "best estimate" value of climate sensitivity is 2.5°C , while the "low" and "high" estimates are 1.5°C and 4.5°C, respectively.

distribution of severe storms. A general warming is expected to lead to an increase in the occurrence of extremely hot days and a decrease in the occurrence of extremely cold days.

Human health, terrestrial and aquatic ecological systems, agriculture, forestry, fisheries and water resources are all sensitive to both the magnitude and the rate of climate change. Whereas many regions are likely to experience the adverse effects of climate change, some effects on climate change are likely to be beneficial. The impacts are, however, difficult to quantify and the existing studies are limited in scope.

IPCC (1996a) presents different profiles for CO_2 emissions which would lead to stabilization at a number of different CO_2 concentration levels. It is, *inter alia*, shown that a stabilization of atmospheric CO_2 concentration at about 60 percent above pre-industrial level (or 25 per cent above the 1994-level) could be achieved if global anthropogenic CO_2 emissions drop to 1990 levels by 40 years from now, and drop substantially below 1990 levels subsequently. This profile for CO_2 emissions would imply that the accumulated anthropogenic emissions of CO_2 over the period 1991 to 2100 would be 630 billion tons of carbon (GtC). For comparison, the IPCC mid-range scenario for emissions leads to an accumulated anthropogenic emissions of CO_2 of 1500 GtC over the same period. Hence, emissions of CO_2 have to be considerably reduced compared to "business as usual" emissions in order to avoid climate change.

Stabilization of CH_4 and N_2O concentrations at today's level would involve reductions in anthropogenic emissions of 8% and more than 50% respectively.

The political process

The United Nation's General Assembly established the Intergovernmental Negotiation Committee for Climate Change (INC) in autumn 1990. The task of the committee was to prepare the negotiations for the United Nations' Framework Convention on Climate Change (FCCC). The convention was signed by 154 governments plus the European Union (EU) at the United Nations' Conference on Environment and Development in Rio de Janeiro in the summer of 1992. The FCCC entered into force 21 March 1994, three months after the first 50 countries had ratified it.

The FCCC states that all Parties commit to "develop, periodically update, publish and make available ……, national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol,…" (article 4.1 (a)). Furthermore, all Parties commit to "Formulate, implement, publish and regularly update national and where appropriate, regional programs containing measures to mitigate climate change…. (article 4.1 (b)).

The FCCC divides the world into three groups of countries; (1) the developing countries, (2) annex I countries, which consists of all OECD-countries as of 1992, EU and countries that are undergoing the process of transition to market economy and (3) annex II countries, which only includes all OECD-countries as of 1992 and EU. The Parties to the convention recognize that the developed country parties should take the lead in combating climate change and the adverse effect thereof.

The FCCC does not include any legally binding quantitative commitments for the signatories regarding neither targets for emission reduction nor introduction of policy instrument to reduce emissions. However, each of the annex I countries has committed to " adopt national policies and take corresponding measures on the mitigation of climate change, by limiting its anthropogenic emissions of greenhouse gases and protecting and enhancing its greenhouse gas sinks and reservoirs" (article 4.2 (a))….."with the aim of returning individually or jointly to their 1990 levels" (article 4.2 (b)). Furthermore, the annex II countries shall "provide new and additional financial resources to meet the agreed full incremental cost incurred by developing country Parties in complying their obligations…" (article 4.3).

The FCCC established a Conference of the Parties (COP) as the supreme body of the convention. The first session of the COP was held in Berlin in March/April 1995. At that time 116 countries plus EU were Parties to the convention and were eligible to vote, meaning they had ratified the convention at least three months before. The COP agreed the so-called Berlin Mandate which concludes "that the present commitments under the Convention, notably the commitment of development countries to take measures aimed at returning to their greenhouse gas emissions to 1990 level by the year 2000, are not adequate" (UNEP press release 7 April 1995). The Berlin Mandate established a process that would enable the Parties to take appropriate actions for the period beyond 2000, including a strengthening of developed countries' commitments, through the adoption of a protocol or another legal instrument. The process will not include any new commitments for the developing countries. It was agreed that the work should be completed as early as possible so that the results can be adopted at the third meeting of COP in 1997. So far, no decision has been made regarding policy instruments to combat climate change. A discussion of properties of climate agreements must therefore be based on some assumptions on possible designs of a climate treaty.

Efficient and cost-effective climate agreements

A possible international climate agreement is often evaluated in terms of its efficiency or cost-effectiveness. A cost-effective climate agreement is one which achieves its goals at the lowest cost possible. An efficient agreement implies not only that the goal is achieved cost-effectively, but also that the goal is optimally chosen.[6]

Emissions of GHGs and the resulting changes in the earth climate represent a cost to the society. Avoiding changes in the climate will therefore be beneficial. On the other hand, measures to reduce the changes in climate represent is costly. Traditional cost benefit analysis attempts to compare all cost and benefits expressed in terms of a common monetary unit. The optimal levels of emissions control at each point of time is determined such that marginal costs equal marginal benefit. An efficient climate policy should give the answers to the questions of *how much*, *when* and *how* emissions of the different GHGs should be reduced. This sort of calculations is extremely complex in the case of global warming. The policy makers will face large scientific and economic uncertainties. Furthermore the different nations which negotiate a climate strategy might disagree on the way of calculating cost and benefits, and comparing the effects over time.[7] Some of these factors are discussed below.

