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Climate Change Policy in a Second-Best World

An Analysis of Policy Options under Conditions of Partial Cooperation and Uncertainty

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Summary

Starting from the premise that climate change policymaking takes place under considerable uncertainty and suffers from a lack of international cooperation, and that this prevents the implementation of a global first-best policy, the present thesis poses the second-best question of what can be done despite these constraints and compares different policy options.

Under conditions of partial cooperation, two questions of the second-best type arise: (i) What can already cooperating countries do to ensure their climate policies are effective and cost-efficient? (ii) How can the highest possible level of international cooperation be achieved? In this thesis, these issues are treated by assessing different institutional forms of emissions trading, in particular the 'linking' of permit markets, and, also, by adopting a game-theoretic view to analyze in how far trade sanctions can help to broaden international cooperation. The results show (a) how institutional incompatibilities and general equilibrium effects could reduce the benefits of a linking agreement, and (b) that tariffs have a significant potential to increase participation in a climate agreement.

Uncertainty, and how it affects different policy instruments, is the other second-best aspect investigated. So-called intensity targets, which index emission targets on GDP, are analyzed with regard to their effect on cost-uncertainty, and their compatibility with international emissions trading. The results suggest that due to the increased complexity and the potentially only modest benefits of an intensity target, conventional absolute targets remain a robust choice for a cautious policy-maker.

Keywords: Economics of Climate Change, Linking, International Cooperation, Intensity Target, Uncertainty.

Zusammenfassung

Ausgehend von der Annahme dass Klimapolitik unter hoher Unsicherheit operiert und dass - unter den derzeit gegebenen politischen Umständen - die Umsetzung einer global optimalen Klimapolitik sehr unwahrscheinlich erscheint, erkundet die vorliegende Arbeit mögliche ‚zweitbeste' Optionen und vergleicht verschiedene Politikinstrumente ihrer Umsetzung.

In einer Welt begrenzter internationaler Zusammenarbeit stellen sich in Bezug auf zweitbeste Optionen folgende Fragen: (i) Wie können bereits kooperierende Länder sicherstellen, dass ihre Klimaschutzmassnahmen wirksam und kosteneffizient sind? (ii) Wie kann ein höchstmögliches Maß an Kooperation erreicht werden? Bezüglich dieser Punkte werden in dieser Arbeit zum einen verschiedene institutionelle Formen des Emissionshandels – insbesondere das ‚Linking' von Zertifikatsmärkten – analysiert. Zum anderen wird aus einer spieltheoretischen Perspektive untersucht, inwieweit Handelssanktionen zu einer Verstärkung von internationaler Klimakooperation beitragen können. Die Ergebnisse zeigen (a) wie institutionelle Unverträglichkeiten und allgemeine Gleichgewichtseffekte den Nutzen eines Linking-Abkommens verringern können, und (b) dass die Anzahl der Beitrittsländer eines Klimaabkommens durch die Anwendung von Handelszöllen signifikant erhöht werden könnte.

Als weiteres Anwendungsfeld von zweitbesten Optionen widmet sich die Arbeit dem Thema Unsicherheit, speziell dem Einfluss von Unsicherheit auf verschiedene Politikinstrumente. Dazu werden sogenannte Intensitätsziele – die die Emissionsobergrenze an die Wirtschaftsleistung (BSP) koppeln – untersucht, sowohl in Hinblick auf ihre Auswirkung auf Kostenunsicherheit als auch auf ihre Anschlussfähigkeit an den internationalen Emissionshandel. Im Ergebnis erscheinen Intensitätsziele aufgrund ihrer höheren Komplexität sowie ihres potentiell recht geringen Nutzenvorteils gegenüber konventionellen absoluten Emissionszielen als weniger robuste Wahl.

Schlagwörter: Ökonomie des Klimawandels, Linking, Internationale Kooperation, Intensitätsziel, Unsicherheit.

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Chapter 1

Introduction

1.1 Motivation and Background: International Climate Policy

In 2012, humanity will have the dubious pleasure of commemorating the official 20th anniversary of climate change as a global policy issue. Sadly–as in this case–one can be reassured of its well-being and further growth. Almost twenty years ago, in 1992, the world's nations gathered at the Rio 'Earth Summit' and unanimously[1] agreed that they must act to "prevent dangerous anthropogenic interference with the climate system" (UNFCCC 1992). Ever since then, they have struggled to also agree on what specific actions need to be taken, and by whom, and at whose expenses – so far resulting in a nearly complete absence of any counteracting measure.

Lacking scientific understanding of climate change cannot explain the ongoing political stagnation. While for some years the debate on the existence and causes of climate change was controversial and sometimes polemic[2] even among scientist, it is today accepted as proven beyond reasonable doubt that climate change is real and that man-made greenhouse gas (GHG) emissions–and not natural variations in solar radiation intensity or changes in the earth's orbit around the sun–are responsible for the overwhelming part of the observed warming (IPCC 2007a).[3] Recent empirical evidence supports this message, e.g. the fact that the ten warmest years ever recorded in meteorological data all occurred between 1998 and 2009 (Hansen et al. 2010). Moreover, because the climate system responds with a significant delay to rising GHG concentrations, the planet is already committed to further warming, i.e. even if emissions had been cut to zero after the year 2000, scientists would still expect an additional global warming of about 0.5°C (Allen et al. 2009).

That said, scientific uncertainty about climate change remains an important issue, but less so in terms of the actual existence or causes of climate change, than in terms of magnitude and local consequences (IPCC 2007b, Kriegler et al.

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[1] As of today, 194 countries are members of the so-called United Nations Framework Convention on Climate Change (UNFCCC). Source: UNFCCC official website www.unfccc.int

[2] For instance, US Senator Inhofe once famously declared climate change to be the „ greatest hoax ever perpetrated on the American people". Source: Floor speech from July 28, 2003, as cited by http://inhofe.senate.gov/pressreleases/climateupdate.htm (accessed 15 September 2010).

[3] The basic principle of the greenhouse effect was described as early as in 1824 by Fourier, and estimated in 1896 by Nobel prize winner Arrhenius (Arrhenius 1896) to lead to a global temperature increase of between 5°C and 6°C in case of a doubling of atmospheric CO_2 concentration.

2009). In fact, the severity and timing of specific impacts that different regions will experience remain hard to foresee, and so are the incremental impacts and economic damages in the relevant temperature range between 1°C and 4°C of global warming above preindustrial levels. Uncertainty clearly matters if we cannot quantify the incremental climate damages for Europe between a 2.0°C and 2.5°C warming scenario, which may be billions of Euros apart in terms of mitigation costs.

At a minimum, however, the scientific advancements of the last years have helped to grow a global consensus that completely unabated climate change poses a high risk of serious negative impacts for all, and would thus be the least desirable of all scenarios. At the 2007 UN climate conference in Bali, all parties affirmed the necessity of "deep cuts in global emissions"[4], and in the 2009 Copenhagen Accord even timidly recognized[5] "the scientific view that the increase in global temperature should be below 2 degrees Celsius". Nevertheless, the long-awaited Copenhagen meeting still fell short of devising a real follow-up agreement to the Kyoto-Protocol, the expiring 'warm-up exercise' in emission control of the UNFCCC. Why, so the puzzling question, is so little achieved in terms of taking coordinated measures against at least the worst case scenarios of climate change?

The answer, as I want to argue, must start by emphasizing that the global problem of climate change is caused by nearly 200 individual nation states. It is humankind's way of organizing itself in many independent local units which makes it so difficult to confront a global challenge that requires a globally coordinated response. Of negligible relevance in the past,[6] this difficulty is becoming critical in the modern era, in which a vast global population in combination with an unprecedented power of technology have for the first time created a human-environment feedback at the planetary scale. The depletion of the ozone layer may constitute one of the first instances of such a direct alteration of 'system earth' by humankind. In view of the now apparent influence on the even more systemic global climate, the need for a collective response capacity of humankind–as if guided by a "global subject" (Schellnhuber 1999)–becomes self-evident.

Thus, at its very heart climate change gives rise to a social dilemma or–speaking more formally–a collective action problem (Olson 1965), possibly ending in a "tragedy of the commons" (Hardin 1968). For now, the only conceivable way forward in climate policy is by international cooperation,[7] which was formally initiated in 1992 when the UNFCCC was founded, but with little tangible progress ever since. Action can only come through actors, i.e. the world's

[4] Source: Bali Road Map, http://unfccc.int/meetings/cop_13/items/4049.php (accessed October 2010).
[5] Source: Copenhagen Accord, http://unfccc.int/home/items/5262.php (accessed October 2010).
[6] Except perhaps for the great epidemics, like flu and pest.
[7] This may change if geo-engineering becomes a feasible option.

nations, which are characterized by heterogeneity and very different incentives to act or not to act on climate change. Namely, while some of the small island states may be wiped out within the next few decades because of sea-level rise, others, like Russia, may partially benefit from global warming due to expanded farmland, and would have much to lose if the world abandoned fossil fuels. Therefore, the *main* challenge regarding climate change is not (anymore) to prove or further improve the science behind it, but to devise effective and politically feasible counter-measures. Only these may help to bring countries to action and lift them out of the current status quo dilemma of doing (almost) nothing. Even if countries still disagree on what exactly they want, clearly, there is room for large improvements, at least of the smallest-common-denominator type.

Three critical issues in global climate policy

In the following, I want to shortly outline the current state of climate policy along three 'grand' issues the world's nations need to resolve in order to avoid the looming 'tragedy': First, agreeing on the maximum acceptable increase in global temperature; second, deciding on how the costs of climate protection are to be shared among countries; third, devising a treaty that gives countries a sufficient incentive to actually comply with their obligations.

(i) Agreeing on a global climate target

Finding common grounds on the first issue has proven difficult, both for positive reasons associated with the factual uncertainty of the costs and benefits of emission reductions, as well as for the intrinsically normative judgements involved. Actually, the problem 'simply' consists of finding agreement on a single number, namely the total cumulative GHG emissions of the 21st century, which were shown (Allen et al. 2009) to relate in a one-to-one correspondence to temperature targets, albeit only in a probabilistic sense. For instance, to have a 75 percent chance of keeping global warming below 2°C, the cumulative centennial global emissions should be limited to around 1000 $GtCO_2$, as compared to the range of 4000 to 6000 $GtCO_2$ expected in business-as-usual scenarios (Meinshausen et al. 2009).[8]

Of course, the mere *statistical* relationship between emissions and temperature rise might hamper an agreement on what the global 'climate target' ought to be. But this vagueness is not expected to be resolved in the near foreseeable future, as it stems from the persistent uncertainties related to the global carbon cycle

[8] Data refers to fossil fuel and land-use related CO_2. The business-as-usual figure is based on IPCC's B2 SRES scenario, see http://www.grida.no/climate/ipcc/emission/ (accessed October 2010)

(how emissions translate into concentrations) and so-called climate sensitivity (how atmospheric GHG concentrations translate into temperature change).[9]

Another 'positive' reason for why countries hesitate to commit to substantial actions stems from the uncertainty about mitigation costs: Decarbonizing the 85 percent[10] of the world's energy system that provide heat, electricity, and transport on the basis of fossil fuel combustion will obviously require very significant investments. Admittedly, model estimates of these costs seem to converge around one or a few percent of global economic output over the century (Edenhofer et al. 2006, Chapter 10 in Stern 2007), but these figures derive from long-term macro-analysis and must be interpreted with some caution, since they represent averaged annualized figures: in the short-run these costs will very likely be higher. In the face of such uncertainty, identifying an optimal climate target would be a challenging task even for a benevolent global social planner, let alone for 200 countries tangled up in strategic bargaining.

Finally, and perhaps most importantly, choosing and agreeing on a global climate target cannot be done without fundamental value judgements, since we are confronted with 'tragic' trade-offs between the present and the far-future, between the global risk of climate change and the costs for avoiding it, and also with the need to assign an explicit value to ecosystem services and the preservation of the natural environment in its current state (Stern 2007, Chapter 2). Under the reasonable assumption that countries' social preferences are not uniform–because of different economic conditions, different cultural backgrounds, different histories–the possibility of a 'one-size-fits-all' target becomes hard to conceive.

As an example, consider the issue of discounting, which figures prominently in this context, i.e. the question of how much an investment becomes less desirable because it pays off only after some time delay. In fact, the most severe consequences from unabated climate change are not expected to occur until the second half of this century (Stern 2007, Chapter 6), whereas the costs for avoiding them would start to rise quickly after 2020 (Leimbach et al. 2010).[11] Mitigating climate change, in other words, requires the current to make a sacrifice for the coming generation(s). As per se, this does not necessarily lead to a normative controversy. The crucial issue on which views differ widely and which makes an agreement on a global climate target difficult is *how much* the current generation should sacrifice. Especially for developing countries with their ambitious economic growth targets, the fact that the near term costs of

[9] What is worse, one is in this case facing hard or so-called Knightian uncertainty, characterized by the absence of a probability distribution for the uncertain parameters at hand. If the latter were available, one would merely have to deal with 'risk'.
[10] Share of oil, gas, and coal in global energy consumption in 2007, according to EIA (2010).
[11] Unfortunately, investments into climate change mitigation will never have an observable pay-off, as their value rests upon the hypothetical–hence unobservable–damages that they avoid.

mitigating climate change are potentially high and only start to amortize after several decades weighs heavily.

(ii) Setting each country's share of total mitigation costs

The second Gordian knot of international climate politics consists of what is known as burden-sharing, i.e. how is the 'bill' for achieving the global climate target to be distributed among countries? In the absence of uncertainty, this would be a purely normative question, since the 'bill' could be calculated directly as a function of the global climate target. Different principles could then be motivated to argue in favour of one or the other cost-distribution, e.g. countries' relative contribution to the problem (historical responsibility / polluter pays principle), their ability to resolve it (ability to pay), their benefits from climate protection (i.e. damages), or their current level of 'excess-consumption' of the global atmosphere as compared to the maximum sustainable level admissible for each earth citizen (equal per capita). Naturally, there are different views on which of these ought to be the decisive principle. Each country will fare better under some principles than under others, depending on its specific circumstances, which is the reason why an agreement on this question is hard to achieve. If possible at all, a universally accepted cost distribution rule will likely be based on a mixture of some of these principles.

Uncertainty complicates the question of how to distribute mitigation costs in several ways. For one, the total bill for achieving a given climate target is uncertain, because neither the required effort (tons of GHG reduction with respect to baseline emissions) nor the costs for reducing a certain amount are very well known. In addition, also some of the parameters that would be needed to apply the aforementioned principles (polluter pays, ability to pay, damages etc.) are uncertain, e.g. the historical contributions of different countries to the current level of climate change, or the specific regional impacts and economic damages from climate change.

Hence, the issue of burden-sharing is characterized by both positive uncertainty and normative idiosyncrasies. In the end, the practical solution of this question can again be represented by numbers, namely by the amount of emission permits (with validity, e.g., until 2099) allocated to each country. If a global budget has already been adopted, this implies selecting and finding agreement for N-1 independent numbers, where N is the number of countries. Conveniently, any desired cost-distribution can be reached by a suitable initial allocation, even though this might mean that some countries actually receive negative permits.[12] In principle, international emission trading would then ensure that global emissions are reduced at the lowest possible costs. In practice, however, this would entail significant cost uncertainties (i.e. the permit

[12] The German Advisory Council on Global Change has computed countries' permit allocations based on different principles and global climate targets, see WBGU (2009).

price cannot be well-predicted), and it also seems questionable whether less developed countries would have–at least in the near to mid-term–the capacity to set up a highly complex institution like the EU ETS (or if they do have it, at what level of transaction costs).

(iii) Devising a self-enforcing treaty

The final stepping stone of international climate policy consists of finding a form of agreement that countries can trust in. Without a global Leviathan as central power, the 'inter-national' world is formally in a state of anarchy, in which countries cannot be coerced (at least not without force) to actually fulfil the promise they make in an international agreement. Due to each country's angst of being cheated by the others, the agreement as a whole becomes prone to failure. A priori, each country has in fact an incentive to let the others 'do the job', and enjoy the resulting climate benefits without contributing to the costs. Formally speaking, international climate policy suffers from a free-rider problem. Thus, the nations' negotiators have to design an agreement in such a way that each country has an incentive to actually deliver, e.g. by means of a sanctioning mechanism that creates at least some credible pressure on countries. The theoretic severity of this problem has been emphasized widely (Carraro and Siniscalco 1993, Barrett 1994), and various proposals towards its solution been made, e.g. participation clauses (Carraro et al. 2009), transfer schemes (Carraro et al. 2006), or trade sanctions (Stiglitz 2006), without, however, reaching a satisfying conclusion yet.

In sum, I have suggested three 'grand' issues standing in the way of an efficient global climate policy, on none of which the world seems to be approaching a solution now or in the near-term future. The unenthusiastic development of the Copenhagen climate conference also supports the view that we have to accept a continued absence of international cooperation for some more time.

However, this should not lead to the conclusion that in the meantime nothing can be done. Rather, acknowledging the current state of affairs constitutes the starting point of this thesis, i.e. to ask what options there are to pursue climate policy in a world characterized by little or partial cooperation. This specific issue area offers its own puzzles and questions and constitutes the main topic of my thesis. As opposed to the three grand issues, the questions posed in this area tend to be more specific, touching on the scope and 'nitty-gritty' issues involved in the setting and implementation of a specific policy instrument. In particular, the coming chapters will present original research revolving around the following questions:

- How can international cooperation be increased?
- How can partial cooperation become cost-effective?
- How can individual countries cope with cost-uncertainty?

By providing new insights on these topics, this research hopes to clarify some critical issues involved and thereby to contribute to the progress of international climate policy.

1.2 Formal Approach and Framing: Climate Change in Economics

Economics, according to a definition by Lionel Robbins given in 1935 "is a science which studies human behavior as a relationship between ends and scarce means which have alternative uses". In this section, I present a brief exposition of how the issue of climate change is accommodated and treated methodologically in economics, allowing to place this thesis into a broader context and to explain the meaning of its title.

1.2.1 Economics of Climate Change: Overview

As a first step, I suggest to differentiate three basic categories of economic analysis directed at climate change, which to some extent reflect the three 'grand' challenges from before: (i) global cost-benefit analysis of climate change, (ii), game-theoretic analysis of climate change, and (iii) analysis of climate policy design and instruments.

(i) Global cost-benefit analysis of climate change

From the bird's eye perspective, climate change is a problem of stock pollutant control, and thus part of the branch of economics called environmental or resource economics. The standard tool used by economists to approach this type of issue is the dynamic cost-benefit analysis. In fact, as early as in 1992 did Nordhaus (1992) develop a numerical model called DICE to find the optimal balance between the benefits from emissions, i.e. fossil fuel usage, and the costs of emissions, i.e. damages from climate change. At the time, his "optimal transition path" foresaw a warming of 3°C above pre-industrial levels by the end of the 21st century.

Nordhaus' results received a lot of attention,[13] much of it criticizing his approach: the overly simplistic damage function (Tol 1994, Roughgarden and Schneider 1999), inaccurate climate modelling with an infinite carbon sink (Price 1995, Kaufmann 1997), absence of endogenous technological change (Goulder and Schneider 1999, Popp 2004), or too high a discount rate (Azar and Sterner 1996) were some of the main shortcomings attributed to the DICE model. While some of these points were remedied even by Nordhaus himself in later versions of the model (Nordhaus 2008), the issue of the 'damage function' has remained contentious, in the sense that even by today no generally accepted way for assessing and modelling the global economic damages from climate

[13] The two original DICE articles Nordhaus (1992) and (1993) count over 500 and the subsequent book (1994) over 1000 citations on Google Scholar, as of September 2010.

change has emerged. As emphasized by Tol (2009), up to now only 14 point estimates for the global damage function are available in the entire peer-reviewed scientific literature.[14]

Perhaps because of the apprehension among economists of the complexity involved in modelling global damages from climate change, many of the presently used so-called integrated assessment models actually exclude it, i.e. they do not incorporate any feedback from the climate system to the economy. Instead, these models restrict themselves to calculating the mitigation costs for an exogenously given climate target, e.g. a temperature or concentration target. In other words, because of its weak empirical basis on the damage side, cost-benefit analysis for finding the optimal amount of climate change has in many cases simplified into a cost-effectiveness analysis, merely identifying the minimum costs for reaching a given target, which in turn may be supplied by a normative evaluation of scientific information in a rather heuristic manner based on guard-rails or maximum acceptable risks, like, e.g., the 2°C target adopted by the EU. The most recent generation of such models, which incorporate a rather detailed description of the energy system, find annualized costs of a few percent of global GDP for achieving climate stabilization (Edenhofer et al. 2010, Stern 2007, Edenhofer et al. 2006).

One feature of the climate change problem that has particularly drawn the attention of economists is its distinctly intertemporal character. The intriguing question of how to compute the present value of avoided climate damages that would occur only in the far future and are highly uncertain has sparked a new debate on the foundations of long-term social cost-benefit analysis (e.g. Lind 1995). The initial conflict focussed on the setting of the pure-rate of time preference, which for some should be done 'positively' so as to lead to model results that are consistent with observed interest rates on capital markets (Nordhaus 2007), while others claim it to be a normative choice parameter which–in the vein of Ramsey (1928)–should be set to zero in order not to unduly discriminate future generations (Heal 2009). If possible at all, a value higher than zero could only be justified by the risk of extinction of humankind, e.g. due to an asteroid hitting earth (Stern 2007).

The debate on the ethics underlying cost-benefit analysis was further extended when Dasgupta (2008) pointed out the relevance of another social parameter, the elasticity of marginal utility. He argued forcefully that the common and seemingly innocent choice of unity for this parameter has significant ethical implications in terms of how inter- and intra-generational inequality is socially valued, and, hence, on what is perceived as optimal climate policy. Finally, unlike any other issue before, cost-benefit analysis of climate change requires to incorporate uncertainty and non-negligible risks of extreme damages (i.e.

[14] However, many more studies on the damages from climate change are available at the local level, e.g. Dorland et al. (1999), Schlenker et al. (2007), Fleischer et al. (2008) etc.

catastrophic events). As an intriguing and perhaps still not fully digested result, Weitzman (2009) showed in his "dismal theorem" that if the probability distribution of future climate damages is characterized by fat tails (likelihood of large damages falls slower than exponentially), then everything should be done to avoid climate change, no matter how high the costs.

The reliance of global economic analysis of climate change on long-term simulations of economic dynamics has also spurred significant methodological advancements in the modelling of growth economics and, in particular, of endogenous and induced technological change (Edenhofer et al. 2006, Hourcade et al. 2006). GHG emissions expected for the business-as-usual depend strongly on future economic growth, and mitigation costs even more heavily on the ability of climate policy to incite the development of carbon-saving technologies. In fact, the mitigation costs of 3–6% of global GDP per year (Grubb et al. 1993) estimated by the early models based on an unspecific and exogenously given technological progress fell considerably when models capable of induced technological change were employed (Edenhofer et al. 2006).