- An efficient, comprehensive climate policy should balance the cost of reducing emissions of each greenhouse gas against the environmental cost following from the emissions of the gas. The environmental cost of emissions is a function of the radiative forcing, which in turn depends on the atmospheric concentration of all GHGs. Estimates of the radiative forcing of the emissions of the different gases based on atmospheric concentration are relatively straight forward to calculate. However, due to the significant variation in the different GHGs' lifetime in the atmosphere, radiative forcing based on *emissions* is more complicated to estimate. Estimates of the different GHGs' radiative forcing based on emissions require a consideration of the different gases instantaneous radiative forcing, their indirect effects on other GHGs and their lifetime in the atmosphere.[8] Since the knowledge of the lifetime and the indirect effects of the emitted GHGs is limited, these calculations will be very uncertain.

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[6] For a further discussion of the difference between cost effectiveness and efficiency of international environmental agreements, see Hoel (1993).

[7] See IPCC (1995c) for a discussion of decision making frameworks for addressing climate change.

[8] Hoel and Isaksen (1994) derive the properties of a climate policy which is efficient across all GHGs where they specify a function for the change in atmospheric concentration of all the different trace gases over time. By using optimal control theory they derive the conditions for intertemporally efficient time paths for emissions of the different GHGs. They do, however not take into consideration the uncertainty about the different gases indirect effects and lifetimes. See also Hoel and Isaksen (1995).

- There are large uncertainties regarding the impact of increased radiative forcing on climate, on average and specially on the geographical distributions of the climate response. Furthermore, the impacts of climate change on physical and ecological systems, human health and socioeconomic systems are perhaps even more uncertain.

- Even if there were no uncertainties regarding the physical impact of climate change, the benefit of slowing the climate change may be difficult to calculate because of the problems of evaluating all effects in monetary terms. There is no consensus how to evaluate non-marketed services and goods such as human health, biological diversity and amenity values.

- The costs of reducing the different GHGs are uncertain. The cost of reducing CO_2 emissions has been calculated in several studies and does not differ considerably. Most studies estimate that a global freeze on CO_2 emissions would cost about 1½ percent to 2½ percent of world GNP in the first half of the 21st century (see Cline (1992) for a survey)). However, little is known about the cost of reducing most of the other GHGs.

- Since knowledge at this time is limited, the value of increased information about the climate change process and the impacts, and the society's responses to them, is likely to be great. At all times, an optimal climate policy should also determine the optimal distribution of effort on seeking more information and reducing emissions. Furthermore, the adverse affects of climate change can be mitigated by adaptation policies (as for instance building dikes). An efficient climate agreement also has to find an optimal distribution of adaptation and abatement strategies over time.

- Many of the GHGs have a very long lifetime in the atmosphere. The lifetime of CO_2 is between 50 and 200 years. Emissions of CO_2 today will therefore have an impact on the climate for generations ahead. Furthermore, there is a very long time lag between emissions of GHGs and the full effects on climate change, due to the thermal inertia of the oceans. It is not certain whether it would take decades or centuries before the new equilibrium occurs. This implies that future generations will get the benefit from reduced emissions today, while the present generation will bear the full cost of abatement policies but only get a part of the benefit. Discounting is the analytical tool for comparing economic effects that occur at different points in time. Due to the long time planning horizon, the choice of discount rate has a decisive effect on the optimal choice of emission reduction. The higher the discount rate, the less future benefits and the more current costs matter in the analysis. Economists generally believe that the discount rate used by governments in the evaluation of public policy can be expressed as the sum of the rate of "pure time preference" and the rate of increase in welfare derived from higher per capita incomes in the future.[9] There are, however, disagreement on the choice of the discount rate. The "pure time preference" term of the discount rate will in climate change projects reflect the valuation of future generations' consumption compared to today's generation consumption. The choice of the "pure time preference" is therefore an ethical question, where people in general has different opinions. Furthermore, there is disagreement on the likely rate of future per capita economic growth.

In spite of the above mentioned difficulties, there are several studies on cost-benefit analyses for controlling global warming in the literature. Among the pioneering work in this area are Nordhaus (1991) and (1993), Peck and Teisberg (1992), Falk and Mendelsohn (1993) and Cline (1992). However, due to the large uncertainties and the and complex nature of the problem all of the cost-benefit analyses have made several simplifications in their calculations.

The very complex problem of finding an optimal climate policy over time is reflected in the Conference of the Parties' (COP) ongoing negotiations for climate agreements. The process aim to set quantified emissions limitations for Annex I countries within specified time-frames. The Berlin mandate states that the process will be carried out in the light of the best available scientific information and assessment on climate change and its impact, technical, social and economic information. However, the process does not require that the quantified emissions limitations is an optimal climate policy following from a cost-

[9] Shelling (1993) argues against the way discounting is generally applied to climate change projects.

benefit analysis. The main challenge for the COP is to design a climate policy where sufficiently many countries are willing to participate in the climate agreement suggested. A broad participation is necessary to achieve significant reductions in the emissions of GHGs. This implies that the decision maker (COP) has to find a way to distribute the cost of a climate agreement which is perceived as sufficiently "fair" for the different countries to participate. Furthermore, an other requirement the agreement should try to meet is *cost-effectiveness*, which means that whatever global emission goal one set, this goal should be achieved at as low cost as possible.[10]

Climate agreements under limited participation, asymmetric information and market imperfections

This thesis focuses on the *cost-effectiveness* of possible climate agreements.
The problem of choosing an optimal level for emissions over time through cost benefit analysis is not discussed in the thesis.[11] The issue of "fair" distribution of burdens of the climate agreements is also ignored. Furthermore, all papers restrict the analysis to climate agreements that only covers the emissions of CO_2.

The focus on only CO_2 in this thesis is chosen for two reasons. The first reason is that emissions of CO_2 are the most important contributors to the man-made enhancement of the greenhouse effect and are relatively easy to monitor. CO_2 will therefore be the first gas to be included in a climate agreement. Emissions of CO_2 have been responsible for over 60 per cent of the increased direct radiative forcing due to man-made emissions of GHGs and are likely to remain the most important contributors also in the future. The locations for the emissions of the different GHGs are not directly observable. However, unlike most emissions to the atmosphere, anthropogenic emissions of CO_2 are almost directly linked to the use of fossil fuels and land use changes.[12] To reduce emissions of CO_2, one may impose instruments on the use of fossil fuels and land use changes. Observing, for instance, the reductions of nitrous oxide (N_2O) and methane (CH_4) emissions is more complicated then for CO_2 since the emissions are more technology-specific, and varies with, among other things, the combustion conditions. Controlling and verifying emissions will have to rely on measurements and site inspections.

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[10] See Hoel (1991a) and Chander and Tulkens (1994) and (1995) and Heal (1994) for a discussion of requirements for international cooperation.

[11] In the theoretical part of one of the papers, (paper 1), the climate agreement studied is *efficient* in the sense that net income minus environmental cost is maximized. However, the environmental cost function is not specified and it is replaced by an arbitrarily chosen emission constraint in the empirical part of the paper.

[12] A minor part (2 %) of the antropoghenic emissions of CO_2 is caused by cement production. (1991/1992 figures from World Resources Institute (1996)).

The other reason for the focus on only CO_2 in this thesis is that it simplify the analysis considerably. Including more gases than CO_2 in a climate agreement will in general not influence the main economic properties of the design of measures aimed at reducing CO_2.

CO_2 is well mixed throughout the atmosphere. This implies a global climate effect that is independent of the location of emissions. A cost-effective distribution of CO_2 emissions reductions implies that the marginal costs of emissions reductions are identical across all sources for emissions. Internationally harmonized carbon taxes or tradable CO_2-quotas have often been proposed as policy instruments in an international climate treaty. Both systems will secure cost-effectiveness and can separate the issue of distribution of burdens across countries from the issue of cost-effectiveness if all countries are small. (Implications of large countries will be discussed below.)

In an internationally harmonized carbon tax system, an international agency could impose carbon taxes on each country where the tax per unit of CO_2 emissions is identical across all countries. It is then optimal for all countries to reduce their emissions of CO_2 until the cost of an additional unit CO_2 abated is identical to the CO_2 tax. This will imply that the marginal abatement costs are identical across all countries, equal to the carbon tax. The distribution of the economic burdens across countries will be determined by the reimbursement rules for the tax revenues.

In a tradable quota system, each country receives an initial amount of CO_2 quotas, which can be traded. It is optimal for all countries to sell (buy) quotas as long as the market price for quotas is higher (smaller) than their own abatement cost since their emissions can not exceed the total amount of quotas held be the country. In equilibrium, the marginal abatement cost is equalized across all countries and equal to the market price on quotas. In this system, the distribution of the economic burdens across countries will be determined by the initial allocation of quotas.

A prerequisite for *global* cost-effectiveness of achieving a global limit in emissions is that all countries participate in the climate agreement. Limited participation in a climate agreement implies that the total cost of achieving the global limit increases. Marginal abatement costs can not be equalized across *all* countries, if not all countries participate. Limited participation in a climate treaty has also important consequences for the optimal choice and the design of policy instruments. The design of the climate treaty should take into account how different policy instruments can be used to influence the emissions from countries which do not participate in the agreement. Consequences of limited participation on the design of climate agreements are discussed in section 0.

Even if all countries participate in an international climate agreement neither tradable quotas nor harmonized CO_2 taxes will ensure cost-effectiveness if some countries are large and act strategically. In section 0 I discuss the impact on cost-effectiveness of a tradable quota system if some countries have market power.[13]

Limited participation in climate agreements

According to FCCC and the Berlin mandate the developing country Parties shall not carry any of the cost of the measures to combat climate change. Any climate agreement reached in the near future will rest on the premise that sufficient number of developed countries are willing to carry the economic burden of the agreement.

[13] See Hoel (1991b) for a discussion on the impact on cost effectiveness of CO_2 taxes when countries take into consideration that their emissions of CO_2 have a significant impact on future climate change and that their own reimbursement of the total international tax revenue are influenced by their own emissions.

One can argue that a stable coalition of cooperating countries among the industrialized countries may not be agreed due to the free rider incentives. If many countries cooperate to reduce emissions, any individual country could be better off if the other countries cooperate, while the country does not take part in the agreement and pursues its own interest. However, it is well known from game theory that it is possible to sustain a tacit collusion as a perfect equilibrium in repeated games.[14] Furthermore as argued in Hoel (1994), countries might not be only concerned about their own welfare, measured in economic terms. Governments also take into account social norms and conventions when designing their policy. If all other countries in a well-defined group, as for instance EU or OECD all participate in a coalition, it might be very “costly” to deviate.

The starting point of paper 1 to 4 is that a limited number of countries participate in a climate agreement in spite of free rider incentives. The countries that participate are referred to either as the participating countries or the cooperating countries, while the countries that do not participate are referred to as either the non-participating countries or the non-cooperating countries. I assume that the participating countries have a target for *global* emissions reductions and have accepted to carry the cost of achieving the target. I will not consider the distribution of costs among the participating countries.