(ii) Game-theoretic analysis of climate change:

Upon leaving the bird's eye perspective of the global social planner, climate change becomes an N-player public good problem. To be precise, the *abatement of emissions* represents the public good, as no country can be excluded from enjoying its benefits (non-excludability) and no country's benefits will be reduced by all other countries' enjoyment of their benefits (non-rivalness).[15] The strategic interactions of sovereign players in such a context is the natural 'habitat' of game-theory, which compares Nash equilibria, i.e. outcomes in the absence of cooperation, with those that would be globally efficient, and studies incentive compatible means and ways to push the former towards the latter.

Prima facie the outlook appears grim, as the game's structure corresponds to a prisoner's dilemma, in which non-cooperative behaviour is the dominant rational strategy.[16] Said differently, every country's preferred situation is one where all countries reduce emissions, except the county itself. As a consequence, of course, no country will reduce its emissions. Theoretically, an agreement on mutual cooperation could make all countries better off, but this effort is undermined by countries' fear of falling victim to free-riding by others, given the limited possibilities to enforce agreements at the international level.

To be consistent with this tragic but undeniable dilemma, economic analysis mostly restricts itself to so-called self-enforcing agreements (Barrett 1994), in which countries stick to their promises only if it is in their own selfish interest to do so. But what levels of cooperation can be achieved under this constraint?

[15] Climate itself depicts traits of an open-access resource, since the atmosphere's capacity to act as a sink for anthropogenic GHGs is, ultimately, limited.

[16] With a sufficiently strong climate change damages, the chicken game becomes a better description, in which all players want to avoid the worst case (Carraro and Siniscalco 1993).

This question constitutes the research objective of non-cooperative game theory, which analyzes the formation and stability of coalitions, i.e. of clubs of countries that cooperate among themselves, but not with the other non-cooperating countries. The benchmark result in this research area, as established by Carraro and Siniscalco (1993) and Barrett (1994), shows that if cooperation must be self-enforcing, then the scope for international agreements under standard conditions is very limited, i.e. the resulting levels of public good provision are still far from the social optimum.

However, when additional 'non-standard' features are introduced in the game, agreements leading to higher levels of cooperation become feasible. This is the general conclusion of a growing literature that has investigated the potential to enhance cooperation by, inter alia, the inclusion of transfer schemes (Carraro et al. 2006), focussing on the benefits of emissions trading in limited regional agreements (Carbone et al. 2009, Schmidt and Marschinski 2010), 'issue linkage', i.e. combining agreements with protocols on mitigation technology or general R&D (Buchner et al. 2005, Lessmann and Edenhofer 2010), or by imposing economic sanctions against non-cooperating countries (Barrett 1997). One part of this thesis, namely Chapter 4 based on Lessmann, Marschinski and Edenhofer (2009), falls into this category of research, and investigates the effect of punitive tariffs on the participation in climate coalitions.

(iii) Analysis of climate policy design and instruments

One principle aim of economics is to propose effective, cost-efficient and incentive-compatible instruments for achieving given policy objectives. Such is the case also in the area of climate change. The debate on 'prices vs. quantities' perhaps constitutes the prime example in this category, i.e. the question of whether–in the presence of uncertainty–climate policy should be implemented by means of a carbon tax or a cap-and-trade system.[17] In their seminal contribution, Newell and Pizer (2003) extended Weitzman's (1974) original result for flow-pollutants to the case of a stock-pollutant, leading them to conclude that for climate change a price mechanism would yield the higher expected welfare. But also other instruments for dealing with cost-uncertainty if, say, a tax is infeasible for political reasons, have been proposed and analyzed, e.g. so-called intensity targets (Ellerman and Sue Wing 2003, Quirion 2005), which will be examined in detail in Chapters 5 and 6, or emissions trading with a maximum 'safety-valve' price (Pizer 2002). Further extensions and modification of the prices vs. quantities issue abound, e.g. with endogenous technological change (Krysiak 2008), under public-finance aspects (Baldursson and von der Fehr 2008), with intertemporally optimizing resource owners (Edenhofer et al. 2010), or in the presence of market power (Requate 1993).

[17] See Hepburn (2006) for a review of prices vs. quantities beyond the issue of uncertainty.

As discussed earlier, mitigation costs for achieving any ambitious climate target strongly depend on the ability of climate policy to induce carbon-saving technological change (Edenhofer et al. 2006). Whether a price on carbon that internalizes the consequences of climate change constitutes a sufficient means in this regard, or, if not, which supplementary policies need to be put in place, became subject of another important strand of research. A common argument in favor of a supplementary renewable energy policy points to the existence of a "carbon lock-in" (Unruh 2000), i.e. a market failure that keeps the established fossil-based technology in place despite it being dynamically inferior to renewable energies. This phenomenon can occur if, e.g., knowledge has a public good character and firms are unable to coordinate their innovation efforts, as shown by Schmidt and Marschinski (2009). Other potential market failures warranting the use of an additional instrument[18] could be high uncertainty, long time horizons, and knowledge or learning spillovers, as discussed in the overview articles of Goulder and Parry (2008) or Fischer and Preonas (2010).

Assuming a technology oriented policy intervention to be necessary, the question arises what combination of instruments is optimal. If carbon pricing is the only option at hand, a tax rate higher than the Pigovian level may be justified (Hart 2008). In general, however, other instruments exist and seem to be politically attractive (Fischer and Preonas 2010), e.g. a renewable subsidy. Fischer and Newell (2008) carried out a systematic study of six different policy instruments in the face of three market failures, namely climate change, learning by doing, and research spillovers, finding that an optimal portfolio of instruments always dominates single instrument solutions, but also that emissions pricing is the most important policy component. Similar, and related in spirit to the prices vs. quantities debate from before, is the comparative analysis of the performance of tradable green quotas[19] and feed-in tariffs. As of today, the issue remains undecided: for instance, based on past performance in the UK and Germany, Butler and Neuhoff (2008) favor feed-in tariffs, whilst Tamas et al. (2010) find higher welfare for a green quota system if the energy market is characterized by imperfect competition.

However, despite these prolific research activities, one should be reminded that whenever a market failure affects all sectors of the economy equally (e.g. imperfect appropriation of innovation), a one-sided policy aimed only at the renewable energy sector may induce negative welfare effects, e.g. due to a crowding out of research in other, equally under-served sectors (Hart 2008). Many models, given their partial nature, ignore these general equilibrium effects. In addition, the overlap of emission- and technology-oriented policies may have other unintended negative consequences, e.g. by lowering the

[18] What is sometimes called the Tinbergen rule, after Tinbergen (1952), states that one corrective instrument is needed for each independent market failure.
[19] Also called renewable portfolio standard, especially in the US.

emission price and thus reducing the incentive for fuel switching, as suggested by Böhringer and Rosendahl (2010).

A third area in which economic analysis is applied to support climate policy regards international feedbacks of national (or regional for the EU case) emission policy. When recent empirical research pointed to the potentially very high amount of carbon leakage triggered by the Kyoto Protocol (Peters and Hertwich 2008), and in general showed how carbon emissions constitute, in effect, an intensely traded international good (Davis and Caldeira 2010), the need to devise policies that both control emissions and limit international leakage became strikingly evident, and confirmed the anticipation of this policy pitfall by earlier theoretical analysis (Felder and Rutherford 1993). Research in this currently very active area partly builds on trade theory, and investigates–inter alia–the scope for sectorally differentiated carbon policy (Hoel 1996, Golombek et al. 1995) and border-tax adjustments (Lockwood and Whalley 2010), the difference between consumption- vs. production-based emissions accounting (Steckel et al. 2010), and provides detailed assessments of the actual competitiveness impacts of carbon policy on different industries (Demailly and Quirion 2008).

Before concluding the section, more examples of economic research belonging to this category of 'policy design and instruments' that may be mentioned–without any claim of completeness–include the analysis of how permit allocation by auctioning or grandfathering affects dynamic efficiency (Harstad and Eskeland 2010), competitiveness (Hepburn et al. 2010), private R&D incentives (Montero 2002), or its implications in terms of distributional impacts (Betz and Sato 2006); the analysis of the compatibility of different emission policies with regard to emissions trading (Fischer 2003, Flachsland et al. 2009b); and, finally, research on the vulnerability of climate policy to 'time inconsistency' and how to overcome it (Helm et al. 2003, Brunner et al. 2010).

1.2.2 Climate Change: a Domain of Second-Best Policies

A characteristic feature shared by several of the above presented research questions is the challenge of finding the best possible policy in the presence of an additional irremovable obstacle or system imperfection. What in such cases is being looked for, technically speaking, are so-called 'second-best' policies. Going back to Lipsey and Lancaster (1956), the theory of the second-best originally states that in order to minimize the loss of welfare in an interdependent economic system provoked by one variable's deviation from its optimal value, all other variables must (in general) also be adjusted and hence move away from their formerly optimal value.[20] Over time, the usage of the term 'second-best' has

[20] Although this is a somewhat unorthodox way of stating the theorem, it stays true to the content and immediately reveals its relevance in the present context.

expanded, and it is now commonly applied whenever a regulator is prevented from directly implementing the socially optimal first-best solution for a given problem, e.g. because of missing information. For the sake of concreteness, consider the following questions which all incorporate a specific imperfection and thus fall into the domain of second-best analysis:

- Imperfect *information*: What is the best-possible regulation if, e.g., the information on firms' costs is not available to the regulator?
- Imperfect *cooperation*: What is the best-possible policy, e.g. for the level of a domestic carbon tax, if other countries do not cooperate?
- Imperfect *competition*: How to set environmental regulation if market power cannot be overcome?
- Imperfect *commitment*: How to set economic incentives for private actors if perfect commitment by the regulator is not feasible?
- Imperfect *appropriation*: What is the best-possible technology policy if private innovators cannot fully appropriate their innovations?

All of these questions turn out to be highly relevant in the field of climate change: For instance, the famous Weitzman 'rule' for choosing between a cap-and-trade and carbon tax policy represents a typical second-best argument[21] in the face of imperfect information on marginal benefits and firms' costs. As another example, Hoel (1994) posed the question of how to set climate policy in the face of non-cooperative behavior by other countries,[22] which prompted his later investigation of sector-wise differentiated carbon taxes as a second-best instrument (Hoel 1996), and is also taken up in the current discussions of carbon tax export rebates and border-tax adjustments (Ismer and Neuhoff 2007). Harnessing energy and innovation markets for climate policy is vital, but these markets are often characterized by imperfect competition (Requate 2005) and knowledge spill-overs (Goulder and Schneider 1999), again requiring second-best policies. A final application arises due to any government's generally imperfect commitment power: for climate policy to be efficient, investors must be convinced of a stern commitment to a sufficiently high and long-lasting carbon price, so as to induce the required investments in carbon saving technology. But how can this be achieved when investors know that future governments might have different priorities and that policies could be changed (Helm et al. 2003, Brunner et al. 2010)?

Because the second-best setting also characterizes parts of the research presented in this thesis, I will elaborate on this issue in some more detail. To this end, three formal examples will be discussed that illustrate how first-best policies differ from second-best policies and how–sometimes–a second-best policy can nevertheless lead to a first-best outcome.

[21] Though never citing Lipsey and Lancaster (1956) in his article, Weitzman speaks of prices vs. quantities as a "second best problem", since generally neither will achieve the first-best outcome.
[22] Markusen (1975) already addressed this issue, but not in the context of climate change.

(i) Illustration of second-best climate policy under market power

The classical textbook example for second-best theory considers a monopolistic market of a single good, the quantity of which is denoted by q. Consumers derive concave benefits $B(q)$, while the direct production costs are captured by the convex function $C(q)$. In addition, the production of the good is associated with an externality that causes indirect social costs, say climate damages, of $D(q)$, which are assumed to be constant at the margin, i.e. $D(q)=d*q$, with a constant $d>0$.

The optimal (=first-best) output level, q^*, is obtained by maximizing the net benefits, leading to the usual first-order condition of 'marginal benefits = total marginal costs', i.e.

$$B'(q^*) = C'(q^*) + d \quad . \tag{1.1}$$

Without regulatory intervention the market equilibrium with competitive firms would not lead to the optimal outcome, since private firms do not take the external effect of q-production into account. For a given market price p, firms would produce until their marginal costs become equal to p, while consumers would buy until their marginal benefits become also equal to p, implying a market equilibrium characterized by

$$p = B'(q^*) = C'(q^*) \quad , \tag{1.2}$$

which obviously contradicts Eq.(1.1). The first-best can be implemented if the regulator introduces a suitable tax τ, say on the consumption of q. Consumers would then stop buying as soon as the net price $p+\tau$ they are facing becomes equal to their marginal benefits, and hence one obtains

$$B'(q^*) - \tau = C'(q^*) \quad . \tag{1.3}$$

Choosing $d=\tau$ reinstates the optimality condition of Eq.(1.1), and corresponds to the classical Pigouvian tax intervention, where the tax level corresponds to the marginal damages associated with the externality.

Now assume that instead of competitive firms, good q is produced by a single monopolist. The latter takes into account how the market price p depends on output q, and thus does not produce until marginal costs reach p, but rather maximizes $q\,p(q) - C(q)$ by satisfying

$$p\left(1 + \frac{q}{p}\frac{dp}{dq}\right) = C'(q) \quad . \tag{1.4}$$

The elasticity $\varepsilon=q/p\ dp/dq$ being negative, this implies that the market price p for any output level q will be higher than in the competitive market case, or, conversely, that the equilibrium output level will generally be lower. This is the market failure assumed to be irremovable for this example, the presence of which–under otherwise perfect conditions–would lead to a welfare loss due to an

underproduction of q. In terms of a second-best analysis, the question then is what the optimal (carbon) tax intervention in such a setting would be. With a tax τ on consumption the market equilibrium becomes characterized by

$$B'(q) - \tau = \frac{C'(q)}{1 - \|\varepsilon\|} \quad . \tag{1.5}$$

Ideally, the regulator would like to recover Eq.(1.1), i.e. choosing τ such that

$$B'(q^*) = \frac{C'(q^*)}{1 - \|\varepsilon\|} + \tau \overset{!}{=} C'(q^*) + d \quad . \tag{1.6}$$

This can, as the reader may easily verify, be achieved by setting

$$\tau = d - C'(q^*)\left(\frac{\|\varepsilon\|}{1 - \|\varepsilon\|}\right) \quad . \tag{1.7}$$

Hence, the second-best policy is to set the tax level *lower* than implied by the conventional 'tax=marginal damages' rule derived under ideal market conditions (it may even become a subsidy). Moreover, with the second-best tax the first-best outcome can be implemented, i.e. a single instrument is sufficient to simultaneously resolve two market imperfections. The intuition for this result is straightforward: a competitive market outcome would produce too much of q, since firms ignore the negative externality. The monopolist's output reduction thus has a welfare-improving effect, which, by means of the tax τ, can be fine-tuned to the optimal level. Thus, in a sense, the monopolist may be viewed as a natural friend of the environmentalist.

(ii) Illustration of second-best climate policy under incomplete cooperation

Consider the following example from the context of international trade, which illustrates that achieving first-best outcomes with second-best policies is the exception rather than the rule. Let there be one country, the reference or 'home' country, as well as two other countries, a foreign country f similar to home, and a resource-exporting country s. The latter's inner structure shall not matter here, and hence the country is represented only through a conventional supply function $S(p)$, where p is the world price of the resource R that the country supplies.

The home country is modeled by means of a representative agent disposing of a concave production technology F and an objective function

$$\max W = U(C) - d(R + R_f) \quad s.t. \quad C = F(R) - pR \quad , \tag{1.8}$$

where C denotes consumption, U is a concave function, and the parameter d captures the linear environmental (climate) damage arising as an externality from global resource use. Furthermore, assume that the foreign country is not

exposed to environmental damages (or is ignorant about it) and will not act cooperatively; it simply maximizes its consumption.

Taking the resource price p as well as the other country's behavior as given (and using the generic output good as numeraire), home's first-order condition becomes

$$\left(F'(R) - p\right)U' = d \quad . \tag{1.9}$$

Different from the standard case, the marginal product F' is not equalized to the resource price p, which is due to the negative external effect associated with R. Instead, the marginal gain in consumption utility from a marginal increase of R is equalized to the marginal damage caused by R. The resulting level of R is thus lower than in the case without negative external effect ($d=0$).

As in the example before, a policy maker would now apply a suitable regulatory tool to reduce the economy's resource intake to the level implicitly defined by Eq.(1.9). Evidently, though in line with the standard approach for internalizing an externality, this would in general not lead to a globally optimal outcome, which cannot be achieved as long as the other country f does not cooperate, as required in the presence of a global externality. It is for this very reason that the problem described here falls into the category of second-best analysis.

The question is, however, whether Eq.(1.9) really defines a second-best policy. The answer is no, because it does not take into account the feedback channel constituted by the international resource market, which will partially offset home's resource reduction effort, i.e., it will cause leakage. Accordingly, the second-best resource policy is defined by

$$\max W = U(C) - d(R + R_f) \quad \Rightarrow \quad \left(F'(R) - p\right)U' = d\left(1 + \frac{dR_f}{dR}\right) \quad , \tag{1.10}$$

where the term dR_f/dR captures the leakage rate. The latter must be smaller than zero for the following reason: if home reduces its intake of resource R, the global supply function $S(p)$ requires the price p to fall. But then the foreign country has an incentive to increase its resource intake, at least under standard conditions.

Therefore, the effect of taking leakage into account amounts to defining an effective damage parameter $d_{eff}=(1-|dR_f/dR|)$ that is smaller than d itself. As a consequence, the second-best policy under non-cooperation is that the home country chooses a resource level R that is higher than defined by Eq.(1.9). In fact, in case of a leakage rate of 100%, the resource level would become equal to the one chosen without environmental damage.

(iii) Illustration of second-best climate policy under imperfect information

Regulating entities often have to base their policy intervention on imperfect information, be it because of firms not granting access to their private information, or because of some genuine underlying quasi-stochasticity (e.g. resource scarcities) or knowledge gaps (e.g. climate damages). Let θ denote the vector of policy relevant information for which the regulator only has an uncertain estimate $\hat{\theta}$. Whenever the optimal regulation Γ^* depends on θ, i.e. $\Gamma^*=F(\theta)$ with some function F, it is impossible (save by pure chance) for the regulator to institute an optimal policy, i.e. $\Gamma = F(\hat{\theta}) \neq \Gamma^*$ in general. However, the average welfare loss caused by the uncertainty about θ may be different for different policy instruments. For this reason one speaks of choosing a second-best policy in this case, even though there is no first-order optimality condition that is violated, such as Eq.(1.4) in the previous example of the monopolist.

The classical example in this area is Weitzman's (1974) comparison of regulation by prices or by quantities. Today, this question has become an intensely debated issue in climate policy (e.g. Newell and Pizer 2003, Krysiak 2008), where the opponents are cap-and-trade vs. carbon tax. As an illustration of how the symmetry between these two instruments is broken due to uncertainty, I will derive Weitzman's result in a slightly alternative way.

Let q denote the quantity of emission abatement. The benefits of abatement are given by a concave function $B(q)$, while the aggregate costs of abatement–incurred by private firms–are represented by the convex function $C(q)$. The challenge for the regulator is to either set a quantity target $\bar{q}$ or an emission price (=carbon tax) p that maximizes expected welfare (i.e. net benefits). Of course, with full information, both instruments would equally lead to the first-best optimal outcome, as determined by the efficiency conditions

$$B'(q^*) = C'(q^*) \tag{1.11}$$

and (*inv* denoting the inverse function)

$$B'(C'^{inv}(p^*)) = p^* \quad . \tag{1.12}$$

However, when the functions B and C are only imperfectly known, policy instruments have to be estimated, and will in general not take on their optimal value, i.e. $p \neq p^*$ and $\bar{q} \neq q^*$. To assess the loss of welfare incurred if $\bar{q}$ deviates by a small amount ε from its optimal value, one can approximate the welfare function to second order in the vicinity of its maximum:

$$W(q^*+\varepsilon) \cong W(q^*) + \varepsilon \left.\frac{dW}{dq}\right|_{q^*} + \frac{\varepsilon^2}{2}\left.\frac{d^2W}{dq^2}\right|_{q^*} = W^* + \frac{\varepsilon^2}{2}\left(B''(q^*) - C''(q^*)\right) \quad . \tag{1.13}$$

The linear term vanishes, because by definition the derivative is zero at the optimum, while the 2nd-order term gives, as expected, a negative contribution, which depends in size on the curvature of the benefit and cost functions.

If the regulator uses a price mechanism, firms will turn it into a quantity according to the equation $p=C'(q)$, since they are assumed to know their costs. A small deviation from a given price will hence lead to a deviation in quantity proportional to $1/C''$. The welfare resulting from a price regulation with an error of η with respect to the optimal value can then be approximated by

$$\begin{aligned} W(p^*+\eta) &\cong W(p^*) + \eta \left.\frac{dW}{dq}\frac{dq}{dp}\right|_{p^*,q^*} + \frac{\eta^2}{2}\left.\left(\left(\frac{dq}{dp}\right)^2 \frac{d^2W}{dq^2} + \frac{dW}{dq}\frac{d^2q}{dp^2}\right)\right|_{p^*,q^*} \\ &= W^* + \frac{\eta^2}{2}\left(\frac{B''(q^*) - C''(q^*)}{\left(C''(q^*)\right)^2}\right) \end{aligned} \quad . \qquad (1.14)$$

The 2nd-order effect of the error on welfare is again unambiguously negative, but the expression is different from the one obtained for the quantity mechanism. However, in order to determine which instrument would lead to a lower welfare loss, an expression of the typical square error ε^2 and η^2 made by the regulator in the setting of the quantity and price instrument, respectively, must be found.

To this end, Weitzman made the assumption that marginal benefits and costs could be approximated by linear functions in the area of interest, i.e. in the vicinity of their intersection. To facilitate the notation, I take them to be globally linear, i.e. $B'(q) = mB_0 - b\,q$ and $C'(q)=mC_0 + c\,q$, with mB_0, mC_0, b, c as positive constants. The first-best quantity and price instrument would then be given by

$$q^* = \frac{mB_0 - mC_0}{b+c} \qquad (1.15)$$

and

$$p^* = \frac{mB_0\,c + mC_0\,b}{b+c} \qquad (1.16)$$

respectively. However, the assumption is that the regulator has only imperfect knowledge; in particular, Weitzman assumes that the levels of marginal costs and benefits, mB_0 and mC_0, are uncertain (and independent), while their slopes b and c are known. Because the unknown parameters enter linearly in the regulator's estimation of q^* and p^*, the average square error, or variance, is simply given by

$$\sigma_{\bar{q}}^2 = \frac{\sigma_{mB_0}^2 + \sigma_{mC_0}^2}{(b+c)^2} \qquad (1.17)$$

and

$$\sigma_p^2 = \frac{c^2\ \sigma_{mB_0}^2 + b^2\ \sigma_{mC_0}^2}{(b+c)^2} \quad , \tag{1.18}$$

where σ_{mB_0} and σ_{mC_0} denote the standard deviation of the regulator's estimate of marginal benefits and costs, respectively. Substituting ε in Eq.(1.13) and η in Eq.(1.14) yields

$$W(\overline{q}) \cong W^* + \frac{1}{2}\frac{\sigma_{mB_0}^2 + \sigma_{mC_0}^2}{(b+c)^2}\left(B''(q^*) - C''(q^*)\right) = W^* - \frac{\sigma_{mB_0}^2 + \sigma_{mC_0}^2}{2(b+c)} \tag{1.19}$$

and

$$W(p) \cong W^* + \frac{c^2\ \sigma_{mB_0}^2 + b^2\ \sigma_{mC_0}^2}{2(b+c)^2}\left(\frac{B''(q^*) - C''(q^*)}{(C''(q^*))^2}\right) = W^* - \frac{\sigma_{mB_0}^2 + (b/c)^2\ \sigma_{mC_0}^2}{2(b+c)} \ . \tag{1.20}$$

Hence, the welfare difference ΔW between an imperfect price and an imperfect quantity implementation results to be

$$\Delta W = \frac{\sigma_{mC_0}^2}{2c^2}(c-b) \quad , \tag{1.21}$$

meaning that a price mechanism is second-best, i.e. it leads on average to a lower loss of welfare with respect to the theoretical maximum, if $c>b$ holds, or, in words, if the (absolute) slope of the marginal benefits is smaller than the slope of the marginal costs. This is the central result of Weitzman (1974).

A final remark on Eq.(1.18): it shows clearly how under certain conditions a price mechanism can lead to a first-best outcome even with cost-uncertainty, namely if marginal benefits are flat ($b=0$) and if there is no uncertainty on benefits $(\sigma_{mB_0} = 0)$. In this special case a simple Pigouvian tax becomes optimal.

1.3 Thesis Overview

Having the title "Climate Change Policy in a Second-Best World", this PhD thesis is in fact closely related to some of the arguments just presented. Starting from the premise that climate change policymaking takes place within a "sea of uncertainty" (Lave 1991), and that current political realities are incommensurate with a straightforward implementation of global first-best policy, it poses the question of what can be done despite this, and compares different policy options. The research and the results it has produced are presented in five chapters, which are based on five independent articles, as indicated in the overview in Table 1.1. The individual articles are summarized in the remaining parts of this section, also highlighting their connections.[23]

[23] Note that for conciseness and readability, references to articles and sources have deliberately been omitted in these summaries, as they can all be found in the main chapters.

As emphasized by the subtitle, this thesis' focus is put on two particular obstacles to first-best solutions, namely the absence of global cooperation and the presence of uncertainty. The reality and effect of the former could be well-observed at the 2009 UN climate conference in Copenhagen, which failed to come up with the hoped-for successor of the expiring Kyoto Protocol. In fact, the persistent difficulty of stipulating an agreement between nearly 200 heterogeneous countries has cast some doubt on whether the so-far unquestioned UN negotiation arena can actually live up to its mandate of preventing dangerous climate change. As a consequence, some policy makers have started to look for alternative, simpler ways to organize cooperation, e.g. by means of the Major Economies Forum,[24] or direct bilateral cooperation between existing emissions trading schemes. Two major questions of the second-best type arise naturally in this context: (i) how can international cooperation be brought to its highest feasible level? (ii) what can those countries that cooperate do to ensure their policies are cost-efficient and effective?

Chapter	Publication	Content	Contribution
2	Flachsland, Marschinski and Edenhofer (2009a), *Energy Policy*.	Comparative analysis of top-down and bottom-up approaches for creating a global carbon market.	All authors developed the research idea; Flachsland and Marschinski contributed equally in the writing of the article.
3	Marschinski, Flachsland and Jakob (2010), submitted to *Resource and Energy Economics*.	Formal general-equilibrium analysis of linking emissions trading systems, with regard to leakage, competitiveness, and welfare.	Marschinski developed research idea; Marschinski and Flachsland designed and analyzed policy scenarios; Marschinski worked out technical results, with contributions from Jakob.
4	Lessmann, Marschinski and Edenhofer (2009), *Economic Modelling*.	Formal numerical analysis of tariffs imposed on free-riding countries as an instrument to increase cooperation on climate change.	All authors conceived research question. Together with Lessmann, Marschinski devised model-solving algorithm and wrote article. Lessmann implemented model and produced numerical results.
5	Marschinski and Edenhofer (2010), *Energy Policy*.	Investigation into several properties associated with a regulation of national emissions by means of an intensity target.	Marschinski and Edenhofer conceived research question, Marschinski derived results and wrote article.
6	Marschinski and Lecocq (2006), *World Bank Policy Research Paper*.	Elaboration of the conditions under which the intensity target reduces cost-uncertainty, by means of analytical and numerical approach.	Both authors developed research question and model framework, and wrote the article. Analytical results and numerical analysis were provided by Marschinski.

Table 1.1: Summary of chapters.

[24] See http://www.majoreconomiesforum.org/

These two questions are addressed in the following three chapters, with the first two taking a certain level of cooperation as given and investigating different forms of emissions trading as an instrument for cost-effectiveness, and the last one adopting a game-theoretic view and analyzing in how far trade sanction can help to increase the level of international cooperation. Methodology-wise, the three chapters are quite diverse: the first represents a qualitative-institutional study, using qualitative economic and political arguments; the second embraces formal analysis of a general equilibrium model, and the third employs numerical simulations of a game-theoretic model of coalition formation.

The other second-best aspect in the focus of this thesis is uncertainty, and how it is handled by different policy instruments. Obviously, no policy instrument can eliminate uncertainty altogether. For instance, the previous section illustrated how by the choice between price or quantity mechanisms at most one uncertainty could be eliminated (at least in the general case). However, the example has also shown that uncertainty can have a different impact on different instruments, and that therefore–depending on the circumstances–one may be preferable to another.

In the area of international climate policy, quantity mechanisms have emerged as the dominant approach, enshrined in, e.g., the Kyoto protocol or the EU ETS. Economists, being aware of Weitzman's argument, often seem to prefer a carbon tax, but for the moment this option seems unattainable due to the general unpopularity of new taxes. However, a third possibility exists that was brought onto the political stage by the political initiatives of the G. W. Bush administration, Argentina, and, most recently, China, which all suggested an approach based on emissions per unit of GDP, a so-called intensity target.

The final two chapters of the thesis analyze this target under various aspects, most prominently uncertainty. For the purpose of comparison, the *status quo* instrument of absolute targets serves as benchmark. The two chapters investigate whether the intensity target leads to relatively lower uncertainty on mitigation costs, but also whether it could be readily integrated in international emissions trading. The methodological approach is mostly based on simple analytical models, which ensures a high transparency. However, to test the validity of some of the analytical approximations, Chapter 6 also employs numerical simulations.

1.3.1 Chapter 2: Global Trading versus Linking: Architectures for International Emissions Trading

Over the last years, various political initiatives aimed at the establishment or enlargement of carbon markets have emerged, often outside the UNFCCC forum. Amongst other things, this reflects the fact that emissions trading is widely seen as an indispensable policy pillar of climate change mitigation, and is expected to constitute a key building block of future international climate policy.

At the moment two general approaches to the formation of a global carbon market can be observed: First, there is the top-down approach, characterized by a centralized multilateral decision-making process and embodied by the UNFCCC negotiations. Second, there is the bottom-up approach, associated with decentralized decision-making of individual nations or sub-national entities that implement emissions trading systems uni-, bi- or multilaterally. These processes yield two different types of institutional architectures for international emissions trading. The backbone of top-down architectures is emissions trading between governments, while bottom-up architectures rest upon the implementation and possible linkage of regional systems, based on company-level emissions trading.

Chapter 2 analyzes five different types of trading architectures, classified into two top-down and three bottom-up approaches. It describes, analyzes and compares these different institutional architectures along three key variables, namely *environmental effectiveness*, *cost-effectiveness*, and *political feasibility*.

The main insights presented in Chapter 2 can be summarized as follows: Because of their inclusiveness, top-down approaches tend to cover a larger share of global emissions and thus offer a higher degree of environmental effectiveness than bottom-up approaches.

If emissions price equalization is the sole criterion, top-down approaches also fare better in terms of economic effectiveness. But if plausible market imperfections associated with emissions trade between governments, such as market power or information asymmetries, are taken into account, price equalization is unlikely to be a sufficient criterion for efficiency, which requires the equalization of marginal abatement costs. Bottom-up approaches, based on pre-existing trading systems between companies, provide a more robust price signal, and can be very efficient once they are 'linked'.

High political feasibility emerges as the main strength of bottom-up approaches, and, at the same time, largest hurdle for top-down architectures. For the latter, a full international agreement on burden-sharing constitutes a condition *sine qua non*, while the former lends itself to the formation of a coalition-of-the-willing with subsequent enlargements.

1.3.2 Chapter 3: Linking Carbon Markets: a Trade-Theory Analysis

In Chapter 2 the linking of emission trading systems (ETS) emerges as a relevant policy option for international cooperation on climate change after the expiry in 2012 of the first commitment period of the Kyoto Protocol. As already discussed in a qualitative way in Chapter 2, benefits from linking are associated with the gains-from-trade arising in the exchange of emission permits, but also with the alleviation of concerns over international competitiveness. However,

from trade-theory it is known that due to general equilibrium effects and market distortions, linking may not always be beneficial for all participating countries.

Chapter 3 follows-up on this debate in a more formal manner, by employing a Ricardo-Viner type general equilibrium model to study the impacts of sectoral linking on carbon leakage, competitiveness, and welfare. To this end, a number of linking scenarios are analyzed, which were designed to capture the most important strategic options for permit market linkages between some of the major players in international climate policy, namely Europe, United States and China. In this, the US is assumed to implement an emissions trading system (ETS) with near complete coverage, while the EU continues with its two-tier strategy of having in parallel an ETS and non-ETS sector. In order to link to either the US or EU, China is assumed to adopt a sectoral business-as-usual target for one sector only; in addition it might adopt an intensity target.

By characterizing the market equilibria before and after linking, and investigating the comparative statics, it is shown that linking to a country without full cap–as would presumably be the case in any link involving China–can induce leakage, i.e. the non-capped sector might increase its emissions. However, whether or not leakage actually occurs is found to depend on the structural relationship between the linked sectors: if their output goods are substitutes, leakage will occur, but if they are complements, negative leakage (or anti-leakage) is induced. As an extension of this analysis, one mechanism that is shown to be ineffective as a means to prevent leakage is an economy-wide intensity target, which has recently been discussed as a politically more feasible option for developing countries than an absolute cap.

If the EU ETS was to establish a link with a hypothetical US system, leakage would not be an issue, as both regions have capped their total emissions. Besides gains-from-trade, a major driver for pursuing this option would be to address concerns about competitiveness, i.e. the idea of harmonizing permit prices in order to 'level the carbon playing-field' (Houser et al. 2008). However, the results indicate that in this case the partial emission coverage of the EU ETS can cause the creation (or amplification) of distortions both between the EU's own sectors as well as between the EU's non-ETS sector and its US counterpart.

1.3.3 Chapter 4: The Effects of Tariffs on Coalition Formation in a Dynamic Global Warming Game

Under current conditions, the emergence of a comprehensive successor agreement to the Kyoto Protocol seems quite unlikely, at least for the foreseeable future. From a game-theoretic point of view, this can be interpreted as a consequence of all countries' strong incentive to free-ride. For this reason, there is a need to identify policy instruments with the ability to stabilize coalitions of cooperating countries. Chapter 4 takes a closer look at one

instrument that has been proposed in this regard, namely trade sanctions directed at non-cooperating countries.

To assess the potential of this instrument to strengthen an international environmental agreement, trade and trade sanctions are introduced into a game-theoretic numerical model of coalition stability. Trade is modelled by having all countries produce a single generic output good and assuming national product differentiation (the so-called Armington assumption). Coalitions have the possibility to impose tariffs on imports from non-cooperating countries, while the latter act as price-takers.

The underlying numerical framework is based on a multiregional optimal growth model. Such models constitute a state of the art tool in the integrated assessment of climate change policy. However, due to the presence of two market distortions–tariffs on trade flows as well as the global emission externality of climate change–the numerical computation of competitive market equilibria becomes quite difficult. As discussed in some detail in Chapter 4, this required the development of a refined version of Negishi´s (1960) basic algorithm, which allowed to compute intertemporal general equilibria in a robust manner.

The model is then applied to analyze the influence of tariffs on international cooperation. The results suggests, first, that there is indeed significant potential to raise participation through trade sanctions, even when goods from different countries are nearly perfect substitutes; second, that the realized gains in global welfare (due to increased cooperation) overcompensate the loss of welfare associated with the trade distortion by a wide margin; and, third, that the threat of trade sanctions remains credible as long as the tariff rate does not become too large.

As a validation of the results, an extensive sensitivity analysis was performed, confirming the robustness of the overall qualitative insights. Naturally, a key role is played by the value assumed for the elasticity of substitution between goods of coalition and non-coalition countries, which, however, was confined to low values in line with other studies and compatible with empirically plausible trade patterns.

1.3.4 Chapter 5: Revisiting the Case for Intensity Targets: Better Incentives and Less Uncertainty for Developing Countries?

Although developing countries currently account for around 50 percent of global GHG emissions, they are so far resisting the idea of accepting hard upper bounds on their national emissions. However, intensity targets, which set a maximum amount of emissions per GDP, have gained some prominence in the post-Kyoto debate as possible alternative to absolute emission limits, not least because of China's declared intention to implement an intensity target for the

year 2020 on a voluntary basis. Several authors have praised the intensity target for offering advantageous properties, like–*inter alia*–a reduction of cost uncertainty, a lowering of the risk of 'hot air', and a better framing of emission reductions in terms of a challenge to decouple growth and carbon. However, some of these claims have not yet undergone formal scrutiny.

For this reason, Chapter 5 re-examines the case for the intensity target by critically assessing a number of these properties, namely (i) the reduction of cost-uncertainty, (ii) the reduction of 'hot air', (iii) the compatibility with international emissions trading, (iv) the incentive to decouple carbon emissions and economic output ('decarbonization'), and, (v) the suitability of an intensity target to work as a substitute for banking and borrowing.

In terms of methodology, the investigation is based on simple analytical models, each designed to capture a specific aspect of the intensity target's mechanics. The following results are derived in Chapter 5: first, the intensity target's effect on cost-uncertainty turns out to be ambiguous and to depend on parameter values that cannot be estimated with high confidence, such as the correlation between forecast errors for emissions and GDP. Second, the same conclusion holds with regard to the intensity target's ability to reduce the risk of 'hot air'. Third, it is shown that the intensity target would distort international emissions trading, as it implicitly subsidizes domestic emissions. Forth, despite potential asymmetries in the preferred choice of abatement technologies between absolute and intensity targets, the incentive for a lasting transformation of the energy system is not necessarily stronger under the latter. Finally, the intensity target's capacity to substitute banking and borrowing mechanisms turns out to depend again on structural parameters characterizing the relationship between economic growth and emissions. On the other side, limited banking and borrowing provisions under an absolute target could well substitute an intensity target.

Overall, the results of Chapter 5 suggest that due to the increased complexity and the potentially only modest benefits of an intensity target, absolute targets constitute a robust choice for a cautious policy maker.

1.3.5 Chapter 6: Do Intensity Targets Control Uncertainty Better than Quotas? Conditions, Calibrations and Caveats

Chapter 5 already provides a fairly comprehensive assessment of the currently widely discussed intensity target. However, the analysis is restricted to the basic form of the intensity target, in which the emission allowance is determined as a *linear* function of GDP, i.e. the output elasticity of emissions has a value of one. A natural generalization allows this elasticity to take on alternative values, e.g. emissions could be linked to the square root of GDP, as proposed by Argentina in 1998. Such a general intensity target–if well-calibrated–is known to lead to a

lower uncertainty on the amount of abatement than absolute emission quotas (Jotzo and Pezzey 2007).

Taking this as the starting point, Chapter 6 sets out to test whether this result holds in a broader framework, and whether it holds for other policy-relevant variables as well. Specifically, an assessment of uncertainty is carried out for the following four variables: effective emissions, amount of required abatement, marginal abatement costs, and total abatement costs over GDP. All of these variables can become uncertain due to climate policy, e.g., the marginal abatement costs associated with a 10 percent reduction vis-à-vis the BAU level are generally not precisely known.

In fact, the future value of these four variables can become uncertain due to uncertainty on future GDP, on future business-as-usual emissions, and on future abatement costs. The analysis presented uses an analytical model capable of representing all of these three underlying uncertainties within a unified framework. The uncertainty performance of one type of target is then measured by computing the implied variance of the four policy variables. The obtained analytical expressions allow to compare the performance of a well-calibrated general intensity target, linear intensity target, and an absolute target.

The results confirm that a general intensity target can always be calibrated to yield a lower variance than an absolute target for marginal costs, but they also show that this is not true for total costs over GDP, and–obviously–for effective emissions (environmental performance).

Finally, using economic and emission scenarios, as well as forecast errors of past projections, ranges of values for the model parameters are estimated. Confirmed by numerical simulations, it is found that absolute targets dominate linear intensity targets over most of this range, that calibrating general intensity targets over this wide range is difficult, and that the latter–even with optimal calibration–would yield only modest reductions in uncertainty relative to absolute targets.

1.4 Concluding Remarks

The research presented in this thesis adds to the existing literature on climate policy design and instruments, which was characterized in Section 1.2.1. However, going beyond the specific results described in the various chapters, what are the overarching insights to be learned from it? I believe there are three points worth mentioning:

First, because climate policy has the potential to affect the entire economy–especially due to its strong link to the energy sector–there is always a chance that general equilibrium effects matter and influence the outcome of policies in

an unexpected way. The thorough embeddedness of carbon emissions in international trade also points in that same direction. As a case in point, consider the recent surge in China's carbon emissions, which may be driven at least to some extent by the Kyoto Protocol (Peters and Hertwich 2008). In such a context, policy recommendations based on partial reasoning may be misleading, as shown for a measure aimed at 'leveling the carbon playing field' in Chapter 3.

Second, policy instruments in climate change may be affected by a 'devil in the details' phenomenon. For example, an intensity target may suit some countries but not others, as shown in Chapter 5 and 6. Likewise, the benefits of joint carbon trading via sectoral linking may depend on the properties of the involved sectors, as suggested in Chapter 3.

Third, a simple and robust choice for a policy instrument may be second-best exactly for being simple and robust. In fact, instruments that are potentially superior but more complex and less understood than others may open the door to obstructing behavior by actors who use uncertainty strategically for undermining negotiations. With complex issues involving multiple uncertainties and competing policy objectives, seemingly contradicting arguments may easily be constructed. Eventually, this again underscores the need for rigorous analysis of the different claims and arguments made, to which this thesis is meant to contribute.

In a sense, carrying out research often seems to diminish the state of knowledge, as it creates new research questions than it answers old ones. This was also the case with this PhD thesis: the general-equilibrium analysis of carbon leakage from Chapter 3 would find its natural continuation in further research on instruments for containing leakage, such as border tax adjustments, export carbon tax exemptions, or consumption-based accounting, as in the joint work presented in Steckel et al. (2010). Yet, the probably most important question remains the challenge of integrating so far non-cooperating–especially developing–countries in climate change mitigation, by creating the right incentives. Such analyses could build on the formal approach presented in Chapter 4, as already done in Lessmann et al. (2010) for an analysis of the influence of offset mechanisms on international cooperation.

Chapter 2

Global Trading versus Linking: Architectures for International Emissions Trading[25]

2.1 Introduction

The last years have witnessed a considerable amount of political activity geared towards the establishment of emissions trading systems. Amongst other things, this reflects the fact that emissions trading is generally seen as an indispensable pillar of climate change mitigation, and is expected to constitute a key building block of future international climate policy (e.g. Stern 2007).

The Kyoto Protocol and the Marrakesh Accords established an inter-governmental trading system that is set to run for five years, from 2008 until the end of 2012. On this market, which covers the emissions of 37 states, representing 29% percent of the world's CO_2 emissions in 2004 (CAIT 2008),[26] governments can trade emission permits–here called Assigned Amount Units (AAU)–which in principle allows to minimize the costs of compliance with their Kyoto reduction targets. They can also use credits generated under the Joint Implementation (JI) and Clean Development Mechanisms (CDM).

Even earlier, in 2005, the European Union launched its Emission Trading System (EU ETS), which regulates about 10,000 facilities that currently emit around 2Gt of CO_2 per year (Skjaerseth and Wettestad 2008). With a value of 50bn US$, the EU ETS dominates the international carbon market, which totaled to 64bn US$ in 2007 (Capoor and Ambrosi 2008). EU policymakers have emphasized that, irrespective of the outcome of the UNFCCC negotiations on a post-Kyoto climate policy package, the EU ETS will remain in place even after 2012 (EU Council 2007).

Plans for the introduction of domestic emissions trading systems are also underway in several other Annex-I countries.[27] These regional activities are

[25] Chapter based on the homonymous article by Flachsland, Marschinski, and Edenhofer, published in *Energy Policy* 37(5):1637-47, 2009. Being there multiple authors, the text now uses the plural 'we'.

[26] Throughout this chapter, data from CAIT (2008) refers to CO_2 emissions of the year 2004, excluding emissions from LULUCF.

[27] On the national level these include New Zealand, Australia, Switzerland, the United States, Canada, and Japan. Sub-national initiatives for emissions trading also exist in the US (the

flanked by the recent establishment of the International Carbon Action Partnership (ICAP), a forum that was created with the explicit intention of exploring the "(…) potential linkage of regional carbon markets" (ICAP 2007).

These developments can be understood as manifestations of two different approaches towards the establishment of emissions trading systems: First, there is the top-down approach, characterized by a centralized multilateral decision-making process and embodied in the UNFCCC negotiations. Second, there is the bottom-up approach, associated with decentralized decision-making of individual nations or sub-national entities that implement emissions trading systems uni-, bi- or multilaterally (Zapfel and Vainio 2002).

These processes yield two different types of institutional architectures for international emissions trading. The backbone of 'top-down' architectures is emissions trading between governments, while 'bottom-up' architectures rest upon the implementation and possible linkage of regional systems, based on company-level emissions trading. This chapter aims to describe, analyze and compare these different institutional architectures.[28]

In the course of our analysis, we will argue that top-down and bottom-up architectures show characteristic differences in three key aspects. These are:

- environmental effectiveness
- cost-effectiveness,
- political feasibility.

Our main findings can be summarized as follows: Because of their inclusiveness, top-down approaches tend to cover a larger share of global emissions and thus offer a higher degree of environmental effectiveness than bottom-up approaches. However, a significant share of global emissions could also be captured by means of a decentralized approach, in which a carbon market is created by linking existing domestic or regional ETS. The environmental effectiveness of both approaches can be enhanced by integrating baseline-and-credit schemes, e.g. the CDM of the Kyoto Protocol.

If emissions price equalization is the sole criterion, top-down approaches also fare better in terms of economic effectiveness. But if plausible market imperfections associated with emissions trade between governments (such as market power or information asymmetries) are taken into account, price equalization is unlikely to be a sufficient criterion for efficiency, which requires

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Regional Greenhouse Gas Initiative (RGGI), California, the Western Climate Initiative (WCI), and the Midwestern Greenhouse Gas Accord), Canada (some provinces are members to WCI), and Japan (Tokyo and and Kyoto).