A global emissions reduction can be achieved either through emissions reductions within the group of participating countries, or (partly) through financing abatement in countries outside the coalition. In the first policy, a cost-effective agreement implies that the participating countries should take into account that their policy might have an indirect effect on the emissions of other non-participating countries. In the other policy alternative, the participating countries directly seek to influence the non-participating countries' emissions in order to reduce the cost of achieving a certain reduction in global emissions.

Limited participation and indirect impact on non-participating countries’ emissions

With limited participation in a climate agreement, reduced emissions from the participating countries may to some extent be counteracted by increased emissions from other countries. This effect of unilateral actions is often measured by the so called "leakage rate," which is the percentage by which resulting global reductions fall short of initial cutbacks. There are three reasons for leakages. First, reduced demand can cause the international fuel prices to fall. The reduction in prices has the undesirable effect of giving other countries an incentive to increase their use of fossil fuels and partly offset the initial reduction. Second, several exported products use fossil fuels as inputs. A national carbon tax may involve higher prices and less export of these products. The reduction in national CO_2 emission may therefore be offset by a higher production of manufactured goods in other countries to meet the international demand. Third, if unilateral abatement reduces the global emissions and therefore the damage potential from climate change, it may weaken the commitments from other countries (if their environmental cost functions are strictly increasing in emissions).

Several authors have estimated the first two reasons for carbon leakages. Barrett (1994b) gives a survey of some of the estimates on carbon leakages in the literature. The results vary considerably.[15] For example, Pezzey (1992) finds, by using the Whally-Wigle model (see Whalley and Wigle (1991)), that a cut in EC-countries’ fossil fuel consumption by 20 per cent causes a leakage rate of 80 per cent. Oliveira-Martins *et. al* (1992a), present simulated carbon-leakages in the GREEN-model. They find that a stabilization of CO_2 emissions at 1990 level in 1995 in EU-countries causes a leakage rate of only 12 per cent.

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[14] See Carraro and Siniscalco (1993), Hoel (1994) and Barrett (1994a) for a further discussion of the existence of a stable coalition in spite of free rider incentives.

[15] Any calculation of the effect on international fuel prices will be highly dependent on how the world energy markets are modeled. Dean and Hoeller (1992) give a comparison of how some of the various global models work

Bohm (1993) discusses different approaches to mitigate the price effect of reduced demand for fossil fuels. He focuses in his article on the options of reducing supply in countries not participating in an international climate agreement.

Two of the papers of this thesis (paper 1 and paper 2) discuss how the direct leakage effect through the prices on fossil fuels should be taken into account when designing a climate policy within the participating countries. In a situation where all countries participate in an agreement to reduce CO_2 emissions, taxes on consumption and production of fossil fuels have identical economic consequences, provided the use of tax revenues is identical in the two situations. This is no longer true when there is limited participation in an international agreement due to the leakages through the changes in the international fuel prices. This has been discussed by Hoel (1994) in the case where the fossil fuel markets are modeled as one aggregate market.

In paper 1, which is a joint paper with Michael Hoel and Rolf Golombek, we analyze whether a differentiation of the carbon tax (per unit carbon) between different types of fossil fuels can be used as a way to influence CO_2 emissions from non-participating countries. The starting point of the paper is that a group of countries cooperate in order to maximize their net income minus their environmental cost, which depends on the sum of CO_2 emissions from all countries. The cooperating countries produce and consume oil, coal and gas. We assume competitive supply of all three kinds of fuels in the cooperating countries. We analyze the optimal design of carbon taxes under two different assumptions about the tax policies: a) taxes on only consumption (or only production) and b) taxes on both production and consumption.

Increased production or consumption of an internationally traded fossil fuel will have an impact on the international fuel prices and thereby the cooperating countries' net import or export revenue and the net emissions from the non-cooperating countries. The impact on the international fuel prices and the net import/export revenue depends on the cooperating countries' and the non-cooperating countries' demand and supply elasticities and the production and consumption of the different fuels in the two groups of countries.[16] The impact on the net export revenue and the non-cooperating countries' emissions of decreased consumption (or production) of fossil fuels in the cooperating countries will in general differ between the fuels. This leads to the conclusion that when the cooperating countries tax only consumption (or production) of fossil fuels, the tax per unit of carbon should in general be differentiated across fossil fuels.

However, when both production and consumption of internationally traded fossil fuels are taxed, the *sum* of the producer tax and the consumer tax should be equal across all fossil fuels per unit of carbon. As an international fuel price only depends on net demand from the cooperating countries, this price does not change when production *and* consumption of the cooperating countries increase by one unit. Hence, the only effect is the increase in emissions from the cooperating countries by one unit of CO_2. With cost-effective production, the total tax per unit of carbon should be equal to the marginal environmental cost of total emissions in the cooperating countries. As our argument is independent of type of fossil fuel, this lead to the conclusion that the *total* tax per unit of carbon should be the same for all fossil fuels. The optimal *combination* of taxes on consumption and production will, however, in general differ across fuels. An extension of this analysis is carried out in Hoel (1996), where also the production and location decisions of energy intensive sectors producing tradeable goods are included in the analysis.

The topic of paper 2 is unilateral actions in adopting carbon taxes in small countries.
Small countries such as Finland, Sweden, the Netherlands and Norway have all taken unilateral actions in adopting carbon taxes. The EU has as a target for the Community as a whole to stabilize the CO_2 emissions at the 1990 level by the year 2000. Unilateral commitments are so far all related to the CO_2 emissions nationally or in a group of countries. However, a country that produces and consumes fossil fuels can also

[16] In the derivation of the optimal design of carbon taxes we have assumed that the non-cooperating countries are price takers. However, we have also pointed out that the main conclusion will hold also under more general market structure than perfect competition. Golombek and Bråten (1994) study optimal carbon taxes in the presence of market failure when not all countries participate in the international agreement. Their results indicate that optimal taxes are not strongly dependent on whether the crude oil producers in the non-cooperating countries are price takers or Cournot players.

influence the *global* CO_2 emissions by reducing its production. The purpose of the paper is to study the cost-effectiveness of a unilateral action in a small country that produces and consumes fossil fuels.[17] It is analyzed whether it is less costly to reduce consumption or production, given that the impact on the *global* reduction of CO_2 emissions is the same in the two cases.