[28] 'Intermediate' architectures situated in between the basic cases of bottom-up and top-down are, of course, also conceivable, e.g. in the form of harmonized national policies. However, since we focus on international emissions trading and the way it is implemented under different architectures, these cases are not treated here.

the equalization of marginal abatement costs. Bottom-up approaches, based on preexisting trading systems between companies, provide a more robust price signal, and can be very efficient once they are 'linked'.

High political feasibility emerges as the main strength of bottom-up approaches, and, at the same time, biggest hurdle for top-down architectures. For the latter, a full international agreement on burden-sharing constitutes a *conditio sine qua non*, while the former lends itself to the formation of a coalition-of-the-willing with subsequent enlargements.

We conclude that the perhaps intuitive view of bottom-up and top-down approaches as (imperfect) substitutes needs to be amended. In as much as bottom-up trading architectures bring about not the optimal, but the feasible, they remain a second-best alternative to a top-down global cap-and-trade system in terms of environmental effectiveness. However, when viewed as building blocks that allow putting a cost-effective and expandable carbon market into place without further delay, their supportive role in the eventual establishment of a global carbon market becomes apparent.

The remainder of this chapter is organized as follows: We begin in Section 2.2 by addressing questions of terminology and definition. Top-down architectures are described and analyzed in Section 2.3, bottom-up architectures are dealt with in Section 2.4. A comparative analysis and discussion is given in Section 2.5. We summarize our findings and present our conclusion in Section 2.6.

2.2 Definitions

Discussions about emission trading systems use a distinct lingo, drawing on a number of terms and concepts (e.g. offset credits) that are relatively new, and sometimes lack a clear definition. Hence, before introducing the conceptual framework for the analysis and comparison of different ETS architectures, we want to briefly clarify the basic terminology, as employed in this chapter.

Cap-and-trade systems set a binding, absolute cap on total emissions, but allow for certificates–corresponding to the right to emit a specific volume of emissions–to be traded among the covered entities, which are either nations or companies. The Kyoto Protocol trading system for Annex-B countries is an example for cap-and-trade at the governmental level, while the EU ETS operates at the company level. In contrast, baseline-and-credit systems define a certain baseline such as a business-as-usual projection or a relative target, and only allow emission reductions that go beyond this baseline to be used as sellable credits (often referred to as 'offsets'). In this study, we understand baseline-and-credit systems as non-binding systems, meaning that there is no penalty if the baseline is exceeded. The CDM and JI mechanisms established under the Kyoto protocol are examples of such non-binding baseline-and-credit systems.

We use the terms carbon market and emissions trading system interchangeably to refer to both cap-and-trade and baseline-and-credit systems. The more general term emissions trading architecture is used to denote the overarching structure of relations between emissions trading systems that are implemented all over the world. Different emissions trading architectures can be compared with regard to their degree of integration or fragmentation.[29] Fragmentation means that there are several trading systems with none or only few linkages and, correspondingly, different prices for permits. Integration occurs if there is either only one global trading system or there are sufficient linkages between different carbon markets to lead to an equalization of permit prices across these systems.

In what follows, we interpret the ongoing political efforts in terms of two systematically different approaches, namely the 'top-down' and the 'bottom-up' approach to international emissions trading. In our comparative analysis, we will argue that the associated emissions trading architectures differ particularly in three aspects, which we set out beforehand.

Environmental effectiveness refers to the capability of an emissions trading architecture to bring about significant reductions in global emissions. Its potential for doing so depends, first of all, on the share of global emissions that are actually covered by the emissions trading regime. But taking that as given and assuming a certain emissions target is, however, not sufficient for evaluating its environmental effectiveness, because the offsetting effect of leakage is neglected.[30] Formally, the *percentage* reduction of global emissions can be expressed by the following equation:

Global Reduction = Regime Reduction x (Regime Emissions / Global Emissions) x (1-Leakage Rate)

Because our study focuses on different approaches towards the establishing of a global carbon market, we deliberately abstain from a political economy discussion of how and at which level emissions targets are ultimately set. However, we realize that–considering the decisive role this parameter plays for the actual environmental effectiveness–for accuracy we should rather speak of the *potential* environmental effectiveness of a trading architecture.

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[29] In distinguishing integrated and fragmented architectures we draw on Biermann et al. (2007) who define universalism–which corresponds to our notion of integration–as "(…) a situation in which all countries of relevance in a given issue area (a) are subject to the same regulatory framework; (b) participate in the same decision-making procedures (…); and (c) agree on a core set of common commitments." Fragmentation occurs if these conditions are violated.

[30] Leakage occurs if the regulation of emission intensive industries in one country leads to an expansion of those industries in other, less or unregulated countries, due to a shift in comparative advantage. The impact of this effect will depend on a number of factors, including the size of the carbon price differential, the trade exposure of affected sectors, and the relative importance of the expected persistence of the cost gap for investment decisions. International sectoral agreements, border tax adjustments and the free allocation of allowances (Neuhoff 2008) have been proposed to address leakage concerns. In general, the available evidence suggests that this effect would not be a serious problem in most sectors, at least in the short- to mid-term (Stern 2007, Neuhoff 2008, The Economist 2008).

Cost-effectiveness requires the minimization of the costs of achieving a given emissions reduction target. Conversely, cost-effectiveness also means that a given amount of abatement expenditure leads to the highest possible emission reduction. From a standard result of environmental economics it is well known that cost-effectiveness depends on the equalization of marginal abatement costs across all regions and sources (e.g. Tietenberg 2003). In theory, market instruments such as permit trade or harmonized taxes ensure cost-effectiveness by associating a unique price with the 'bad' emissions, which, in equilibrium, corresponds to the marginal abatement costs. In practice, however, the emerging emissions price under a permit trading scheme may deviate from marginal abatement costs, in particular if (i) one or more actors possess market power[31], (ii) regulators trade on behalf of firms but do not have full information on the abatement costs incurred by the latter (Kerr 2000), and (iii) not all economic sectors are included in the scheme.

Finally, the question of *political feasibility* cannot be sensibly excluded from the discussion of any carbon market architecture extending beyond the national domain. It is mainly related to requirements of participation and consensus, and to transaction costs. Evidently, in order to establish a highly integrated trading architecture, players need to agree on a common regulatory framework, and especially on a set of mutually acceptable emission caps. The latter generally have significant distributional implications, as allocations represent each player's cost free endowment and thus largely determine the required effort. In consequence, bargaining over burden-sharing becomes a strategic game where self-interested players have an incentive to free-ride on the mitigation efforts of others by implementing targets with low stringency (Helm 2003, Rehdanz and Tol 2005). This turns the negotiation of regional emission budgets into the single-most important stumbling block in the creation of an inclusive international climate policy, and impedes high levels of participation in integrated trading structures.[32] Thus, we compare different architectures in view of their chance of successful implementation given these difficulties. In addition, trading architectures can be compared in terms of the transaction costs that arise from creating the necessary institutional structure for government- or company-level trading systems, or baseline-and-credit schemes. In this context, we assume that high transaction costs reduce political feasibility.

In the following two sections we discuss five top-down and bottom-up architectures of international emissions trading. After outlining their principal

[31] A case in point would be Russia's bargaining power with its large amounts of 'hot-air' within the Kyoto trading framework. See also Böhringer and Löschel (2003).

[32] This is confirmed by studies in non-cooperative game theory that mostly come to rather pessimistic conclusions about the chances of full cooperation on the climate problem (see, e.g. Carraro and Siniscalco 1992, Barrett 1994). Limited cooperation in the form of 'climate coalitions' seems more likely to emerge, possibly facilitated by linking the cooperation to other issues such as research and development (Carraro and Siniscalco 1997), or free-trade (Barrett 1997).

features, we analyze their characteristics along the three dimensions just described.

2.3 Top-Down Architectures

We differentiate between two different types of top-down architectures: a 'global cap-and-trade' architecture, which serves as the benchmark for our analysis, and a 'Kyoto-II' architecture, which builds on the structure of the existing Kyoto trading system and could act as a starting point for a follow-up agreement.

2.3.1 Global Cap-and-Trade

A global cap-and-trade architecture implies that every country in the world adopts a well-defined and limited GHG emissions budget for its entire economy, and that emission allowances can be traded between governments (e.g. Vattenfall 2006). As the sum of these national emission caps represents a definite upper bound on total global emissions (assuming compliance), the environmental effectiveness of this architecture would be maximal.

Theoretically, global-cap-and-trade can achieve cost-effectiveness, because a single price for emissions is established across all sectors and regions in the world. Integrated coverage of all world regions and sectors maximizes the gains from trading, as emissions are reduced in places where this can be achieved at the lowest possible costs.

However, given that a large share of all tradable allowances will very likely be concentrated in the hands of a rather small group of countries,[33] vesting them with considerable market power, permit trade between governments will arguably be characterized by strategic– i.e. price influencing–behavior. In fact, it seems questionable whether a single, world-wide price of carbon would emerge at all, given that many transactions can be expected to occur in an 'over-the-counter' fashion, i.e. on the basis of bilateral bargaining and without public disclosure of the price.[34] With such constraints on competition, efficiency losses become inevitable and a potentially sharp increase in total abatement costs is to be expected, as was shown, e.g., in simulations by Böhringer and Löschel (2003).

Moreover, even in a perfectly competitive intergovernmental permit market, information asymmetries between governments and companies would limit the former's knowledge about the true marginal abatement costs incurred by the latter. In particular, this would be the case if national emission targets are not implemented by means of a domestic emissions trading scheme (Hahn and

[33] In 2004, the biggest five emitters, i.e. the US, China, Russia, Japan, and India accounted for 51% of global CO_2 emissions (Source: CAIT 2008).
[34] See e.g. Point Carbon's (2008) reporting on the confidentiality of the negotiations about trading Assigned Amount Units between Japan, Hungary and Czech Republic.

Stavins 1999). Thus, unless an appropriate price revealing mechanism is put into place, it will be difficult for governments to optimize their trading positions on the global carbon market (Kerr 2000). Finally, even if goverments had perfect knowledge about domestic abatement costs, one cannot assume them to act as pure cost-minimizers, as in the case of firms.

Possibly the greatest hurdle to an implementation of a global cap-and-trade architecture consists in its prerequisite, i.e. an agreement on global burden-sharing. Not only have countries different views on the urgency and their responsibility for the climate problem (Ott et al. 2008), but there also is a constant risk of blockade by players with vested interests when negotiations for a comprehensive global trading system involve 192 voting parties.

Another barrier to political feasibility are high transaction costs, as the reaching of global agreement on carbon market rules and the implementation of the corresponding national provisions such as monitoring, reporting and verification systems (MRV), as well as emission registries, constitutes a formidable challenge. The rules agreed upon–after long and painful negotiations–in the Marrakesh accords (Yamin and Depledge 2004) as well as the experience and the regulatory framework developed in regional trading systems like the EU ETS could of course serve as a starting point. Still, their implementation would remain challenging, not only, but especially for least developed countries (Victor 2007).

On the whole, a global cap-and-trade architecture would promise high environmental effectiveness due to its universal emissions coverage. Cost-effectiveness, however, is likely to be compromised as long as emissions are traded by governments. Finally, large doubts remain with regard to its political feasibility, at least in the short term, given the high transaction costs and the need to achieve a global consensus on international burden-sharing.

2.3.2 Kyoto II: Global Trading with and without Caps

Some of the difficulties of the global cap-and-trade scheme can be mitigated by implementing a global carbon market where only a limited group of countries–e.g. Annex-I countries–implements a cap-and-trade system while all other countries–e.g. developing countries–participate by means of 'trade without cap'. This architecture would closely resemble the Kyoto Protocol's framework, in which only Annex-B countries assume binding targets while all others can host CDM baseline-and-credit projects. Given the critique of the CDM in its current form, e.g. with regard to additionality and transaction costs (Schneider 2007, Michaelowa 2003), various reform proposals for the baseline-and-credit system are currently discussed (UNFCCC 2008). For instance, it would be conceivable to have a menu of schemes suiting different sectoral and regional conditions.

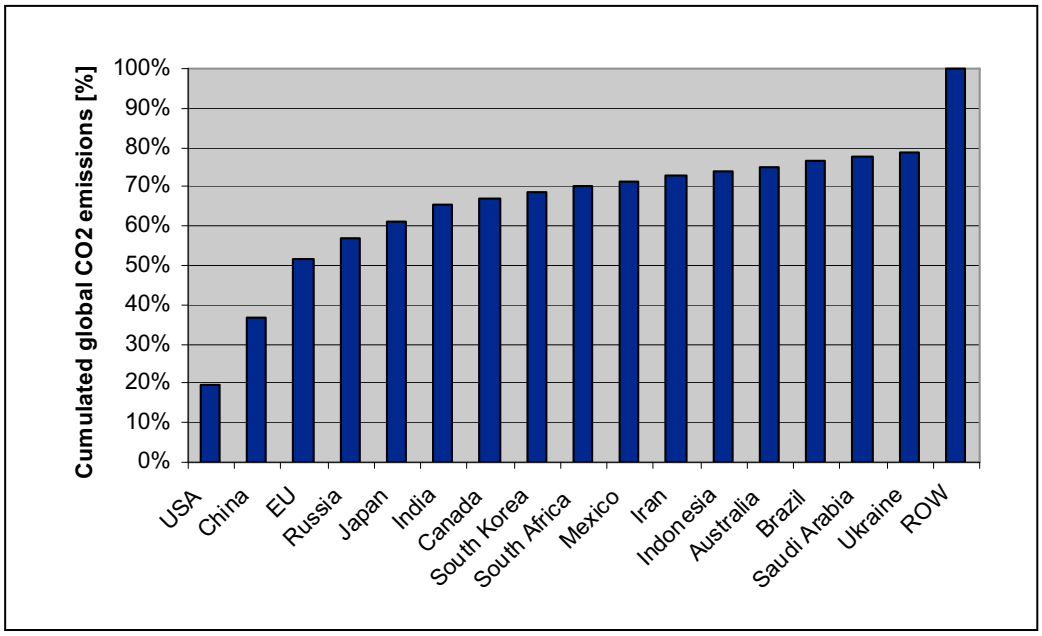

Figure 2.1: Largest emitters' cumulative shares of global CO_2 emissions. Data for year 2004, excluding LULUCF. Source: CAIT (2008)

The environmental effectiveness of this architecture is a priori limited because of its incomplete emissions coverage. As shown in Figure 2.1, the distribution of CO_2 emissions across countries implies that the climate problem is rather inapt to be solved by a limited size coalition-of-the willing: even though three big players (US, China, EU) stand out, they still only account for 52% of all emissions.[35] In fact, if one wants to reach a 90% threshold of global emissions, already 48 countries are needed. In particular, any ambitious effort based on a partial cap-and-trade needs to include the currently second largest emitter, China, and thus cannot circumvent the difficult issue of burden sharing vis-à-vis developing countries.[36]

Furthermore, the fact that developing countries and/or other countries are free to refrain from adopting binding emission targets opens the door to leakage. In principle, this is true even if all uncapped countries are integrated by means of non-binding baseline-and-credit systems. However, such schemes may be designed in such a way as to make sure that countries can only sell credits if their emissions stay below some predetermined level, e.g. below business-as-usual emissions (Philibert 2000). Offering such incentives for emission control to uncapped parties, in particular developing countries, would enhance the environmental effectiveness of a Kyoto-II type architecture.

[35] In this context, Barrett (2007) characterizes the global public good problem associated with climate change mitigation as an 'aggregate efforts' problem: the provision of the public good depends on the *combined* efforts of all states.

[36] As a whole, the group of Annex-I countries represent 49.2% of global CO_2 emissions (CAIT 2008).

Within the core group of cap-and-trade countries, this architecture has the same potential for cost-effectiveness and the same problems due to market imperfections as the global cap-and-trade system. However, in presence of baseline-and-credit mechanisms, the overall cost-effectiveness will depend on the specific design of the latter, e.g. whether there are restrictions on imported credits (such as in the Kyoto Protocol by means of a poorly defined 'supplementarity' provision), and on the incentives provided for uncapped regions. Ideally, baseline-and-credit systems introduce opportunity costs for emissions in uncapped countries, remain uncontroversial in terms of baseline definitions, and keep transaction costs at the minimum level. In reality, of course, there is no widely agreed upon and easily implementable approach to setting baselines (Baron and Ellis 2006). Therefore, such mechanisms are likely to merely pave the way towards the eventual adoption of absolute caps, where concerns about environmental and cost-effectiveness would lose their relevance.

Regarding political feasibility, formal agreement on burden-sharing would only be required between cap-and-trade regions in this architecture, as other countries would not have to assume binding targets. However, in view of the past reluctance of a key emitter like the United States to accept a binding target, this hurdle nevertheless seems high.[37] Also, setting the necessary baselines for the baseline-and-credit mechanisms cannot be done without considering distributional aspects, since baselines determine the amount of credits that can be generated and sold into the capped market. Less stringent baselines increase the volume of profitable credit sales–but also the risk of 'hot air'–while they are reduced by more stringent baselines (Philibert 2000).

Compared to the global cap-and-trade architecture, transaction costs are lower, because only capped countries need to establish the full institutional infrastructure required in cap-and-trade systems. Annex-I countries, for instance, have already implemented MRV and registry infrastructure in order to comply with the Kyoto Protocol. Still, there may be need for revision, and the institutional requirements for some baseline-and-credit systems under discussion may be substantial (Baron and Ellis 2006).

To sum up, a Kyoto-II type architecture only approximates a global cap-and-trade one, and thus can at best come very close to the latter's environmental and (potential) cost-effectiveness. However, the fact that it includes the option for countries to participate without having to accept binding emissions caps, and thereby to contribute to emission reductions, significantly enhances political feasibility. Still, reaching a full, detailed agreement, in particular with regard to burden-sharing and the parameters of the baseline-and-credit mechanism, would constitute a considerable political challenge.

[37] Even though the prospects of US participation might have increased with the advent of the Obama presidency in 2009, one should keep in mind that any international treaty needs to be confirmed by a two thirds majority in the US Senate.

2.4 Bottom-Up Architectures

We distinguish three bottom-up architectures with a gradually increasing degree of integration. First, 'fragmented markets' serves as the benchmark case characterized by a complete absence of intentional linkage of regional markets. Second, in the 'indirect linking' architecture carbon markets are linked indirectly as they accept credits from the same baseline-and-credit systems. Finally, 'formal linking' refers to fully integrated regional carbon markets in which all certificates are mutually recognized.

2.4.1 Fragmented Markets

In the presence of two or more independent emissions trading systems that are installed at the national, supra- or sub-national level, and that do not have any intentional linkages between them, we speak of 'fragmented markets'. Even though international trade in goods already induces a certain tendency towards permit price convergence across different emissions trading systems,[38] prices will in general vary and thus prevent a cost effective outcome. The degree of inefficiency increases–ceteris paribus–in proportion to the price differential between carbon markets.

Based on current expectations, fragmented markets would encompass only a small share of global emissions (see Figure 2.2), implying that any reduction efforts would be particularly vulnerable to emission leakage. Moreover, without any coordinated measures taken by the independent ETSs there will be a very limited scope for baseline-and-credit schemes in developing countries, since demand for such credits would come from at most one of the independent trading systems (otherwise it would be the case of 'indirect linkage', discussed next). Hence, unless a large number of countries chooses to implement autarkic domestic cap-and-trade systems in the mid- to long-term, environmental effectiveness will remain low.

Since they operate independently, fragmented markets cannot ensure the equalization of permit prices and marginal abatement costs and, in consequence,

[38] In a trade-theoretic analysis, Copeland and Taylor (2005) argue that a cost-effective outcome (i.e. equalization of permit prices) can be reached even in absence of permit trade between carbon markets, due to the effects of trade in goods on the prices of non-traded inputs. However, their results are derived within a stylized theoretical model and based on strong assumptions, e.g. identical technologies and tastes across all countries, which are–at best–idealizations of the real world. This means that their results should for practical purposes be interpreted in the sense that 'international trade in goods induces a *certain tendency* towards equalization of the permit price'. That this is indeed plausible can be understood by a simple look at trade in fossil fuels: assume two identical countries with equal emission caps and a common domestic permit price. Now one country adopts a more stringent cap. As a consequence, its domestic permit price rises, and its consumption of fossil fuels must drop (neglecting CCS). In as much as that prompts the world market price of fossil fuels to fall, the opportunity costs of not using fossil fuels in the second country rise, and so does its domestic permit price.

fall short–possibly by a very large margin–of being cost effective. Moreover, smaller systems may additionally suffer from efficiency losses if large domestic players with market power are present (e.g. very large utility companies).

Being close to a world of laisser-faire, fragmented markets require no cooperation and thus there is no need for an international agreement on burden-sharing. Transaction costs are the lowest among all carbon market scenarios, since the only requirement consists of the implementation of domestic systems in some industrialized countries, without any need for coordination and harmonization with other systems.

Recapitulating, the fragmented market architecture represents a politically highly feasible option due to very low transaction costs and no obligation for an international agreement. However, environmental and especially cost-effectiveness are both low.

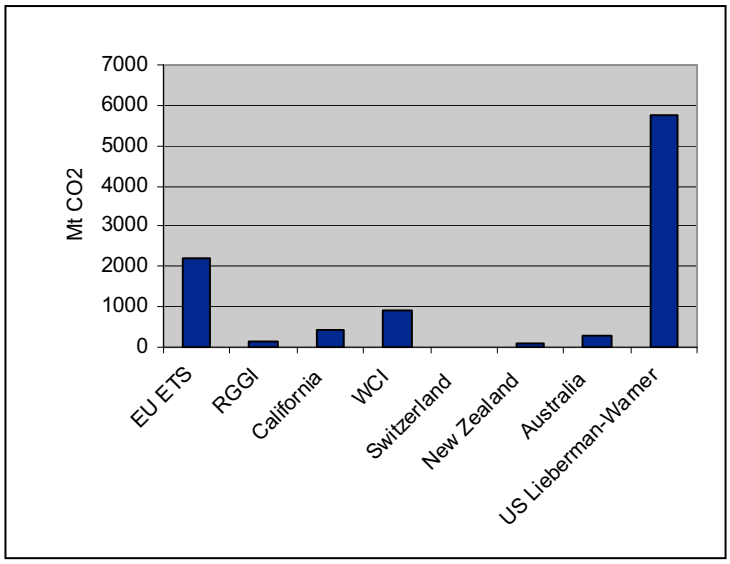

Figure 2.2: Sizes of emerging regional carbon markets. Taken together (counting US regional and federal systems only once), they account for 27% of all global CO_2 emissions in 2004. Sources: Capoor and Ambrosi (2008), RGGI (2008), California (2007), WCI (2007), FOEN (2008), New Zealand (2007), Australia (2007), CAIT (2008).