Reduced consumption (or production) of fossil fuels in a small country will have only a very small effect on international fossil fuel prices. However, even a minimal change in the international fuel prices will have an impact on consumption in the rest of the world. Although the impact on the consumption in the rest of the world is negligible in relation to total global consumption, it can be significant in relation to the initial national reduction. The final impact on global emission reduction can thus be significantly less than the initial reduction in national consumption (production).

Norway produces and consumes fossil fuels and had a preliminary target to stabilize its CO_2 emissions at the 1989 level by the year 2000.[18] In the empirical part of the paper I compare the cost of a reduction in consumption of fossil fuels in Norway to the cost of a cut in production, given that the effect on global CO_2 emissions is identical. In the calculation it is assumed that only Norway takes action. The starting point of the comparison of the cost of the different climate policies is the calculations presented in the report from the Environmental Tax Committee (ETC) (1992). The report presents the estimated cost of achieving the national target through imposing taxes on fossil fuel consumption. The cost of that "consumption tax" policy is compared to an estimated cost of reducing national fossil fuel production in the year 2000. The calculation reveals that the cost of reducing national production of gas or oil can be a less costly policy to achieve a certain reduction in global CO_2 emissions than the "consumption tax" policy presented by ETC.

Limited participation and direct impact on non-participating countries' emissions under asymmetric information

Inducing non-cooperating countries to reduce their emissions, through side-payments, could reduce the cooperating countries' costs of achieving their target for *global* emissions reductions. Several studies have pointed out the differences in CO_2-abatement costs across countries, and hence the scope for cost savings by an efficient distribution of abatement across countries. See UNEP (1994) for a comparison of abatement costs in some developing countries and Kram and Hill (1996) for a comparison of abatement costs in selected industrialized countries. Several of the global models for abatement costs divide the world into different regions. The Edmond-Reilly model (see Barns et al. (1992)), the Manne-Richels model (See Manne (1992)) and the OECD model GREEN (See Oliveira-Martins *et al.* (1992b)) have all compared the cost of achieving a global abatement target through cost-effective abatement across regions with a system of a given percentage reduction in each of the regions. Dean (1993) gives a comparison of the cost-reductions due to trade in emission quotas in the case of a 2 percentage annual emissions reductions relative to baseline in the different models. All of the models show gains from emission trade. The largest gain is for GREEN where the global output loss halves from two percent to one percent of global GDP in 2020.[19]

Even large emissions reductions in the developed countries may not be sufficient for a significant global emissions reduction in the future. The reason for this, in addition to carbon leakages, is that the developed countries' share of global emissions will be considerably reduced in the future. OECD countries contributed to 38 % of global CO_2 emissions in 1990.[20] This ratio will, according to the mid-range IPCC emissions scenario, decrease to 30 % in 2025 and 22 % in 2100. If the Conference of the Parties does not introduce any new commitments for the developing country parties, side- payments to

[17] In this paper it is hence only one country that "participate" in the climate "agreement".

[18] The Norwegian Government announced in 1995 that this stabilization target will not be met.

[19] The Manne-Richels model provides figures for carbon taxes in the no-trade and the trade case, but not GDP-figures.

[20] This figure includes land use changes. OECD's share of global emissions due to energy use was 47% in 1990.

induce the developing countries to implement abatement strategies may not only reduce the cost of achieving a global emissions target but also be necessary for achieving significant global emissions reduction. Side-payments to induce countries to join a climate treaty is *inter alia* discussed in Barrett (1991), Carraro and Siniscalco (1993) and Hoel (1994).

The FCCC states that developed country Parties and other parties included in annex I countries may implement policies and measures *jointly* with other Parties in contributing to the achievement of the objective of the Convention.[21] So called "Joint implementation" (JI) or "activities implemented jointly" is a mechanism for reducing the global cost of achieving a cut in global emissions of greenhouse gases through international cooperation. The idea of JI is to reduce the total cost of a given reduction in the emissions of greenhouse gases by separating the commitment of each country Party from the implementation of measures. The Berlin mandate decided to establish a pilot phase for activities implemented jointly. However, no credits shall accrue to any Parties during the pilot phase.

The concept of JI has been widely discussed in the literature.[22] The term "JI" is usually used for investment in specific abatement projects. The investor finances JI projects and receives abatement credits for the abatement achieved through the projects. A major criticism of JI refers to the problem of estimating the actual net abatement of JI projects between an investor in a country that has made binding commitments for emissions reductions and a host in a country without. Estimating net abatement requires an estimate of an unobservable baseline for the emissions in the *absence* of the JI project. Furthermore, the impact on emissions of the realization of a JI project could be difficult to observe. Even in the case where the emissions *ex post* from the firm which implement the project are manageable to estimate, the nationwide effects may fall significantly short of the firmwide effects. The project may have a significant impact on fossil fuel use in other activities through market interactions. It is thus in general a difficult and costly task to estimate baseline scenarios for the host countries and to estimate the total impact on emissions of a JI project. These problems are *inter alia* discussed in Bohm (1994). He also points out that the investor and the host may have a common interest in misrepresenting the net abatement effect

[21] See article 4.2 (a) of FCCC.