2.4.2 Indirect Linking

If at least two regional cap-and-trade systems accept credits from the same baseline-and-credit scheme, an indirect link between them is established (Egenhofer 2007). Depending on the supply curve for credits, cap levels, marginal abatement cost (MAC) curves, and quantity limits on the import of credits, indirect linking will lead to a complete or incomplete convergence of the allowance price in indirectly linked cap-and-trade markets. Figures 2.3a-c identify the underlying mechanics for three cases.

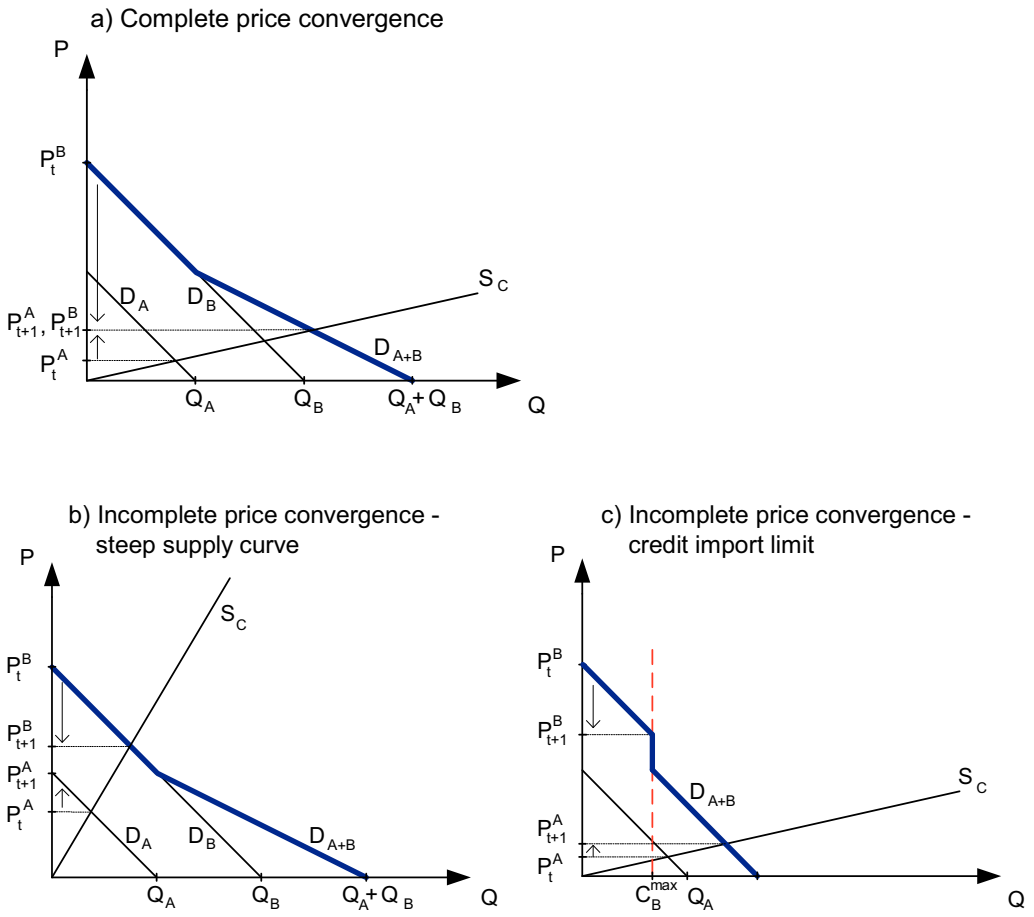

Figure 2.3: Price convergence when trading systems are linked indirectly via credits. D_A and D_B are credit demand curves for systems A and B, and D_{A+B} is the aggregate demand curve. S_C is the supply curve for credits. Q_A and Q_B are reduction amounts (BAU emissions minus cap) in systems A and B. The price level in system A prior to system B's joining of the credit market is P_t^A. The autarky price in system B without any linkage is P_t^B. The price levels in A and B after the entry of B into the credit market are P_{t+1}^A and P_{t+1}^B, respectively. In Figure (c), C_B^{max} is the import limit for credits in system B. The arrows indicate the direction of price changes resulting from indirect linking.

For each case we compare two periods. In the first period t, only cap-and-trade system A accepts credits from the baseline-and-credit scheme C, while cap-and-trade system B operates in autarky. In period t+1, system B also allows the import of permits from the baseline-and-credit scheme C, thereby establishing an indirect link between systems A and B. The cap-and-trade systems are assumed to have identical MAC curves (the slope of D_A and D_B is identical), but system A has a less ambitious cap than system B ($Q_A < Q_B$).

Figure 2.3-a illustrates the case of complete price convergence due to the indirect link. The price in system A increases from P_t^A to the new equilibrium price P_{t+1}^A (= P_{t+1}^B), while the price level in B decreases from P_t^B to P_{t+1}^B (= P_{t+1}^A).

In Figure 2.3-b, price convergence is incomplete because of the steep credit supply curve S_C. When entering the market for credits, system B buys credits at a market clearing price P_{t+1}^B which exceeds the maximal willingness to pay of system A. The latter then resorts to domestic abatement only, leading to a new and different internal allowance price P_{t+1}^A. Here, indirect linking brings about partial price convergence as the allowance price level in A increases, while it decreases in B.

Finally, in Figure 2.3-c price convergence also remains incomplete, this time because system B has adopted an import limit C_B^{max} on credits. In t+1 system B exhausts its import quota and purchases $\overline{OC_B^{\max}}$ credits at the credit price P_{t+1}^A. However, the domestic equilibrium allowance price in B nevertheless settles at the higher price P_{t+1}^B. Again, even though prices in A and B are not fully equalized, some price convergence occurs due to the indirect linking.

Therefore, a carbon market architecture with indirect linkages between regional trading systems will improve cost-effectiveness vis-à-vis the fragmented market case. By how much depends on the level of price convergence across systems, which, in turn, was shown to largely depend on the flatness of the credit supply curve. Therefore, a baseline-and-credit scheme that clears the way for large scale investment opportunities into abatement, e.g. in the power sector, would be conducive to cost-effectiveness. In addition, company-level trading helps to ensure that true marginal abatement costs are revealed, while at the same time reducing concerns about market power, since–relative to top-down and fragmented architectures–a higher number of market participants are present.

As in the preceding case, environmental effectiveness depends on which sectors are included in the regional trading systems,[39] the extension of trading systems across regions, the scope for leakage, and the specific design features of baseline-and-credit schemes. Theoretically, the architecture with indirect links can affect a larger share of global emissions than fragmented markets, since the combined demand from different cap-and-trade schemes increases the scope for a larger-scale implementation of baseline-and-credit schemes. Nevertheless, on the whole one can expect environmental effectiveness to be lower than for top-down architectures, at least in the short- to mid-term, where only few domestic trading systems will emerge.

Like 'fragmented markets', the indirect linkages architecture requires only limited commitment to international cooperation. The establishment of

[39] For instance, the RGGI system only covers the power sector.

commonly accepted baseline-and-credit schemes in third countries (likely development countries) is the one requirement that raises transaction costs relative to the latter architecture. However, concerns might arise in some countries that a 'flood' of low-price credits would lead to a deterioration of the domestic permit price. Although this would imply significant cost-savings in the short-run, it might be inconsistent with long-term objectives such as the transformation of the energy system or the achievement of an ambitious climate target.

In sum, a bottom-up architecture with indirect linkages improves cost-effectiveness relative to the previous case of fragmented markets. This holds to a lesser extent for environmental effectiveness. Both can be expected to remain below the level promised by top-down architectures. There are no significant barriers in terms of political feasibility.

2.4.3 Formal Linking

Formal linking occurs whenever two (or more) regional emissions trading systems mutually recognize each others' allowances, i.e. they accept emission certificates issued in other systems as valid for compliance within their own system. A formal linking architecture is thus established through a concerted linking-decision of different regional trading systems (Tangen and Hasselknippe 2005, Victor 2007, Edenhofer et al. 2007).[40] Evidently, an immediate consequence of linking is the formation of a common emissions price.[41]

The benefit of enhanced cost-effectiveness comes, however, at the cost of contagiousness: once two emissions trading systems are linked, changes in the design or regulatory features in one system that influence the price formation automatically diffuse into all other systems.[42] For instance, if only one country decides to adopt a price ceiling in form of a so-called safety valve,[43] then the entire linked market is in effect capped at the same price. Thus, there is a partial loss of control for domestic regulators over their own system, necessitating a high degree of coordination–and mutual trust–in the management of the joint carbon market. Relevant design issues with implications for the whole linked carbon market include, inter alia[44]

[40] We only consider bilateral linkages. A unilateral link is established if cap-and-trade system A accepts allowances from another system B for compliance, but not vice-versa. In such a system, the allowance price in A would remain at or below the price level of B. See e.g. Jaffe and Stavins (2008).

[41] The permit price might differ by a constant factor if systems use different measurement units, e.g. metric and short tons. The latter unit is in fact envisaged for RGGI.

[42] Depending on the level of price convergence, this will also be the case in the indirect linking case.

[43] A safety valve indicates a provision under which the regulator issues additional emission permits if a certain maximum permit price is reached. See e.g. Jacoby and Ellerman (2004).

[44] These issues are treated in-depth by, e.g., Flachsland et al. (2008), IEA (2005), Jaffe and Stavins (2007).

- the setting and modification of emission caps
- upper and lower ceilings for permit prices
- links to baseline-and-credit schemes, e.g. CDM
- banking and borrowing provisions
- compatible registries
- rules for monitoring, reporting and verification (MRV) of emissions
- penalties and enforcement of compliance

To address these issues, institutional provisions in the form of linking agreements and joint regulatory bodies are required, both before and during the linking operation (Flachsland et al. 2008). In fact, as a first step in that direction, several countries and regions with existing or emerging regional cap-and-trade systems and with an openly expressed interest in linking have already joined forces and established the International Carbon Action Partnership (ICAP) in 2007. As one of its tasks, ICAP is to assess barriers to linking and work out solutions where such impediments may exist (ICAP 2007).

Nevertheless, even if formal linking should become the preferred road for developing the international carbon market, there are three reasons why a concrete realization before 2013 seems very unlikely (see Figure 2.4 for a timeline of emerging regional systems). First, most systems are still in the process of establishing their own domestic institutions, while the EU ETS is for the time being occupied with its own internal expansion and harmonization process. Second, linking partners will very likely want to first observe test phases of new trading systems in order to appraise their performance (e.g. Delbeke in ECCP 2007). Third, strategic decisions on the future shape of international climate policy are not expected to emerge before the UNFCCC's Conference of the Parties in Copenhagen 2009, suggesting that until then regions will generally be reluctant to commit to anything substantial.

Due to the limited coverage (regional, sectoral) that goes along with this bottom-up approach, its environmental effectiveness will be similarly limited as that of the indirect linkage architecture. For instance, the linked carbon markets of those emerging systems that are currently supporting the ICAP initiative and have at least proposed first drafts for a domestic ETS would correspond to about 3.6Gt CO_2eq annual emissions, representing 12% of total global CO_2 emissions in 2004.[45] Leakage concerns are eliminated between linking partners, but persist with respect to uncapped third regions.

As already indicated, a carbon market architecture characterized by bottom-up linking of regional systems will lead to full price equalization across all involved systems, thereby enhancing the cost-effectiveness of the overall effort (Anger 2008). An expanded and quasi unified permit market also means more liquidity

[45] Own calculation based on the sources indicated in Figure 2.2.

and efficiency, as large scale trading at the company level all but eliminates information asymmetry and market power problems.

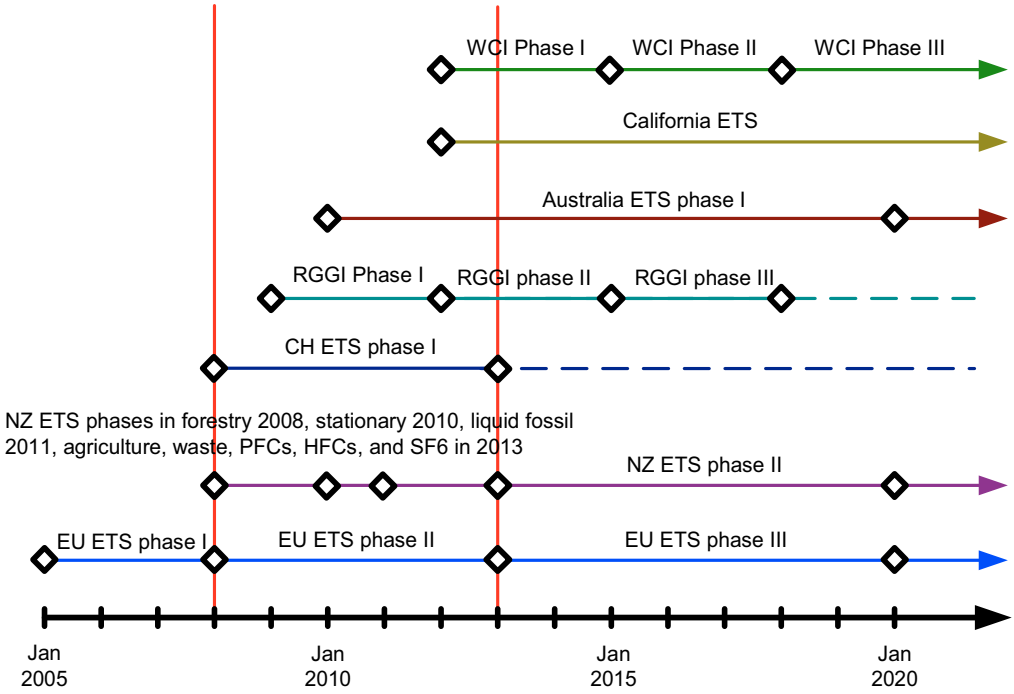

Figure 2.4: Timeline for emerging Emissions Trading Systems (ETS). The two vertical lines indicate the time span of the Kyoto Protocol's first commitment period.

Somewhat different from the other bottom-up architectures, formal linking can face problems in achieving high levels of participation because linked cap-and-trade systems need to agree on burden-sharing to some extent. This may seem surprising at first, since linking involves the coupling of presumably already capped trading systems. However, one can argue that a country with a relatively high domestic emissions price would be reluctant to link its permit market to that of another country with a relatively low emissions price, in as much as that would entail massive imports–and corresponding financial flows–of emission permits.[46] Also, regions with ambitious overall climate policy targets will use linking and the implicit efficiency gains as a bargaining chip in climate policy negotiations, which will make them reluctant to link to systems with low stringency. Linking to a low price permit market could also undermine a country's efforts to spur technological innovation via high permit prices (Neuhoff 2008). So, even though a link in such circumstances would allow both countries to lower their short-term abatement costs by trading emission permits, it may

[46] In fact, linking faces an immanent free-riding problem, as there is an incentive to relax caps in order to generate additional revenue from exporting allowances (Helm 2003, Rehdanz and Tol 2005).

not be a desirable option for reasons of political economy and long-term strategic climate policy considerations (Flachsland et al. 2008).

The linking of regional trading systems incurs some transaction costs, as several design features of trading systems may need to be harmonized prior to linking.[47] This might constitiute a decisive disadvantage in comparison to indirect linking, as stressed by Jaffe and Stavins (2008). These costs can, however, be contained if emerging systems incorporate the prerequisites for linking already during their design phase, thereby circumventing the need for costly ex post changes of already implemented systems. Given that, and taking into account the lower number of negotiation partners, we conclude that formal linking should incur lower transaction costs than top-down approaches.

Overall, the formal linking architecture promises high cost-effectiveness. Being similar to the indirect linking case, environmental effectiveness remains lower than under a full global trading system, at least in the short- to mid-term. Political feasibility becomes more problematic compared to the other bottom-up approaches, since linking markets need to mutually accept each others' reduction efforts and implied range of permit prices. Transaction costs will be higher than for the other bottom-up architectures, but lower than under top-down approaches.

2.5 Discussion

Table 2.1 summarizes the key characteristics of the five carbon market architectures under investigation. It illustrates how the choice between integrated top-down and fragmented bottom-up architectures corresponds to a trade-off between high environmental effectiveness on the one hand, and political feasibility on the other. The picture is less clear-cut for cost-effectiveness.

Concerning environmental effectiveness, a top-down architecture with global-cap-and-trade obviously offers the best possibility for significant cuts in global emissions. On the other end of the spectrum, a bottom-up architecture consisting of fragmented markets is unlikely to significantly curb global emissions. The situation is less definite for the other, 'intermediate' architectures: with a sufficient number of committed participants, the indirect linkages and especially the formal linking approach may come close to the environmental effectiveness of a Kyoto II architecture. In fact, while a bottom-up approach may be more likely to start out with lower initial emissions coverage, it can expand step-by-step, thereby gradually increasing the share of global emissions that it covers.

[47] These issues are treated in-depth by, e.g., Flachsland et al (2008), IEA (2005), Jaffe and Stavins (2007).

Both the Kyoto II and all of the bottom-up schemes have to face the challenge of controlling emissions leakage; as with Kyoto II, the formal and indirect linking architectures can be extended to provide economic incentives for emission control to third countries in the form of appropriately designed baseline-and-credit mechanisms. Finally, short-term concerns leakage can be mitigated if most or all of those countries that are close trade competitors participate in the linked carbon market.[48]

		Integrated global trading	*Kyoto II*	*Formal linking*	*Indirect linkages*	*Fragmented systems*
Environmental effectiveness	*Coverage*	++	+ depends on CDM design	**o (+)** depends on participation	**o (+)** depends on participation	**-** depends on participation
	Prevention of leakage	++	+	**o**	**-**	**--**
Cost-effectiveness	*Price convergence*	++	++	++	+	**-**
	Overcoming MAC information asymmetry	**o**	**o**	++	++	++
	Limiting market concentration	**-**	**-**	++	+	**o**
Political feasibility	*Ease of achieving agreement on cooperation*	**--**	**-**	+	++	++
	Low transaction costs	**--**	**-**	**o**	+	++

Table 2.1: Comparison of the five carbon market architectures. The ratings, from very high (++) to neutral (o) to very low (--) represent a relative measure of differences between architectures.[49]

Among participating countries, top-down architectures always allow for a complete equalization of the permit price. But concerns over market power distortions and doubts about the proper revelation of domestic marginal abatement costs reduce the cost-effectiveness prospects of these architectures. By contrast, bottom-up approaches lead to permit price equalization only in the formal linking case or–under the condition that the credit supply curve is sufficiently flat and no restrictions are imposed on credit imports–in the indirect

[48] We neglect the options of compensation schemes and border tax adjustments (see Neuhoff 2008).
[49] Note that the ratings for environmental effectiveness of the three scenarios 'Kyoto II', 'formal' and 'indirect linking' crucially depend on the level of participation (number and size of systems) and the design of baseline and credit schemes. Ratings should thus be interpreted as sort of 'average' assessments.

linking case. However, the price signal may be more robust, since company-level trading systems are better suited to resolve the information asymmetry between governments and companies and are less prone to market power distortions.

In terms of political feasibility top-down approaches resemble 'all-or-nothing' options: without international consensus on burden-sharing, complete political standstill is imminent. This constitutes a very tangible threat, given that any kind of agreement can rather easily be blocked by countries with vested interests. Similarly, agreement on the design details of the trading and accounting system will be more difficult to achieve than for bottom-up approaches with fewer participants. In fact, the latter will always enable cooperating regions to jointly reduce emissions in a cost-effective manner, even in absence of a global accord on burden-sharing and regulatory design.

Finally, transaction costs of top-down architectures are relatively high, because a larger number of players need to implement the institutional infrastructure needed to participate in the common carbon market. Albeit to a lesser extent, direct linking also incurs significant costs, since it requires extensive regulatory harmonization, which possibly justifies a preference for indirect linking in the short-run (Jaffe and Stavins 2008).

On longer time horizons, the main issue in a comparison between top-down and bottom-up architectures must be the climate target they are able to support. Game theoretical considerations of international agreements typically suggest a dichotomy of 'narrow and deep' versus 'broad and shallow', that is, agreements with fewer members can achieve higher levels of cooperation than those with many members (Downs et al. 1998). Intuitively, such a pattern can be expected whenever the level of cooperation and ambition embodied in an agreement corresponds to a lowest common denominator outcome. Such reasoning seems to be applicable in the realm of climate change, where the 'shallowness' of the Kyoto Protocol fits well into the scheme.[50]

However, due to the global public good nature of climate change, which manifests itself through concerns about free-riding and leakage, a coalition of few or several like-minded countries is unlikely to implement the deep emission cuts that would fit into the 'narrow and deep' picture. Therefore, the current situation can better be characterized in terms of a dichotomy of 'broad and shallow' versus 'narrow and shallow': unless global agreement on an ambitious long-term target, burden-sharing, and institutional design is achieved, a broad (i.e. top-down) agreement will reflect the lowest common denominator interest of all parties. Likewise, within narrow (bottom-up) approaches, countries' reduction efforts cannot be expected to significantly exceed those occurring in a situation without any cooperation, due to concerns over leakage and free riding.

[50] The targets of the Kyoto Protocol–without counting the US–correspond to a reduction of global emissions by about 5% with respect to the business-as-usual emissions in 2010, as expected in 1997. Source: own calculation based on EIA (1997).

In view of an ambitious long-term climate objective, such as the European Union's target to limit global warming to 2°C above pre-industrial levels (EU Council 2007), only two scenarios remain viable: either the international community decides to cooperate and agrees on global targets, burden-sharing and a regulative system to implement a 'broad and deep' climate policy in top-down mode; or it embraces a bottom-up approach, initially 'narrow and shallow', but with a successively broadening participation and deepening commitment. Such an increase in participation, in fact, does not seem implausible once the key uncertainties of the climate change problem (e.g. technologies, costs, and climate damages) are reduced and the feasibility of carbon trading is demonstrated by a group of frontrunners. This process, however, would need to proceed quickly in order to generate emission reductions in line with low-stabilization scenarios suggested by the IPCC (2007c).

Hence, if ambitious climate policy targets require swift emission reductions, top-down architectures appear quasi indispensable. Moreover, their major weakness–low political feasibility due to the need to resolve the burden-sharing issue–can in a way be understood as a strength: the very crux of the climate problem is addressed at once, which keeps up the pressure on negotiators, and prevents procrastination up to a point in time where low stabilization becomes unfeasible. Thus, within this long-term point of view, bottom-up architectures appear as imperfect substitutes of top-down approaches, serving as fallback option if a global agreement cannot be achieved right away. Consequently, they would mainly serve to bring new momentum to the currently stagnant efforts to establish a global, integrated system.

On the other side, the two approaches can be viewed as complementary in the sense that bottom-up architectures may serve as essential building blocks for more comprehensive top-down architectures. This way, efficient regional carbon markets can already be put into place, while the delicate question of burden-sharing is deferred for some time. For example, it would be conceivable that after the Kyoto Protocol's expiry in 2012 a group of countries willing to adopt binding economy-wide caps proceeds with the protocol's intergovernmental cap-and-trade system, and formally link their emerging domestic trading systems within this overarching structure. By devolving inter-governmental permit trading to the company level the economic performance of the international carbon market would be improved.[51] But unlike the Kyoto scheme, this architecture can be designed as an open system, where countries can join by linking-up their domestic ETS whenever they feel ready, or whenever the political momentum in the country has reached a sufficient level.[52] Such an approach could be environmentally and economically more effective than pure

[51] This approach is represented by the EU ETS, where transactions of allowances across country borders are mirrored by transfers of AAUs between national Kyoto registries.
[52] As it was the case with Australia and the Kyoto Protocol (Keohane and Raustiala 2008).

bottom-up approaches, while being less prone to political deadlock than the top-down approach.

2.6 Conclusion

A comprehensive global system represents the benchmark for any future international emissions trading architecture, at least in terms of effective climate protection and access to low-cost abatement opportunities. However, given the considerable political challenge posed by top-down approaches–well reflected in the current multilateral climate policy negotiations–they suffer from the risk of a political deadlock of indeterminate duration.

On the other hand, the bottom-up road to international emissions trading is constantly challenged by the question of whether emission reductions in this context can have a significant environmental impact at all. Still, this institutional approach may better suit the current state of politics, and therefore could help to bring about not the ideal but at least the feasible. Also, permit trade among companies is preferable to permit trade among governments on efficiency grounds since distortions due to high market concentration are avoided and the liquidity and transparency of the emerging emissions market are reinforced. By linking up with countries that have similar export profiles, leakage concerns can be mitigated at least partially. Suitably designed, bottom-up approaches enable a gradual integration of initially fragmented trading architectures, resulting in increasing environmental and cost-effectiveness. They allow countries to join whenever they feel ready, or whenever the political momentum in the country reaches a sufficient level.

If top-down and bottom-up approaches are seen as complements rather than substitutes, following both tracks in parallel via UNFCCC and ICAP appears to be a robust strategy, especially in view of the current uncertainty surrounding the multilateral climate policy negotiations. In case of a break-down of the latter, bottom-up linking of regional trading systems stands ready as a fallback option and alternative to the continuation of the Kyoto trading system. In any case, integrated trading architectures imply considerable challenges to international coordination, particularly regarding joint regulation. Therefore, exploring governance options for carbon market regulation in multilateral architectures should be a key objective for further research on international emissions trading.

Chapter 3

Linking Carbon Markets: A Trade-Theory Analysis[53]

3.1 Introduction

In view of the expiry in 2012 of the Kyoto Protocol's reduction obligations, the bottom-up linking of existing national or regional emission trading systems (ETS) has become a widely discussed policy option (Buchner and Carraro 2007, Flachsland et al. 2009a, b). For example, the creation of an OECD-wide carbon market that in some way becomes linked to developing countries is now a central pillar of the European Union's climate strategy (EU Commission 2009), in line with various legislative cap-and-trade initiatives in the United States and Australia that have signaled a strong willingness to link their systems (Tuerk et al. 2009).[54] In fact, after COP-15 in Copenhagen did not yield a legally binding multilateral agreement, this approach appears ever more relevant (Stavins 2009).

The merits of international emission trading are well-understood and include efficiency-gains (e.g. Tietenberg 2006), but also the alleviation of competitiveness concerns through the elimination of carbon price differentials and access to cheap abatement options in developing countries (e.g. Alexeeva-Talebi et al. 2008). Some observers, however, have cautioned that in the presence of market distortions and general-equilibrium price effects, the linking of regional emission trading systems may not always be beneficial (Babiker et al. 2004, Anger 2008), and, in addition, might facilitate undesirable international spillovers of shocks in permit markets (McKibbin et al. 2008).[55]

This chapter follows up on this debate and employs an analytic Ricardo-Viner type general equilibrium model with international trade in goods and fossil fuel resources to study the impacts of sectoral linking on emission leakage, competitiveness, and welfare. The scenarios under investigation are designed to

[53] Chapter based on the homonymous article by Marschinski, Jakob, and Edenhofer presented at the 2010 World Congress of Environmental and Resource Economists in Montreal, and submitted to the journal *Resource and Energy Economics*. Being there multiple authors, the text uses the plural 'we'.

[54] OECD regions preparing the implementation of cap-and-trade systems include the United States, Australia, Japan, South Korea, as well as individual US states and Canadian provinces organized in the Western Climate Initiative (WCI) or Midwestern Greenhouse Gas Reduction Accord.

[55] For a review of merits and demerits of linking cap-and-trade systems, see, e.g., Flachsland et al. (2009b).

mimic the most important strategic options for permit market links between some of the major players in international climate policy, namely Europe, United States and China.

The EU has specified a comprehensive climate policy package for the time up to 2020, featuring *inter alia* an economy wide emission reduction target to be implemented on one hand by means of the EU ETS–which covers around 40% of European GHG emissions–and on the other hand by various policies and measures aimed at the remaining sectors (European Union 2009a, b). One focus of our analysis is on the potentially adverse impacts such a segmented policy approach may entail. In contrast, if the United States were to implement a climate policy package along the lines of the Waxman-Markey draft, its economy-wide cap-and-trade system would cover about 85% of US greenhouse gas emissions (Larsen and Heilmayr 2009). For China we analyze scenarios representing the implementation of a scaled-up Clean Development Mechanism or sectoral trading scheme (EU Commission 2009, Schneider and Cames 2009), but we also take into account the possible simultaneous presence of an economy-wide intensity target.[56]

By comparing the pre- and post-linking equilibria between two countries, we find that leakage can arise if one of the 'linked' countries lacks a comprehensive cap on its total emissions. In this case, an increased uptake of fossil fuel resources in the non-capped sector would be observed. However, whether or not leakage actually occurs turns out to depend on which industries are linked in the joint permit market: if their respective output goods are imperfect substitutes, leakage does not occur or may even become negative (what we call anti-leakage). As an extension of this analysis, one mechanism that is shown to be ineffective as a means to prevent leakage is an economy-wide intensity target, which has recently been discussed as a politically more feasible option than an absolute cap, at least for developing countries.

If the EU ETS was to establish a link with a hypothetical US system, leakage would not be an issue because both regions would face a limit on total emissions. Besides gains-from-trade, a major driver for implementing such an option would be to address concerns about competitiveness, i.e. the idea of harmonizing permit prices in order to 'level the carbon playing-field' (Houser et al. 2008). However, our results indicate that due to the EU ETS' partial coverage of total EU emissions, this can only be achieved to a limited extent. As will be shown, under such circumstances linking can create (or increase) a distortion both between the EU's own sectors as well as between the EU's non-ETS sector and its US counterpart.

[56] Prior to the COP-15 meeting at Copenhagen, China announced its intention to reduce the carbon intensity of its economy by 40-45% from 2005 to 2020.

Finally, our analysis provides an explicit representation of the welfare effects of linking in a general-equilibrium setting. Namely, the overall effect is decomposed into an always positive gains-from-trade and a terms-of-trade effect. Because the sign of the latter depends on which goods a country exports and imports, the net effect turns out to be ambiguous.

The remainder of this chapter is organized as follows: The next section reviews the relevant literature. Section 3.3 sets out our model. Results are derived and discussed in Section 3.4 and–for the special case in which one good becomes non-traded–in Section 3.5. Section 3.6 concludes.

3.2 Literature Review

Studies on linking different emission trading systems can roughly be divided into three categories: (i) qualitative-institutional studies, (ii) game-theoretic approaches, and (iii) numerical partial and general equilibrium analyses.

The first category contains a number of studies which have investigated the institutional aspects involved in linking, focusing on the different systems' design compatibility as well as qualitative economic and political impacts (e.g. Sterk et al. 2006, Tuerk et al. 2009, Flachsland et al. 2009a,b). They mainly provide detailed analyses of proposals for new cap-and-trade systems, identify needs for harmonization of system design features, or compare different institutional arrangements for the governance of joint carbon markets. However, due to the nature of these studies, the scope for economic analysis remains rather limited.

The second strand of more game-theoretic research focuses on strategic interactions between countries that unilaterally implement domestic trading systems and consider linking, i.e. international emission trading, as a policy option. Helm (2003) provides evidence that in such a case the anticipation of linking creates an incentive for low-damage countries to relax their cap in order to benefit from increased permit sales. Rehdanz and Tol (2005) discuss suitable instruments, in particular import quotas, which enable buyers to contain such inflationary tendencies on the sellers' side. Carbone et al. (2009) employ a computable general equilibrium (CGE) framework with international trade in goods, resources, and permits, and allow countries to anticipate the impact of their quota allocation decision. They identify the possibility of oligopolistic behaviour, i.e. that the incentive of net permit sellers to raise permit prices by increasing the stringency of their cap may outweigh their incentive to relax the cap, especially in the presence of additional positive effects on international resource markets.

Finally, with a focus on the internal dynamics of the EU ETS, Dijkstra et al. (2008) as well as Böhringer and Rosendahl (2009) analyze the partition between ETS and non-ETS sectors as a strategic game of EU countries against each

other, constrained by the fixed EU ETS total emission cap. While the former specify the conditions for welfare gains and losses when additional trading sectors enter the system, the latter pursue an empirical analysis and find evidence for a strong role of political economy forces.

In the third group of studies, partial equilibrium analyses of permit markets using regionally and sectorally specified marginal abatement cost curves allow studying the impact of carbon market linkages on allowance prices and regional abatement costs (Anger 2008, Anger et al. 2009, Stankeviciute et al. 2008, Russ et al. 2009). One main conclusion to draw from partial market modeling is that unless linking is assumed to be accompanied by the introduction of severe market distortions, it will be welfare enhancing for all countries due to the standard gains-from-trade effect (Anger 2008, Anger et al. 2009). Linking cap-and-trade systems to the CDM offers particularly high efficiency gains due to the expected large supply of low cost abatement options in developing countries. However, by definition these models ignore the general equilibrium effects of permit trade, e.g. a loss of competitiveness or carbon leakage occuring due to changes in relative prices.

To capture such effects in the context of climate policy, several CGE models were developed and first applied to assess the economic implications of the Kyoto Protocol (e.g. Bernstein et al. 1999, McKibbin et al. 1999) and, more recently, the impacts of bi- and plurilateral linking. For example, Babiker et al. (2004) and Paltsev et al. (2007) show that an increase in the domestic price of carbon after joining international emission trading can reinforce pre-existing distortions associated with inefficiently high fuel taxes – up to the point where the corresponding welfare losses outweigh the primary gains in efficiency from emission trade. Most closely related to our work–in terms of the issues addressed–is Alexeeva-Talebi and Anger (2007) and Alexeeva-Talebi et al. (2008): the first study finds that whenever linking the EU ETS to another country's system leads to an inefficient emission allocation between ETS and non-ETS sectors in the latter (assuming perfectly efficient policies in the no-linking case), the link is welfare decreasing for the EU partner country and has hardly any impact on EU welfare. The subsequent study analyzes the competitiveness impacts on the EU economy from unilateral climate policy, and finds them to be largely negligible if the EU ETS establishes a link with the CDM market, due to the resulting much lower allowance price. However, because of the numerical character of CGEs, such analyses can only provide limited insights on the underlying mechanisms at work, which is the objective of our contribution.

Thus, our study aims to complement previous contributions through its analytical general equilibrium framework based on trade-theory. This allows for a theoretical investigation into the economic and environmental impacts of linking carbon markets, taking into account the interplay of permit trade and

trade in sectorally differentiated goods and fossil fuel resources. In that sense, our adoption of a trade-theory point of view follows the work of Copeland and Taylor (2005), although–differently from us–they used a long-run oriented Heckscher-Ohlin framework and focused on the strategic effects of trade in a model with endogenous emissions choice.

3.3 Model Definition and Country Specification

Model definition

We consider an extended Ricardo-Viner model with two countries, home h and foreign f (index i), as main protagonists, and an additional country s as supplier of fossil fuel resources R, which are an essential input factor for production in both h and f.

Each country's economy is composed of two sectors, producing goods X and Y (index j).[57] The corresponding constant-returns-to-scale technologies, F and G, use fossil fuel resources as well as other inputs–such as capital and labor–for production. We adopt the short- to mid-term point of view of the Ricardo-Viner (or specific factor) model (Mayer 1974, Neary 1978),[58] assuming the fossil fuel resource as being perfectly mobile across sectors, while the other inputs are sector-specific and hence immobile in the short- to medium-run. Thus, they are implicitly included in the specific functional forms of F and G without the need to explicitly write them down as arguments:

$$X^i = F^i(R_X^i) \qquad\qquad Y^i = G^i(R_Y^i) \quad , \tag{3.1}$$

with strictly concave functions F^i and G^i (declining returns for each individual production factor), and $R_X^i + R_Y^i = R^i$ capturing the sectoral allocation of resource inputs in country i. Emissions are assumed to be identical with the amount of fossil fuel resources employed in production; the two terms are therefore used interchangeably throughout this article.

In view of the symmetry of the problem, we choose the resource as the numeraire (i.e. p_R=1), and p_x and p_y as the price of good X and Y, respectively.[59] Firms in each country maximize profits under perfect competition and hence satisfy the usual first-order conditions for the marginal product of the resource input:

$$1 = p_x\, F_R^i(R_X^i) = p_y\, G_R^i(R_Y^i) \quad , \tag{3.2}$$

[57] The resource supplier's production of X and Y is supposed to be negligibly small.
[58] This approach has the merit of avoiding the tendency towards full specialization that arises in a Heckscher-Ohlin model when factors become traded (Markusen 1983).
[59] While usually one of the goods is chosen as the numeraire, our choice preserves the symmetry between X and Y and thus allows for a more intuitive presentation of the results.

where the subscript R is used to denote the derivative with respect to R, i.e. the marginal product. Note that as payments accrue to the other (immobile) factors of production, the value of output of X and Y exceeds the value of the resource used in their production, even though firms do not have market power. Inverting Eq.(3.2) allows obtaining the resource demand function of country i:

$$R^i = F_R^{i\,inv}(p_x) + G_R^{i\,inv}(p_y) \quad . \tag{3.3}$$

In line with the short-run focus of this analysis, we ignore potential changes in the environmental damage level resulting from variations in the amount of fossil fuel combustion (i.e. emissions).[60] That is, in our model consumer preferences are represented through a utility function U which only depends on the realized consumption bundle $U = U(C_x^i, C_y^i)$. Furthermore, we assume that tastes are homothetic and uniform across countries. Thus, taken prices as given, all consumers spend the same fraction η of their income I^i on good X and $1-\eta \equiv \tilde{\eta}$ for consumption of good Y, where η depends only on the parameters of the utility function and the relative price between goods, which for convenience we denote in shorthand form by $p_{x/y} \equiv p_x / p_y$. Demand for good X and Y in country i is thus given by, respectively, $\eta\, I^i / p_x$ and $\tilde{\eta}\, I^i / p_y$. Welfare can be expressed as a function of real income using the indirect utility function:[61]

$$W^i = U\left[\frac{I^i}{\phi(p_x, p_y)}\right] \quad , \tag{3.4}$$

where ϕ is the exact price index of consumption goods. Finally, we assume that the resource supply side can be characterized by a supply function S

$$R = S[\phi(p_x, p_y)] \quad , \tag{3.5}$$

that is strictly decreasing in ϕ. Using R as the numeraire, its nominal price remains constant. Supply, however, is determined by its real price, i.e. the nominal price divided by the price index ϕ. As rising goods prices decrease the real price of R, its supply is negatively related to p_x and p_y. Such a functional form can be derived by assuming either that (i) resource extraction is associated with increasing social costs (e.g. disutility from supplying labor), or (ii) goods X and Y are necessary inputs for the extraction of R,[62] or (iii) there is a tendency of forward-looking extractors to postpone extraction in the face of falling resource prices.

To summarize, in this model a global competitive equilibrium is defined by prices p_x and p_y such that (i) firms maximize profits, i.e. Eq.(3.2) is satisfied in

[60] Climate change is a stock pollutant problem with a significant delay between emissions and damages.
[61] We sometimes use brackets [..] to emphasize the argument of a function.
[62] We thank Gabriel Felbermayr for this suggestion.

both countries, (ii) consumers maximize utility, i.e. their demand is determined by the function η, (iii) each country's income I^i equals its GDP (corresponding to the factor income of the non-resource inputs, e.g. labor), i.e.

$$I^i = p_x X^i + p_y Y^i - R^i \quad , \tag{3.6}$$

(iv) world markets for goods clear, i.e.

$$\frac{\eta(p_{x/y})}{p_x}\left(I^h + I^f + I^s\right) = X^h + X^f \text{ and } \frac{\tilde{\eta}(p_{x/y})}{p_y}\left(I^h + I^f + I^s\right) = Y^h + Y^f \quad , \tag{3.7}$$

and, finally, (v) the competitive resource market clears, i.e.

$$S\left[\phi(p_x, p_y)\right] = R^h(p_x, p_y) + R^f(p_x, p_y) \ . \tag{3.8}$$

Eq.(3.8), together with the four independent conditions implied by Eq.(3.2), and the equation obtained by dividing through the market clearing conditions from Eq.(3.7) form a set of six equations allowing to uniquely determine the six independent variables p_x, p_y, and R_j^i, from which–by using $\eta(p_{x/y})$–the individual consumption levels follow directly. Note that combining Eq.(3.6) and Eq.(3.7) implies that trade is always balanced, as the value of consumed goods must by definition equal national income.

Any trade equilibrium will comprise flows of resource R from s to h and f, and flows of goods X and Y towards s, as well as–possibly–an exchange of Y and X between h and f. For example, the production functions of h and f could be strongly asymmetric, such that h produces almost only good X, and f almost only good Y. In this case both countries would trade with the resource supplier but also with each other. On the other side, if h and f are perfectly symmetric, they will still trade with the resource supplier but not with each other. In other words, the home and foreign country will always be net exporters of either Y or X, or of both.

Country specification

The model has the aim to provide a stylized representation of the climate policies of the United States, Europe, and China. For the case of the United States we assume the adoption of the Waxman-Markey Bill as described in Larsen and Heilmayr (2009). Europe has already adopted a comprehensive climate policy package (European Union 2009a,b), and China is assumed to implement a scaled-up CDM or sector-based trading mechanism (EU Commission 2009), possibly on top of its currently proposed economy-wide intensity-target.

The Waxman-Markey cap-and-trade system would cover 85% of US (here denoted as 'f') greenhouse gas emissions and can therefore be modeled as an economy-wide cap-and-trade system with an upper bound $\overline{R}^f$ on national

emissions.[63] As a consequence, this policy always leads to an efficient domestic sectoral burden sharing of the abatement effort, which in formal terms means that in both sectors the same gap arises between the value of the marginal product and the (normalized) world price of the resource:

$$p_x \, F_R^f(R_X^f) = p_y \, G_R^f(\overline{R}^f - R_X^f) > 1 \quad , \tag{3.9}$$

Due to the policy-prescribed limit on national resource intake, the market clearing condition for the global resource market from Eq.(3.8) simplifies to

$$S\left[\phi(p_x, p_y)\right] = \overline{R}^f + R^h(p_x, p_y) \quad . \tag{3.10}$$

In Europe ('*h*'), the EU ETS encompasses only 40% of all GHG emissions.[64] To model this case of a far more limited coverage of the trading system, we assume one sector, say *X*, to be the cap-and-trade sector with a given upper limit $\overline{R}_X^h$ on the resource intake, while the other sector, *Y*, is regulated by an adjustable command-and-control policy or resource tax τ_y.[65] Constraining the production in sector *X* by a fixed absolute resource cap $\overline{R}_X^h$ implies for the marginal product in this sector

$$p_x \, F_R^h(\overline{R}_X^h) > 1 \quad . \tag{3.11}$$

The other sector's resource intake can then be viewed as being subjected to a tax τ_y^h

$$p_y \, G_R^h(R_Y^h) = 1 + \tau_y^h \quad , \tag{3.12}$$

which is set to ensure that the resource demand of sector *Y* always stays at the level needed for compliance with the economy's overall emissions cap:[66]

$$G_R^{h^{inv}}\left(\frac{1+\tau_y^h}{p_y}\right) \overset{!}{=} \overline{R}^h - \overline{R}_X^h \qquad \Rightarrow \quad \tau_y^h = p_y \, G_R^h(\overline{R}^h - \overline{R}_X^h) - 1 \quad . \tag{3.13}$$

[63] Sectors not covered by the cap-and-trade system envisaged by Waxman-Markey are: (i) sources below the ETS compliance threshold, (ii) land-use and land-use change, (iii) landfill gases, (iv) HFC, (v) CFCs, (vi) nitrous oxide from nitric acid plants, and (vii) coal mine methane emissions. Given that sectors (ii) to (vii) do not use fossil fuel resource inputs, we assume them to be negligible in the context of our analysis.

[64] The major non-covered sectors are road transport and heating fuels.

[65] The European Union aims at a 20% economy-wide emission reduction relative to 1990 by 2020. Since the policy package allows the use of CDM credits in order to achieve the envisaged reductions for the non-ETS sectors (European Union 2009a), one may argue that a crediting mechanism should also be incorporated in our model. However, since there is a comparatively low 3% limit on CDM use in the non-ETS sectors, and a total reduction target of 10% below year 2005 emission (EU Commission 2008), we assume that domestic policies–here represented by an emission tax–will nevertheless be the principle means for meeting the objective.

[66] The tax is assumed to be recycled back to households via lump-sum transfer. Note that for the purpose of our analysis, there is no need to include the tax receipts in Eq.(3.6) or elsewhere, since they have no influence on the country's total income, which only depends on its GDP measured in international prices.

The market clearing condition in the resource sector is the same as in the case above for the United States, Eq.(3.10). However, since in this case the internal burden-sharing between sectors may not be efficient, a representation of the equilibrium in terms of allowance price (or implicit resource tax) τ_x^h and emission tax τ_y^h must be written in a sector-wise differentiated way as

$$S\left[\phi(p_x, p_y)\right] = R_X^h(\tau_x^h, p_x, p_y) + R_Y^h(\tau_y^h, p_x, p_y) + R^f(p_x, p_y) \quad . \tag{3.14}$$

China and other developing countries currently reject binding economy-wide emission caps, but might implement crediting mechanisms modeled on the Kyoto Protocol's Clean Development Mechanism (CDM). Since the current project-based CDM approach is plagued by doubts over additionality (Schneider 2007) and lack of scale (Stern 2008), several suggestions have been made on how an upscaling could be achieved. These include proposals for absolute or intensity-based no-lose crediting baselines for emissions on a sectoral level, and policy or programmatic approaches that bundle projects in order to reduce transaction costs (EU Commission 2009, Schneider and Cames 2009).