[22] See inter alia Barrett (1993a) and (1993b), Jones (1993), Bohm (1994) and Hanisch *et al*. (1993).

following from a JI project. Asymmetric information between the host and the investor on one side and the agency which awards the abatement credits, (hereafter referred to as the crediting agency), on the other side may have an adverse effect on global emissions of a JI-regime.

In paper 3 I focus on the possible adverse effect on global emissions of a JI regime, *even if* it is possible to estimate the correct abatement of the project *ex post* and the crediting agency has access to the same information as the investor. I relate the analysis to the micro level, where investor firms in one country with a binding target for emissions, offer abatement contracts to host firms in another country without an emission target. I analyze the design of the abatement contracts within a principal-agent framework.

Principal-agent models in the literature are used to study contracts under asymmetric information.[23] One party, called the principal, pays another party, called the agent, to perform a task. The two parties make a contract in a situation where the agent acquires an informational advantage about her type, her actions, or the outside world. The informational constraints force the principal to design a contract which is "second-best." A second-best contract is optimal given informational asymmetry, but differ from the optimal contract designed when the principal and the agent have the same information set.

When investors (principals) invest in abatement projects in another country, they might face asymmetric information. Some of the relevant information about the impact on the abatement or the cost of an investment may be private information held by the host (agent). Furthermore, the actions taken by the host to implement the projects might not be observable to the investor. Private information held by the host has an impact on the design of JI contracts. A main characteristic of the design of a JI contract under asymmetric information is that private information held by the host may be beneficial for her. The potential host firms may act strategically to take advantage of their private information. One type of strategic behavior is to abstain from investing in less polluting technology today in order to retain the possibility of being offered a profitable JI contract in the future. In paper 3 I show that this kind of strategic behavior implies that a JI regime could cause an increase in global emissions even though the crediting agency only awards abatement credits for actual net abatement. The reason for this is that the crediting agency cannot adjust the abatement credits for the impact of a JI regime on abatement in the host country *ex ante* of the implementation of the JI projects.

In the process of planning, developing, implementing, monitoring and controlling JI projects there are transaction costs.[24] The transaction cost share of total costs is probably larger for small-scale JI projects than for larger JI projects. Bohm (1994) argues that for this reason a typical JI project will not be small.

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[23] Surveys of this literature can be found in, for example, Hart and Holmstrøm (1987), Kreps (1990) and Rasmusen (1989).

[24] See Barrett (1993b) for a discussion of transaction costs and the development of institutions to reduce such costs.

In paper 4 I have considered a JI project that is "large" in the sense that the cooperating countries finance a non-cooperating country for reducing its emissions through a range of abatement investments. The non-cooperating country can choose which and how many abatement investments to implement. The non-cooperating country is paid by the cooperating countries depending on the emission reduction achieved. An example of this kind of contract could be a non-cooperating country that reduces the emission of CO_2 by substituting some of the national consumption of coal by gas for heat supply.[25] The non-cooperating country can choose how much of the coal use it will replace by gas.

In paper 4 I analyze the cooperating countries' policy toward a non-cooperating country in a situation where relevant information about the non-cooperating country's abatement cost is costly to obtain for the cooperating countries. I have assumed that the non-cooperating country has access to private information both before an after the climate contract is signed. The purpose of the paper is to analyze the optimal design of a climate contract and evaluate under what circumstances and at what time it is valuable for the cooperating countries to acquire more information about the non-cooperating country's abatement cost, although this is costly. I analyze the optimal design of the abatement contract and the value of information within a principal-agent framework. The principal acts on behalf of the cooperating countries and the agent acts on behalf of the non-cooperating country. (The problems of estimating the correct abatement following from the contract and possible adverse effects on global emissions due to strategic behavior, as discussed paper 3, is ignored in paper 4.)

The cooperating countries have two options for what time they can acquire information. Information about the non-cooperating country's expected abatement cost can be obtained before the contract is offered, or the cooperating countries can

[25] A coal-to-gas conversion pilot project, partly financed through a grant from The Global Environmental Facility (GEF) and the Government of Norway, is about to be implemented in Poland. (GEF is managed by the World Bank, the UNDP and UNEP). The grant partly covers the cost of a replacement of coal fired boilers with condensing gas fired boilers for heat supply and a replacement of coal fired boilers with a cogeneration unit based on gas supplying heat and electricity. See Selrod and Sørensen (1994) for a description of the project.

design a contract that will give them access to the same information as the non-cooperating country obtains when implementing the various abatement projects. The latter type of information can be acquired if the cooperating countries monitored the implementation of the projects.

I have assumed that both the cooperating countries and the non-cooperating country are risk neutral. Furthermore, since the climate contract considered in this paper is a contract between countries, I have assume that it is not possible for the cooperating countries to enforce the non-cooperating country to fulfill the contract if it finds it more beneficial to breach the contract. The only instrument for inducing the non-cooperating country to fulfill the contract is the monetary transfer specified in the contract. Hence, if the non-cooperating country, after observing all relevant information, realizes that it is less costly to breach the contract and get no payment than to fulfill the contract and get the payment specified in the contract, the non-cooperating country will breach the contract.

I have analyzed two different situations regarding the non-cooperating country's cost of breaching the contract in the paper. If the non-cooperating country learns the complete abatement cost at an early stage, that is, when only a few abatement projects have been implemented, the sunk cost of the non-cooperating country's investments in abatement projects is low. I have referred to that situation as a situation where the non-cooperating country's cost of breaching the contract is low. I have assumed that the cost of breaching the contract in that situation is so low that the cooperating countries have to take into account that they have to prevent the non-cooperating country from breaching the contract, when they design the optimal contract.

If a lot of projects have been implemented before the complete abatement cost is learned, the cost of breaching the contract and hence get no payment could be very high. That situation is referred to as a situation where the non-cooperating country's cost of breaching the contract is high. The non-cooperating country's cost of breaching the contract is assumed to be so high that the cooperating countries do not have to take into account that they have to prevent the non-cooperating country from breaching the contract, when they design the contract.

In the paper I have showed that private information at the time of entering into a contract is beneficial for the non-cooperating country both when the cost of breaching the contract is low and when it is high. The optimal abatement contract in case of asymmetric information will leave the non-cooperating country with a positive profit. Furthermore, the contract will not ensure cost-effective distribution of abatement between the non-cooperating country and the cooperating countries. Acquiring information before the contract is offered has therefore a positive value for the cooperating countries. Whether it is optimal to acquire that information depends on the cost of obtaining information.

The cooperating countries' cost of the contract will be reduced if the non-cooperating country has to announce its private information at the points of time when information is observed compared to a simultaneous announcement after both types of information have been observed.

If the non-cooperating country's cost of breaching the contract is high, I find that the cooperating countries can achieve the first best contract if they get access to the same information as the non-cooperating country has before the contract is offered. The distribution of abatement between the cooperating countries and the non-cooperating country is in that case cost-effective and the cooperating countries extract all rent. In that situation there will be no additional benefit for cooperating countries to monitor the implementation of the abatement projects. However, if the non-cooperating country has some private information about the cost function before the contract is signed, private information obtained after the contract is signed will increase the non-cooperating country's expected profit. Monitoring the implementation of the abatement projects will hence in that situation increase the cooperating countries' expected benefit of the contract (exclusive the cost of monitoring).

The cooperating countries' access to the same information as the non-cooperating country has before the contract is signed will not be sufficient to ensure the first best contract if the non-cooperating country's cost of breaching the contract is low. Private information after the contract is signed implies, in that situation, that the optimal contract will leave the non-cooperating country with a positive expected profit. It could therefore be beneficial for the cooperating countries to monitor the implementation of the abatement projects even if they have the same information as the non-cooperating country when the contract is signed.

The cooperating countries' value of monitoring the implementation of the various abatement projects is always higher when the non-cooperating country's cost of breaching the contract is low than when it is high.

Non-competitive market for tradable quotas.

It has long been established that market power within a system of tradeable quotas could give inefficiencies. Two aspects of the market power problem have been discussed in the literature. First, agents may use their market power to influence the quota price in order to reduce their cost of the climate policy. Second, agent may also use quotas to influence the behavior of rivals in the same industry. The first kind of strategic behavior is *inter alia* discussed in Hahn (1984). He shows how a price setting buyer (seller) of quotas will force down (up) the quota price below (above) the competitive level. The monopsonist (monopolist) will buy (sell) too few quotas relative to the cost-effective solution. The second kind of strategic behavior is *inter alia* discussed in Misiolek and Elder (1989) who analyze a dominant firm facing a fringe of price-taking competitors in the product market. They argue that the manipulation of the quota market can be an effective strategy to increase the dominant firm's market share and profit. Depending on the initial distribution of the quotas, market power in the product market can sometimes increase and sometimes decrease the abatement inefficiencies identified by Hahn (1984). Von der Fehr (1993) analyses tradeable quotas and oligopolistic interaction. He shows that tradeable quotas can serve as an instrument for monopolization. Strategic considerations strengthen incentives for investment in quotas.

It is shown by Hahn (1984) that the efficiency loss from market power depends on the initial allocation of quotas. Hence, there is no longer separability between the issue of distribution of burdens across countries and the issue of cost-effectiveness.

In paper 5, which is a joint paper with Hege Westskog, we look at a tradable CO_2-quotas system where one country acts strategically to influence the quota price. We analyze the possibility of improving the cost-effectiveness of a tradable quota system by making the quotas last for several periods and arrange trade of quotas in each period.

The starting point of the paper is that some countries (or all countries) participate in a climate agreement where they have agreed on a ceiling on the global CO_2 emissions during a certain time period. The period is divided into two equally long sub-periods. The participating countries have also agreed on the initial distribution of quotas among the participating countries. We assume that one of the countries is a large seller of quotas and exercises market power in the quota market. This country is referred to as the monopolist.[26] All other countries are so small net buyers or sellers of quotas that they can be considered as price takers. These countries are referred to as the fringe. In total, the fringe is a net buyer of quotas. We compare two different designs of tradeable quota systems.

[26] The main conclusions of the paper is not affected whether we have a monopolist or a monopsonist, or if there are more than one larger seller (or buyer) of quotas

1) A system where the quotas entitle the holder to emit a fixed amount of CO_2 emissions over both sub-periods with no restrictions on the allocation of emissions between the different sub-periods. Trade is arranged at the beginning of the period. This system is referred to as a *flexible quota system*.

2) A system where the quotas entitle the holder to emit a certain amount of CO_2 emissions in each sub-period. (The quota may specify different amounts of CO_2 emissions in each sub-period). Trade is arranged at the beginning of each sub-period. This system is referred to as a *durable quota system*.