Within our model, these approaches are equivalent since all imply the setting of a sectoral cap against which emission reductions are credited. Hence, we represent this mechanism by an absolute sectoral business-as-usual (BAU) cap $\overline{R}_j^f$ for sector *j*, while the other sector faces no resource constraint. Since the presence of such a crediting mechanism implies that the affected sector faces an additional opportunity cost when using the resource input, it leads to the same first-order condition for the marginal product that holds for the EU ETS sector in Europe, Eq. (3.11). The difference to the European policy case is the absence of an economy-wide reduction target and corresponding resource tax (or command-and-control policy) for the non-ETS sector.[67]

Although China's position on the non-acceptance of a binding absolute emission target has remained firm, its government recently announced that it plans to reduce the carbon intensity of the national product (i.e. CO_2 emissions per unit of GDP) by 40 – 45% below its 2005 level by the year 2020. If implemented, any type of crediting mechanism would operate in parallel to this domestic intensity policy. In our model, this can be represented by introducing the additional constraint

$$\overline{R}^f(\overline{\gamma}) = \overline{\gamma}\, I^f \quad , \tag{3.15}$$

where $\overline{\gamma}$ represents the policy-imposed intensity level.

[67] Another difference consists in the non-binding character of the business-as-usual cap, which, however, is irrelevant in a model without uncertainty like ours.

3.4 Economic Impacts of Linking

Focusing on the linking options from the point of view of the European Union towards the United States and China, we analyze the following linking scenarios in terms of their economic and environmental consequences (leakage), and discuss impacts on competitiveness and welfare:

1. EU ETS and sector *X* in China
2. EU ETS and sector *Y* in China
3. EU ETS and sector *X* in China, with national intensity target for China
4. EU ETS and economy-wide United States ETS

Case 1: EU ETS and China link along X-sectors (symmetric link)

The European Union officially envisages a link of its EU ETS to sectoral crediting schemes in major developing countries such as China (EU Commission 2009, Russ et al. 2009). In this scenario, we consider economic impacts of linking the European trading scheme ('home') to sectors in China ('foreign') that are symmetric to those covered by the EU ETS, i.e. power generation and a number of emission intensive industries such as iron and steel, aluminum, and cement production.

Proposition 3.1: *Let the home country be fully capped at* $\overline{R}^h$*, with an ETS in sector X holding* $\overline{R}_x^h$ *permits, and an adaptable emissions tax* τ_y^h *in sector Y that ensures a constant intake* $\overline{R}_y^h$*. If the foreign country adopts a sectoral BAU target* $\overline{R}_x^f$ *for its X-sector in order to establish an emissions-trading link with home's X-sector ('linking'), then*

(i) the price p_x *of good X falls,*

(ii) the price p_y *of good Y rises,*

(iii) the resource R appreciates in real terms,

(iv) the resource intake (=emissions) in foreign's Y-sector increases, i.e. leakage occurs, and

(v) the emission tax τ_y^h *must rise.*

Proof: *See Appendix 3.7.1*

When foreign implements a BAU cap[68] for its *X*-sector and links with home's ETS, the joint output of the two *X*-sectors rises to its efficient level. In order to

[68] We focus on a BAU cap since in the context of a sectoral link with a developing country this appears to be an empirically relevant case. However, our results from Propositions 1,2,3 and 6 also hold if country 'f' has already implemented a more stringent sectoral cap before joining the linking agreement.

absorb the increased global supply of good X, its price p_x must fall. But due to the homothetic preferences, consumers now also have a higher demand for good Y, leading to an increase in its price and creating an incentive to expand its production in foreign's uncapped sector Y, which causes linking-induced leakage. Because firms' incentive to produce good Y also increases in the home country, the corresponding resource tax τ_y^h has to be increased in order to keep the resource intake constant. For a segmented system like the EU's, this means that if the 'price of carbon' was initially equalized across trading and non-trading sectors, this will no longer be the case after linking, since the latter leads to a reduction of the permit price in home's sector X, and at the same time to a higher fossil resource tax in sector Y.

In terms of welfare, there are several effects of linking that must be taken into account: the direct effect from emission trading, the terms-of-trade effect due to changes in p_x and p_y, and the expansion of foreign's Y sector, although in a marginal analysis the latter does not contribute. As said before, we also ignore the long-run negative environmental effects associated with a short-term increase in fossil fuel usage.

Proposition 3.2: *Under the conditions of symmetric linking described in Proposition 3.1, the marginal change in welfare for home and foreign is given by*

$$dW^i = \frac{U'}{\phi}\left(p_x\, dX_T^i + \left(X^i - C_x^i\right)dp_x + \left(Y^i - C_y^i\right)dp_y\right) \quad , \tag{3.16}$$

where X_T^i denotes country i's increase in available X-goods due to gains-from-trade. It is ambiguous whenever country i is a net exporter of good X or a net importer of good Y, or both. On the other hand, it is always positive for the resource supplier country.

Proof: *See Appendix 3.7.2*

Linking leads to an increase in the joint output of X-goods. Dividing the achieved surplus between the two countries gives the expected positive gains-from-trade effect for both home and foreign, the first term in Eq.(3.16). However, the terms-of-trade effect embodied in the next two terms turns out to be ambiguous, possibly leading to a loss of income and welfare. Depending on the functional specification of the production function, the home country may be a net exporter of both or of only one good (e.g. if home and foreign are ex-ante symmetric it will export both goods). Clearly, if home is a net exporter of good X, or a net importer of good Y (or both), then the linking-induced fall of p_x and rise of p_y can lead to an overall loss of welfare due to linking. The same reasoning applies to the foreign country. In fact, because changes in the terms-of-trade represent a zero-sum-game at the global level, and because the supplier country always improves its position (the resource becomes more expensive in real terms, otherwise supply would not increase), home's and foreign's combined

terms-of-trade effect is negative, meaning either that one of them benefits and the other loses, or otherwise that they both lose.

Therefore, in the present scenario of symmetric linking the resource supplier is the only guaranteed winner. Home and foreign both realize efficiency gains, the distribution of which will depend on the functional specification of the production functions. With regard to terms-of-trade, no more than one of the two countries can benefit, which–in the face of a falling price for good *X* and a rising price for good *Y*–will be the country that is relatively more specialized in the production and export of good *Y*. For larger, non-marginal changes, the foreign country also benefits from the expansion of its *Y* sector, a possibility from which the home country is excluded.

Case 2: EU ETS and China link between X and Y sector (asymmetric link)

In view of the previous analysis, a natural question is to ask whether it would make any difference if the link between the EU ETS and Chinese sector is established in an anti-symmetric manner, i.e. from sector *X* in the European Union to sector *Y* in China. The following proposition confirms that this is indeed the case:

Proposition 3.3: *If, under the same conditions as in Proposition 3.1, the link for emission trading is established between sectors X in the home and Y in the foreign country, then*

(i) *the price p_x of good X falls,*

(ii) *the price p_y of good Y rises,*

(iii) *the resource R depreciates in real terms,*

(iv) *global resource intake (=emissions) is reduced, i.e. negative leakage occurs, and*

(v) *the emission tax τ_y^h must rise.*

Proof: *See Appendix 3.7.3*

In principle, asymmetric linking produces the same kind of effects as symmetric linking: sector *X* in the home country imports 'emission permits' and expands, thereby increasing the world supply of good *X* and inducing a fall of p_x. The difference is that foreign has to reduce the output of *Y* in order to enable the profitable generation and sale of credits to home's capped sector *X*. In this case the fall of p_x gives foreign's *X* sector an incentive to reduce its production and, hence, its usage of resources. This reduction in both of foreign's sectors–while emissions remain controlled at the 'cap-plus-credits' level in the home country–leads to what may be termed 'anti-leakage'.

In practical terms this scenario may represent a hypothetical sector crediting mechanism implemented in China's transport or heating sector, which on the one hand would induce cost-effective emission reductions in these sectors, and on the other lead to lower European Allowance (EUA) prices in the EU ETS. European ETS industries will expand their production in the presence of lower EUA prices, thereby lowering world prices for these products, with the effect of crowding out some industrial production in China.

Hence, from an environmental perspective an asymmetric linking to crediting schemes appears preferable to a symmetric one, since it avoids the leakage effect discussed before. However, as in the symmetric case the rise of p_y necessitates an increase in the fossil resource tax τ_y^h at home, which can aggravate distortions stemming from the different values of the marginal resource product in home's *X* and *Y* sectors. Finally, Proposition 3.2 also remains valid in terms of the linking-induced changes of the two countries' welfare, except for the resource supplier, who now experiences a negative terms-of-trade and welfare effect.

Case 3: Symmetric link between EU ETS and China, with intensity target in China

In the run-up to COP15, the Chinese government announced its intention to unilaterally reduce the carbon intensity of China's national product (CO_2 emissions per unit of GDP) by 40 to 45 percent below the year 2005 level. In view of the possibility for symmetrical sectoral links to induce leakage discussed in case 1, the question arises of whether the implications of Proposition 3.1 could be averted if China's total emissions are constrained by an intensity target, or, in other words, whether or not an intensity target could serve as a safeguard mechanism against unintended leakage. To assess this question, we consider a symmetric link between the *X*-sectors of home and foreign just as in case 1, but assume that in addition a binding but not too stringent (to ensure foreign is an exporter of permits) intensity target for total emissions is implemented in the foreign country.[69]

Proposition 3.4: *Let home's total emissions be capped at* $\overline{R}^h$*, with an ETS in sector X endowed with* $\overline{R}_x^h$ *permits, and an adaptable emission tax in sector Y. Furthermore, assume foreign's total emission level to be constrained by a binding intensity target* $\overline{R}^f = \overline{\gamma} \cdot I^f$*, which, however, implies a lower emission price than in home's ETS. In order to establish an emission trading link with home's X-sector, resource use in foreign's X-sector now becomes capped at its pre-linking*

[69] There is no need to discuss output-based sectoral intensity targets, i.e. limits on the emissions per unit of sector output. In our framework the choice of production technologies is fixed in the short-term, and hence an absolute cap $\overline{R}_x$ in the *X*-sector is fully equivalent to a sectoral intensity target of $\overline{\gamma}_x = \overline{R}_x / F(\overline{R}_x)$.

level $\overline{R}_x^f$ *. An adaptable emission tax is levied in foreign's Y-sector to ensure compliance with its intensity target. In this case,*

(i) the price p_x *of good X falls,*

(ii) the price p_y *of good Y rises, and*

(iii) resource intake (=emissions) in foreign's Y-sector can increase or decrease (i.e. positive or negative leakage), depending on the net effect of linking on foreign's GDP.

Proof: *See Appendix 3.7.4*

As in case 1, linking home's ETS to foreign's less strongly constrained *X*-sector results in an efficiency-enhancing reallocation of resource inputs to the home country, raising the global output of *X* while keeping the combined resource use of both countries' *X*-sectors constant at $\overline{R}_x^h + \overline{R}_x^f$. As a consequence of the increased supply of good *X*, good *Y* will become relatively more expensive, creating an incentive for firms in both countries to increase the production of *Y*.

The difference to the standard symmetric linking of case 1 is that in presence of a binding intensity target, foreign's *Y*-sector cannot expand unless its GDP has grown due to linking. Under an intensity target, the allowed emission level is proportional to GDP, meaning that any additional emissions would exceed the target unless GDP has grown. As discussed before, gains-from-trade in the *X*-sector in combination with the ambiguous terms-of-trade effect due to the changing prices p_x and p_y mean that foreign's GDP might be both higher or lower than in the no-linking case. Therefore, positive or negative leakage equal to the intensity target times the change in foreign's GDP occurs, demonstrating that the intensity target cannot substitute a comprehensive absolute emissions cap as an effective safeguard against leakage.[70]

Case 4: Link between EU ETS and United States ETS

This scenario involving two fully capped systems can be interpreted as a stylized representation of a hypothetical link between the current EU ETS and a Waxman-Markey like US system. One would expect the US to become a net exporter of permits in this case, given that the EU Commission (2008) expects a year 2020 EU allowance price of 30€/tCO_2, while a study by the EPA (2009) suggests a lower price of about 16$/t$CO_2$ for US allowances. Besides efficiency gains, the main motivation for such a linking project would be to harmonize the price of emissions across regions and thereby address the issue of competitiveness. Because both regions have binding national emission targets,

[70] We do not consider the case of asymmetric linking with an intensity target. As we have demonstrated in case 2, asymmetric linking leads to negative leakage. In this case, an additional 'emissions per GDP' intensity target would simply become non-binding and hence irrelevant.

there is no concern with regard to leakage in this case. However, the fact that the EU's policy is built on an internal segmentation with a trading and non-trading sector gains particular relevance.

Proposition 3.5: *Let foreign have an economy-wide cap-and-trade system and home a cap on total emissions implemented through a sectorally segmented policy, with an ETS in the X-sector and an adaptable emission tax* τ_y^h *in the Y-sector. Suppose the (implicit) price of emissions in home's two sectors is initially the same, and higher than in the foreign country. If the two countries establish a link between foreign's ETS and home's X-sector,*

- *(i)* *the price* p_x *of good X falls,*
- (ii) *the price* p_y *of good Y rises,*
- (iii) *the permit price in home's X-sector decreases, while the emission tax in its Y-sector must increase, and*
- (iv) *the emission tax differential between home's and foreign's Y-sector may become greater (competitiveness), e.g. if foreign's post-linking output of Y has increased with respect to the pre-linking level.*

Proof: *See Appendix 3.7.5*

The proposition shows that linking may fail to 'level the carbon playing-field'. With an internally inefficient policy such as the EU's, the first-best prescription of creating a joint market in order to harmonize emission-permit prices actually enlarges the internal domestic distortion between trading and non-trading sector, and might increase the gap in competitiveness between home's and foreign's *Y*-sector. The latter formally depends on the details of the production and utility functions, but in the plausible scenario where the gains in global efficiency are used to increase the global output of both *Y* and *X*, the assertion always holds.[71] This can be seen by recalling that before linking the marginal product G_R^i in the *Y*-sector is higher at home than in the foreign country, implying that a uniform global increase in p_y would already widen the emission-tax gap (which is given by the difference in the *value* of the marginal products: $p_y G_R^h - p_y G_R^f$). If, in addition, foreign's *Y*-sector expands, thereby further decreasing its marginal product G_R^f, the gap becomes even larger.

3.5 Extension: The Case of Non-Traded Goods

The above discussed model with two main countries and traded goods is oriented on the standard approach in trade economics and allows developing an intuition

[71] The efficiency gains from linking allow re-producing the global pre-linking output without having to use all resources. Unless *X* and *Y* are close substitutes, the extra *R* will be used to obtain more units of both.

about the potential effects and forces at work. Admittedly, the stylized character of these models–indispensable for an analytical treatment–is often at odds with the idiosyncrasies of reality. In this section, we explore a formal modification of the model aiming to acknowledge the empirical fact that a large share of emissions arises in the production and consumption of goods–such as electricity–that are not heavily traded, at least not between far distant regions such as Europe and China. Specifically, we are referring to the transport and building (i.e. heating) sectors, and in particular to the energy sector (mainly electricity), which in total make up about 65% of all CO_2 emissions in the EU (EEA 2009). Prominent sectors that are emission intensive and characterized by heavy trade include, e.g., the cement, steel, and aluminum industries.

In view of a potential linking proposal involving such 'domestic' sectors, the question arises in how far the previously derived results still hold. E.g. the EU could link its ETS to China's electricity sector, or the transport sector, as suggested by Schneider and Cames (2009). To explore such a scenario, we modify the general model by assuming that the sector *Y* is a purely domestic industry in both countries. As a consequence, the price for good *Y* will in general be different across countries, and trade between *h* and *f* will not occur in the absence of linking. In formal terms, a competitive equilibrium in this model is now described by the following equations for the prices p_x and p_y^i: (i) profit maximization, i.e.

$$p_x F_R^i(R_X^i) = p_y^i G_R^i(R_Y^i) = 1 \quad , \tag{3.17}$$

(ii) consumers maximize utility, i.e. their demand is determined by $\eta^i := \eta(p_x / p_y^i)$, (iii) each country's income I^i is given by its GDP, i.e. $I^i = p_x X^i + p_y^i Y^i - R^i$, (iv) markets for all goods clear, i.e.

$$\eta^h I^h + \eta^f I^f + R = \left(X^h + X^f\right) p_x \quad , \tag{3.18}$$

$$\tilde{\eta}^i I^i = Y^i p_y^i \quad , \tag{3.19}$$

for good *X* and good *Y*, respectively, and

$$S(p_x) = R^h(p_x) + R^f(p_x) \tag{3.20}$$

with *S'<0* for the resource market. Note how the resource supply function in Eq.(3.20) has simplified, since it is now an argument only of the relative price p_x of good *X*. In fact, because goods of type *Y* are not internationally traded, their prices p_y^i play a role only for internal accounting, and do not matter at the international level. On the other hand, the share η^i of income spent on good *X* can now be different across regions, since it depends on the ratio of the international price p_x and the country-specific price p_y^i of the domestic good.

To analyze the impacts of linking, it is assumed that an 'emission market' for trade in R is established between the EU ETS and one of China's sectors, either the one integrated in international trade or the domestic sector.

Proposition 3.6: *Let the home country be fully capped at* $\overline{R}^h$*, with an ETS in sector X having* $\overline{R}_x^h$ *permits, and an adaptable emission tax in sector Y that ensures a constant intake of* $\overline{R}_y^h$*. If the foreign country adopts a sectoral BAU target* $\overline{R}_x^f$ *for its X-sector and an emission trading link with home's X-sector ('linking') is established, then*

(i) the price p_x *of good X falls,*

(ii) resource intake (=emissions) in foreign's Y-sector increases, i.e. leakage occurs across sectors.

If instead foreign's Y-sector is capped at the BAU level and linked to home's X-sector,

(iii) global resource intake remains constant, i.e. leakage does not occur.

Proof: *See Appendix 3.7.6*

The intuition essentially remains the same as in the model where both goods are traded internationally: Linking the X-sectors has the direct gains-from-trade effect of increasing the amount of available X-goods in the foreign country. This changes the marginal rate of substitution of its consumers, which then prefer to renounce at some X-goods in order to increase their consumption of Y-goods. As a consequence, the country responds by expanding production in its Y-sector and paying for the additional resource intake–i.e. leakage–with some of its X-goods obtained from emission trading. The leakage effect will, however, be relatively weaker than in the case where both goods are traded, since the foreign country expands its Y-sector only to supply its own consumers, and not also those of the other country.

In case of an asymmetric link from home's X to foreign's Y-sector, the foreign country receives additional X-goods as 'compensation' for the amount δR that is re-allocated from foreign's domestic Y-sector to home's X-sector. Foreign's only degree of freedom is to adjust its X-sector, since the Y-sector is held fixed as part of the linking agreement. However, the first-order condition 'resource price equals value of marginal product' for efficient production in the X-sector remains unaltered by the linking-induced trade in R. In fact, positive leakage would necessarily require a rise of p_x, in contradiction to the supply side relation Eq.(3.20), which necessarily requires p_x to fall in order for global resource supply to grow. Hence, the foreign country becomes 'stuck' in a corner solution (consumers would like to exchange some X for some Y-goods but cannot do so), which in this case prevents the occurrence of leakage.

Overall, the introduction of a domestic good has led to a certain weakening of our results, but qualitatively they remain valid. This effect is in line with intuition, in as much as all of our results are driven by trade effects, which can be expected to become weaker when one good is by definition excluded from trade, as in this section. Nevertheless, it was shown that our principle results are robust against this modification of the model framework.

3.6 Conclusions

This chapter has analyzed the impacts of linking emission trading systems on carbon leakage, welfare, and competitiveness within a tractable Ricardo-Viner general equilibrium model with international trade in goods and resources. The considered scenarios were designed to mimic the strategic options for future permit-market linkages between some of the major players in international climate policy, namely Europe, United States, and China.

By analytically comparing pre-linking and post-linking market equilibria, we have shown that a link involving an economy without national emissions cap can provoke leakage in form of an expansion of the non-capped sector. However, the occurrence of leakage actually depends on which industries are linked to form the joint permit market: in case of asymmetric linking, i.e. when the respective output goods are imperfect substitutes, leakage is prevented and may even become negative. These results were shown to prevail qualitatively even in the presence of a non-tradable good.

Hence, from the point of view of environmental integrity, a link of the EU ETS to a sectoral trading system in China (or elsewhere) that covers similar sectors bears some negative implications. Linking across asymmetric sectors (e.g. transport, heating, and in fact any sector producing non-tradable goods) tends to reduce global emissions and thus appears favorable from the EU perspective.

One approach for regulating economy-wide emissions in developing countries is the intensity target, which was recently adopted on a voluntary basis by China. However, our analysis has shown that such a target cannot work as a substitute for an absolute cap, i.e. it does not prevent the occurrence of leakage when one of China's sectors is linked to the EU ETS, and–in terms of policy implications–should therefore not be viewed as an instrument to facilitate participation in emissions trading.

If the EU ETS establishes a link with a hypothetical US system, leakage will not occur since both regions have an economy-wide cap. The main motivation for pursuing this policy option would be to address concerns about competitiveness, i.e. the idea of harmonizing permit prices in order to 'level the carbon playing-field'. However, our results indicate that due to the EU ETS' internal segmentation this can only be partially achieved, as linking can create and

increase distortions both between the EU's two sectors as well as between the EU's non-trading sector and its US counterpart.

The modeling analysis of Böhringer et al. (2009) of the EU 2020 climate policy package suggests that non-ETS sectors face higher marginal abatement costs than the EU ETS sectors. Linking the EU ETS to a US system could intensify such concerns. An obvious remedy is to include all EU sectors in the EU ETS. Alternatively, the segmented caps can be adjusted to harmonize marginal abatement costs across sectors. In the context of our model this implies tightening the EU ETS cap after linking to a US system (e.g. in form of a buy-back of permits by the EU regulator), a step that may require *ex ante* policy coordination if e.g. the resulting increase of the US allowance price raises political concerns.

Finally, the analysis allowed for an explicit representation of the ambiguous welfare effect of linking in a general-equilibrium setting. Each country's welfare change can be decomposed into an always positive gains-from-trade effect, and a terms-of-trade effect, where the sign of the latter depends on the country's trade specialization, i.e. its export and import position. In case the terms-of-trade effect turns out to be negative, the welfare impact of linking on the individual country becomes ambiguous.

3.7 Appendix

3.7.1 Proof of Proposition 3.1

Emission trading–in our model in the equivalent form of resource trading–will take place since the home country's binding resource constraint implies that the value of its marginal resource product is higher than in the foreign country. In the post-linking equilibrium, the marginal products F_R^i become equalized and world production of X efficient, leading to a larger world supply of good X. The size of this increase, denoted with a superscript w for 'world' by δX^w, only depends on the properties of the production functions, which is also true for the amount of traded resource, denoted by δR (δ denoting some finite change, as opposed to infinitesimal changes indicated by d). In the following, we can therefore treat both quantities as given–yet undetermined–positive constants.