A durable quota is comparable to a durable good. It is shown in the literature that when a good is durable and sold by a monopolist in different periods, it is profitable for the monopolist to lower the price in subsequent periods in order to sell additional quotas. (See for instance Tirole (1988) or Rasmusen (1989) for a simple analysis of a durable good monopoly.) The buyers will expect that the monopolist will lower the price in future periods in order to sell more quotas. These rational expectations hurt the monopolist because the buyers are willing to pay less for quotas today, when they anticipate a fall in the prices in the future. The monopolist's incentive to sell additional units in each sub-period in the durable quota system can reduce some of the efficiency loss from market power compared to a flexible quota system. However, we show that the durable quota system could give rise to efficiency losses across periods due to a non-optimal distribution of abatement across periods.

In a flexible quota system each country will distribute abatement cost-effectively across periods. The difference in marginal abatement costs across countries could however be higher compared to a durable quota system. Hence, we face a trade-off between a cost-effective distribution of abatement across periods and reduced adverse effects of market power. The trade-off between these two effects is the main topic of the paper.

We show that the difference in total abatement costs of the two different quota systems depends on the initial distribution of quotas and the changes in abatement costs and "business as usual" emissions over time.

We close the paper by some numerical illustrations of the cost differences between the two systems by the use of the CO_2-abatement cost functions taken from Bohm and Larsen (1994) and "business as usual" emissions scenarios taken from the IPCC second comprehensive assessment report.

Conclusions

Marginal abatement costs differ among countries. A climate treaty that specifies fixed emissions reductions for the different countries that participate will therefore, in general, not achieve a cost-effective distribution of abatement across countries. International CO_2-taxes, tradable quotas and joint implementation (or other kinds of side-payments) have often been suggested as policy instruments in an international climate treaty, because they can reduce the total cost of achieving a certain global target for emissions relative to "fixed reduction" types of agreements.

The cost-effectiveness of taxes, tradable quotas and joint implementation or other kinds of side-payments may be reduced in the case of limited participation in the climate treaty, asymmetric information and market imperfections. In the thesis I have pointed out how these factors influence the cost-effectiveness and the optimal design of the policy instruments. The main conclusions of this thesis are as follows:

- In that case of limited participation in a climate agreement, the initial reduction in emissions from the participating countries can be partly offset by increased emissions from the non-participating countries due to a fall in the international fossil fuel prices. In a situation where *all* countries participate in an agreement to reduce global CO_2 emissions, taxes on consumption of fossil fuels and taxes on production of fossil fuels have identical economic consequences, provided the use of the tax revenue is identical in the two cases. This is no longer true when there is limited participation in the agreement. When both production and consumption of internationally traded fossil fuels are taxed, a particular combination of producer and consumer tax exists which is optimal under limited participation. The *sum* of the consumer tax and the producer tax should be equal across all fossil fuels per unit of carbon. When the participating countries use tax on consumption (or production) as the only policy instrument, the tax per unit of carbon should in general be differentiated across fossil fuels.

- Several countries have taken unilateral actions to reduce their own emissions of CO_2, through taxes on consumption of fossil fuels. However, if these countries aim at contributing to a reduction in *global* emissions of CO_2, policies to reduce their production of internationally traded fossil fuels should also be considered when designing their climate policy. For countries with high marginal abatement cost, a certain contribution to a global emissions reduction can be achieved less costly through reduced national fossil fuels production than through reduced national fossil fuels consumption. Norway both produces and consumes fossil fuels and has high marginal abatement cost for CO_2. Some quite rough calculations carried out in this thesis conclude that a cost-effective climate policy in Norway, given a target for global emissions reduction, implies a reduction in the production of oil rather than introducing uniform taxes on fossil fuels consumption.

- When there is a limited number of countries that participate in a climate agreement, inducing agents in non-participating countries to reduce their emissions, through joint implementation (JI) projects, can reduce the participating countries' cost of achieving a certain target for global emissions. However, the potential cost savings from JI can be reduced due to asymmetric information. Furthermore, private information held by agents in the non-participating country can have an adverse effect on global emissions reductions. Private information will leave the agents in the non-participating countries with a positive profit. The prospects of participating in profitable JI projects in the future may prevent agents from investing in less polluting technology today.

- Side-payments to induce governments in a non-participating country to implement various abatement projects is another option for reducing the participating countries' cost of achieving global emissions reductions. Even though the non-participating country may have some private information about its abatement cost when entering into an abatement contract, the complete abatement cost function may not be known to the country at that time. However, the non-participating country may privately observe its complete abatement cost when it starts to implement various abatement projects. In that case the non-participating country has access to private information both before and after the abatement contract is signed. Private information held by the non-participating country at the time of entering into an contract is always costly for the participating countries. Private information *after* the contract is signed is costly *in combination* with private information at the time of entering into a contract, even though the non-participating country is risk neutral. The participating countries' cost of the non-participating country's access to private information both before and after the contract is signed depends on whether the non-participating country may breach the contract if its abatement cost turns out to be very high.

- It is a well-known result that market power can reduce the cost-effectiveness of a tradable CO_2 quota system. In this thesis it is studied the possibility of improving the cost-effectiveness of a tradable quota system by making the quotas last for several periods and arrange trade of quotas in each period (refereed to as a durable quota system). The durable quota system is compared to the quota system usually examined in the literature, where the quotas are traded only once. We show that the durable quota system suggested in the thesis can reduce the efficiency loss due to market power and therefore *cet. par.* reduce the total cost of a tradable quota system. However, durable quotas can cause an increase in total abatement cost due to an non-optimal distribution of abatement across time. Whether the durable quota system suggested in this thesis is more cost-effective than a quota system where the quotas are only traded once depends on the initial distribution of quotas among countries and the changes in abatement costs and business as usual emissions over time.

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