By taking the ratio of the global clearing conditions for the Y- and X-markets given in Eq.(3.7), we obtain for the post-linking equilibrium

$$\frac{\tilde{\eta}\, p_{x/y}}{\eta} = \frac{\bar{Y}^h + Y^f}{\bar{X}^w} \quad , \tag{3.A1}$$

where a bar indicates a constrained, fixed variable. Since sector X is fixed after linking, i.e. it does not respond to price movements (assuming, as we do, that the constraint remains still binding after linking), the post-linking equilibrium can

be characterized by investigating the comparative statics of the last equation, and of the supply side relation implied by Eq.(3.8)

$$S\left[\phi(p_x, p_y)\right] = \overline{R}_X^w + \overline{R}_Y^h + R_Y^f[p_y] \tag{3.A2}$$

with respect to an exogenously given small increase dX^w –the effect of linking–in the world supply of X. The left hand side of Eq.(3.A1) is a function only of the prices p_x and p_y, while the world supply Y^w depends only on p_y, and hence one obtains for the total differential

$$\sigma\left(\frac{dp_x}{p_x} - \frac{dp_y}{p_y}\right) = \frac{1}{Y^w}\frac{\partial Y^f}{\partial p_y}dp_y - \frac{dX^w}{X^w} \quad , \tag{3.A3}$$

where σ>0 denotes the elasticity of substitution of the underlying utility function. Likewise, written in differential terms Eq.(3.A2) becomes

$$S'\phi_x dp_x = \left(\frac{\partial R_Y^f}{\partial p_y} - S'\phi_y\right)dp_y \quad \Rightarrow \quad \frac{dp_x}{p_x} = \frac{\left(p_y\left(\partial R_Y^f/\partial p_y\right) - \phi S'\tilde{\eta}\right)}{\phi S'\eta}\frac{dp_y}{p_y} \tag{3.A4}$$

where we used the relationship

$$\frac{p_x\,\phi_x}{\phi} = \eta \qquad \text{with} \quad \phi_x := \frac{\partial\phi}{\partial p_x} \tag{3.A5}$$

derived from Roy's identity. In view of S'<0 and the positive dependence of the foreign Y-sector's resource intake on the price p_y, the first term on the right-hand-side must be negative. This implies that dp_y and dp_x have always opposite signs. Substituting Eq.(3.A4) into Eq.(3.A3) yields

$$\frac{dX^w}{X^w} = \left(\frac{p_y}{Y^w}\frac{\partial Y^f}{\partial p_y} + \frac{\sigma}{\eta}\left(1 - \frac{p_y\left(\partial R_Y^f/\partial p_y\right)}{\phi S'}\right)\right)\frac{dp_y}{p_y} \quad , \tag{3.A6}$$

which demonstrates that linking (dX^w>0) always leads to a positive dp_y and negative dp_x, given that the term in parenthesis is unambiguously positive. Moreover, since the resource intake in foreign's Y sector depends positively on p_y, $dp_y>0$ is a sufficient condition for leakage to occur and–by Eq.(3.12)–for the need to increase the resource tax τ_y^h in order to keep the resource intake in home's Y sector constant. Finally, in order for Eq.(3.5) to be consistent with an increased global supply, the real price of the resource must rise. □

3.7.2 Proof of Proposition 3.2

The impact of linking on each country consists of a direct gains-from-trade effect (i.e. an increased availability of X), and the effect from the fall of p_x and the rise of p_y.

Note that the permit price, say p_E, does not need to be taken into account explicitly, since it is determined by the value of the marginal product in the X-sector, and hence proportional to p_x:

$$p_E = p_x F_R^h(R_x^h + \delta R) = p_x F_R^f(R_x^f - \delta R) \quad , \tag{3.A7}$$

where δR can be interpreted as the number of permits that are traded due to linking. For home, the partial income effect associated with the gains-from-trade generated by emission trading can thus be expressed as

$$\begin{aligned} \Delta I^h &= \left(p_x F^h(\overline{R}_x^h + \delta R) - p_E\, \delta R\right) - p_x F^h(\overline{R}_x^h) \\ &= p_x \left(F^h(\overline{R}_x^h + \delta R) - \delta R\, F_R^h(\overline{R}_x^h + \delta R) - F^h(\overline{R}_x^h)\right) =: p_x \left(X^h + \delta X_T^h\right) \end{aligned} \tag{3.A8}$$

i.e. as a fixed increase of available X-goods denoted by δX_T^h, the size of which only depends on the properties of the production functions F^i. For the foreign country we get δX_T^f, in complete analogy. With welfare as function of real income as defined in Eq.(3.4), the marginal change in welfare for both countries can be computed by evaluating the net effect of an exogenous increase in X:

$$\frac{dW^i}{dX^w} = \frac{dW^i}{d(I^i/\phi)} \frac{d(I^i/\phi)}{dX^W} = U' \cdot \left(\frac{1}{\phi} \frac{\partial I^i}{\partial X^i} \frac{\partial X^i}{\partial X^w} + \frac{\partial\left(I^i/\phi\right)}{\partial p_x} \frac{\partial p_x}{\partial X^w} + \frac{\partial\left(I^i/\phi\right)}{\partial p_y} \frac{\partial p_y}{\partial X^w} \right). \tag{3.A9}$$

Applying the envelope theorem and Eq.(3.A5) to evaluate the terms-of-trade effect, we obtain the following expression, valid for both countries:

$$\phi\, dW^i = U' \cdot \left(p_x\, dX_T^i + \left(X^i - C_x^i\right) dp_x + \left(Y^i - C_y^i\right) dp_y\right) \quad , \tag{3.A10}$$

where the differentials on the right-hand-side still depend on dX^w. The two terms in parenthesis represent the net exports of good X and Y, respectively. Hence, if home is a net exporter of good X or a net importer of good Y (or both), then the linking-induced fall of p_x and rise of p_y can lead to an overall loss of welfare.

Finally, by summing up the terms-of-trade contributions for home and foreign one finds

$$\left(X^h - C_x^h + X^f - C_x^f\right) dp_x + \left(Y^h - C_y^h + Y^f - C_y^f\right) dp_y = C_x^s\, dp_x + C_y^s\, dp_y \quad , \tag{3.A11}$$

which–apart from a factor of minus one–represent the terms-of-trade effect experienced by the resource supplier country, thus illustrating how terms-of-trade effects constitute a zero-sum-game at the global level. Since the last expression can be written as $I^s\left(\eta\, \hat{p}_x + \tilde{\eta}\, \hat{p}_y\right)$ which–by invoking the supply side relation Eq.(3.5) and Eq.(3.A5)–results to be negative if global resource supply increases, i.e. $dS > 0 \;\Rightarrow\; \eta\, \hat{p}_x + \tilde{\eta}\, \hat{p}_y < 0$, we can conclude that the supplier country's welfare always increases due to the positive terms-of-trade effect. □

3.7.3 Proof of Proposition 3.3

In this case, home imports resources R from foreign until the price-weighted marginal products becomes equalized, i.e.

$$p_x\, F_R^h(\overline{R}_X^h + \delta R) = p_y\, G_R^f(R_Y^f - \delta R) \quad . \tag{3.A12}$$

Thus, the amount of traded permits δR now depends not only on the functions F^i, but also on the price ratio $p_{x/y}$. However, assuming that emission trading from foreign to home actually takes place, the resulting effect will in all cases be some increase in X-output at home and a corresponding fall in Y-output abroad. Thus, let us assume the world supply of X rises by dX^h, and that of Y falls by dY^f. Consider again Eq.(3.A1) written in differential form as in Eq.(3.A3), now modified for the case of X-Y linking:

$$\sigma\left(\frac{dp_x}{p_x} - \frac{dp_y}{p_y}\right) = \frac{dY^f}{Y^w} - \frac{dX^h}{X^w} - \frac{1}{X^w}\frac{\partial X^f}{\partial p_x}dp_x \quad , \tag{3.A13}$$

which can be rearranged to

$$\left(\sigma + \frac{p_x}{X^w}\frac{\partial X^f}{\partial p_x}\right)\frac{dp_x}{p_x} = \frac{dY^f}{Y^w} - \frac{dX^h}{X^w} + \sigma\frac{dp_y}{p_y} \quad , \tag{3.A14}$$

where the term in parenthesis is always positive, and–by assumption–we also have $dX^h > 0$ and $dY^f < 0$. It follows that if p_y falls, then also p_x must fall. Next, consider the clearing condition for the resource market, and its total differential, in analogy with Eq.(3.A4):

$$S\left[\phi(p_x, p_y)\right] = \overline{R_X^h + R_Y^f} + \overline{R}_Y^h + R_X^f[p_x] \quad \Rightarrow \quad \left(\eta - \frac{p_x}{S'\phi}\frac{\partial R_X^f}{\partial p_x}\right)\frac{dp_x}{p_x} = -\tilde{\eta}\frac{dp_y}{p_y} \tag{3.A15}$$

Because the last parenthesis is always positive, it follows that dp_y and dp_x must have opposite signs. But then p_y cannot fall, since this would also require p_x to fall, by Eq.(3.A14). Therefore p_y must rise, which, by Eq.(3.A15), means that p_x falls. Finally, since the resource intake of foreign's X sector only depends on p_x, and p_x falls, the resource intake and output of this sector must fall, i.e. negative sectorial leakage occurs. In contrast to the case of X-X linking, the relative rise of p_y is in this case less pronounced, i.e. it does not overcompensate the fall of p_x, and thus leads to a net increase of the cost ϕ for one unit of utility (i.e. $\eta\,\hat{p}_x + \tilde{\eta}\,\hat{p}_y > 0$) and–consistent with negative leakage–a drop of the (real) price of R. □

3.7.4 Proof of Proposition 3.4

In principle, this proof follows the same line of argumentation as the one for Proposition 3.1. Again, the amount of resource traded between foreign's and

home's X-sector in the course of linking is fully determined by the condition of marginal product equalization, i.e. it is only a function of $\overline{R}_X^h, \overline{R}_X^f$, and the production technologies, as in Eq.(3.A8). Also as before, the global efficiency gains in the production of good X imply a fall of p_x and a simultaneous rise of p_y.

A rising price for Y constitutes an incentive for firms in the foreign country to increase their production of this good and thus use more resources, such that leakage would occur. However, for a scenario in which foreign has adopted an intensity target, the supply side relation Eq.(3.A2) has to be rewritten as

$$S\left[\phi(p_x, p_y)\right] = \overline{R}_X^w + \overline{R}_Y^h + \min\left\{R_Y^f[p_y], \overline{\gamma} \cdot I^f - \overline{R}_X^f\right\} \quad , \tag{3.A16}$$

implying that in the present case a higher resource intake is only consistent with the intensity target if foreign's income has become higher in the course of linking. In fact, the emission-of-GDP intensity target may even become non-binding, if the increase of foreign's income is sufficiently high. In this case, however, the scenario with intensity target would simply reduce to case 1, i.e. Proposition 3.1 holds. On the other side, if linking has an adverse effect on foreign's GDP, the intensity target tightens the constraint on emissions and leads to negative leakage.

Specifically, let us consider gross domestic product (as defined by the expenditure method), which is given by the value of consumption plus exports minus imports:

$$I^f = p_x X^f + p_y Y^f - \overline{R}_X^f - R_Y^f \quad . \tag{3.A17}$$

Hence, in presence of a binding emission-per-GDP target $\overline{\gamma}$, resource use in foreign's Y-sector can be expressed as:

$$R_Y^f = \overline{\gamma}\left(p_x X^f + p_y Y^f - \overline{R}_X^f - R_Y^f\right) \quad , \tag{3.A18}$$

which in differential terms implies (denoting the income from the gains-of-trade in emissions trading by dX_T^f)

$$dR_Y^f = \frac{\overline{\gamma}}{1+\overline{\gamma}}\left(p_x dX_T^f + X^f dp_x + Y^f dp_y + p_y G_R^f \, dR_Y^f\right) \tag{3.A19}$$

and, by rearranging,

$$\left(1 - \frac{\overline{\gamma}}{1+\overline{\gamma}} p_y G_R^f\right) dR_Y^f = \frac{\overline{\gamma}}{1+\overline{\gamma}}\left(p_x dX_T^f + X^f dp_x + Y^f dp_Y\right) \quad . \tag{3.A20}$$

The term $\overline{\gamma}\, p_y G_R^f$ represents the marginal increase in foreign's emission allowances 'generated' by the intensity target if sector Y increases its resource input by one marginal unit. Clearly, with a binding intensity target a *ceteris paribus* expansion of the Y-sector (and thus GDP) must lead to fewer new

allowances than would be needed to fully cover the additional resource consumption. Therefore we can conclude that $\bar{\gamma}\, p_y\, G_R^f$ must be smaller than one and, accordingly, that the parenthesis on the left hand side of Eq.(3.A20) is always positive. The parenthesis on the right hand side represents the partial (i.e. when holding the production of Y constant) income effect arising from linking in form of gains-from-trade and price changes. Thus, foreign's production of Y increases (decreases) and positive (negative) emission leakage occurs, if the income effect induced by linking is positive (negative). □

3.7.5 Proof of Proposition 3.5

Since foreign has by assumption the lower permit price, the initial effect of linking is that home buys 'permits' and imports resources into its X-sector. If the barred variables denote pre-linking allocations, then the post-linking equilibrium is characterized by a common implied resource tax τ in all but home's Y-sector:

$$1+\tau = p_x\, F_R^h(\bar{R}_X^h + \delta R_X^h) = p_x\, F_R^f(\bar{R}_X^f + \delta R_X^f) = p_y\, G_R^f(\bar{R}_Y^f + \delta R_Y^f) \qquad (3.A21)$$

subject to $\delta R_X^h + \delta R_X^f + \delta R_Y^f = 0$, as the trading system is neutral with respect to total resource use. Because foreign has an economy-wide ETS, the last part of Eq.(3.A21) is valid at all times, also during the linking process, and can thus be used for comparative statics. In differential terms it becomes:

$$\frac{p_x}{p_y} = \frac{G_R^f(R_Y^f)}{F_R^f(R_X^f)} \quad \Rightarrow \quad \frac{dp_x}{p_x} - \frac{dp_y}{p_y} = \frac{G_{RR}^f}{G_R^f} dR_y^f - \frac{F_{RR}^f}{F_R^f} dR_x^f \quad . \qquad (3.A22)$$

At the same time, the differential of the global supply-demand constraint Eq.(3.A1), in analogy with Eq.(3.A3), is given by

$$\sigma\left(\frac{dp_x}{p_x} - \frac{dp_y}{p_y}\right) = \frac{dY^f}{Y^w} - \frac{dX^w}{X^w} = \frac{G_R^f}{Y^w} dR_y^f - \frac{F_R^f}{X^w} dR_x^f - \frac{F_R^h}{X^w} dR_x^h \quad . \qquad (3.A23)$$

Substituting Eq.(3.A22) into Eq.(3.A23) leads to the following expression:

$$\left(\sigma \frac{G_{RR}^f}{G_R^f} - \frac{G_R^f}{Y^w}\right) dR_y^f = \left(\sigma \frac{F_{RR}^f}{F_R^f} - \frac{F_R^f}{X^w}\right) dR_x^f - \frac{F_R^h}{X^w} dR_x^h \quad . \qquad (3.A24)$$

The factors in parenthesis are clearly negative. Hence, given our assumption that home will be a net importer of resource permits, i.e. $dR_x^h > 0$, the term dR_x^f cannot be positive, since this would imply also a positive dR_y^f, which in turn would mean foreign is a net importer of permits. Therefore, linking must lead to a reduction of foreign's production of good X. Although for foreign's Y-sector the change in output remains ambiguous, the change in the price ratio $p_{x/y}$ is

uniquely determined: if dR_y^f >0, then the right-hand-side of Eq.(3.A24) becomes negative, and hence d($p_{x/y}$)<0. If, on the other hand, dR_y^f <0, then $dY^w<0$ and $dX^w>0$ follow, which means that the middle-part of Eq.(3.A23) becomes negative, and again d($p_{x/y}$)<0 must hold. Moreover, since total global resource supply must remain constant under the considered cap-and-trade system, the cost of utility function ϕ, which actually represents the inverse of the real price of one unit of the resource, must also stay constant, which by Eq.(3.5) and Eq.(3.A5) requires $\eta\,\hat{p}_x + \tilde{\eta}\,\hat{p}_y = 0$, i.e. the change in p_y and p_x must be of opposite signs. Therefore we can conclude that p_x falls and p_y increases, which proves assertion (i) and (ii).

Given the rise in p_y, it also becomes evident that the tax τ_y^h in home's *Y*-sector must be increased in order to keep this sector's total resource intake constant, as the latter is governed by $1+\tau_y^h = p_y\, G_R^h(\overline{R}_y^h)$. On the other hand, if home's *X*-sector is to expand, despite the falling price of p_x, then the corresponding resource tax (or emission permit price) must have decreased due to linking, thus completing the proof of assertion (iii).

It remains to show that it is possible and plausible for the gap between the emissions prices in home's and foreign's *Y*-sector to increase. In formal terms, this requires

$$d\tau_y^h = G_R^h(\overline{R}_y^h)\,dp_y \;>\; d\tau^f = G_R^f(\overline{R}_y^f)\,dp_y + p_y\, G_{RR}^f(\overline{R}_y^f)\,dR_y^f \qquad (3.A25)$$

to be true. Given that we have $G_R^h > G_R^f$ by assumption, the inequality holds whenever dR_y^f is positive, or negative but sufficiently close to zero, i.e. whenever linking leads to an expansion or only small contraction of foreign's *Y*-sector. Conversely, a closing of the emissions-price gap can only occur if foreign's *Y*-sector contracts sufficiently. This would correspond to a case in which resources from both foreign sectors are reallocated to home's *X*-sector. Although theoretically possible, such a scenario is not very plausible, as it would mean that all efficiency gains realized in the global production of good *X* are used to produce more only of good *X*, and that the global production of *Y* actually decreases. Eq.(3.A24) implies that this could happen if *X* and *Y* are very close substitutes, since for $\sigma\to\infty$ one infers that the sign of both dR_x^f and dR_y^f must be negative. Conversely, if *X* and *Y* are perfect complements, i.e. $\sigma\to 0$, Eq.(3.A23) requires that both dX^w and dY^w must be positive, and thus $dR_y^f>0$. □

3.7.6 Proof of Proposition 3.6

Consider first a symmetric *X*-*X* link. As before, we assume that the foreign country sells some amount δR of resource to the home country, receiving an amount of δX in return which exceeds the loss of domestic *X* production and

which is defined solely by the condition of marginal product equalization, and hence does not depend on any prices. Prior to linking, the foreign country's firms and consumers–taking the price p_x as given–implicitly maximize

$$\max_{R_x^f, R_y^f} U^f \left[F^f(R_x^f) - \frac{\left(R_x^f + R_y^f\right)}{p_x}, G^f(R_y^f) \right] \quad . \tag{3.A26}$$

Regarding the optimal choice for sector Y, a homothetic utility implies

$$\frac{\partial_x U^f}{\partial_y U^f} =: MRS\left(\frac{C_y^f}{C_x^f}\right) = p_x\, G_R^f \qquad , \tag{3.A27}$$

where MRS denotes the marginal rate of substitution. After linking to the home country's X-sector, the maximization problem in Eq.(3.A26) is simplified to one of a single variable, namely R_y^f, because foreign's X-sector is now fully determined by the condition of marginal product equalization. Foreign's general equilibrium reaction to a positive 'shock' δX can thus be evaluated by considering the comparative statics of Eq.(3.A27), written as

$$MRS\left(\frac{G^f(R_y^f)}{\overline{X}^f + \delta X - \left(\overline{R}_x^f + R_y^f\right)/p_x}\right) = p_x\, G_R^f \quad , \tag{3.A28}$$

where the pre-linking equilibrium defines the parameters $\overline{X}^f$ and $\overline{R}_x^f$. Computing all derivatives yields

$$\left(\frac{\partial\left(C_y^f / C_x^f\right)}{\partial X^f} dX^f + \frac{\partial\left(C_y^f / C_x^f\right)}{\partial R_y^f} dR_y^f + \frac{\partial\left(C_y^f / C_x^f\right)}{\partial p_x} dp_x\right) MRS' = G_R^f\, dp_x + p_x\, G_{RR}^f\, dR_y^f \, . \tag{3.A29}$$

Noting that the derivative MRS' is positive and since, evidently, we have

$$\frac{\partial\left(C_y^f / C_x^f\right)}{\partial X^f} < 0 \qquad \frac{\partial\left(C_y^f / C_x^f\right)}{\partial R_y^f} > 0 \qquad \frac{\partial\left(C_y^f / C_x^f\right)}{\partial p_x} < 0 \tag{3.A30}$$

the equation can be written in a qualitative way ('neg' denoting negative terms, 'pos' positive ones) as

$$\left(G_R^f - [...neg...] \cdot MRS'\right) dp_x + \left(p_x\, G_{RR}^f - [...pos...] \cdot MRS'\right) dR_y^f = [...neg...] \cdot MRS'\, dX^f \quad . \tag{3.A31}$$

The still needed relation linking dp_x and dR_y^f can be obtained from the resource supply relation Eq.(3.21). With a binding constraint, the resource intake for all sectors except foreign's Y-sector remains constant, and thus any change in the global supply must be due to a change in R_y^f :

$$dS = dR_y^f = S'\,dp_x \quad . \tag{3.A32}$$

Substitution into Eq.(3.A31) yields

$$dp_x = \frac{[...neg...]\cdot MRS'}{\left(G_R^f - [...neg...]\cdot MRS' + p_x\, S'\, G_{RR}^f - [...pos...]\cdot S'\; MRS'\right)} dX^f \quad , \tag{3.A33}$$

which–given the unambiguous negative sign of the coefficient–demonstrates that linking leads to a fall in the price p_x. By virtue of Eq.(3.A32), it follows that foreign's Y-sector expands, i.e. leakage occurs. Finally, the efficiency condition $p_y^f\; G'(R_y^f) = 1$ also implies that the price p_y^f increases.

In case of an asymmetric link from home's X to foreign's Y-sector, the foreign country receives additional goods X as 'payment' for the amount δR of resource that is traded from its domestic Y-sector to home's X-sector. Foreign's only degree of freedom is to adjust its X-sector, since the Y-sector has become 'fixed' as part of the linking agreement. However, the first-order condition for efficient production in the X-sector remains unaltered by the linking-induced trade in R, since foreign's maximization problem after linking

$$\max_{R_x^f} U^f\left[F^f(R_x^f) + \delta X - \frac{\left(R_x^f + \overline{R}_y^f\right)}{p_x}, G^f(\overline{R}_y^f - \delta R)\right] \tag{3.A34}$$

only implies the equalization of resource price and value of marginal product:

$$p_x\, F_R^f(R_x^f) = 1 \quad . \tag{3.A35}$$

Therefore, foreign's X-sector expands only if p_x increases. But since the supply relation Eq.(3.A32) allows an increase in global resource supply only for a decrease in p_x, this cannot happen, allowing to conclude that global resource use must remain unaltered. □

Chapter 4

The Effects of Tariffs on Coalition Formation in a Dynamic Global Warming Game[72]

4.1 Introduction and Motivation

Combining elements of the economic, the energy and the climate system, Integrated Assessment Models (IAMs) have become an indispensable formal tool in the realm of climate policy analysis. There are numerous examples, ranging from Nordhaus' (1994) seminal DICE model to the latest generation of regionalized models featuring high levels of sectoral and technological detail.[73]

A prominent class within the IAM family consists of optimal growth models; these build on a tradition going back to Ramsey (1928), and view accumulation and economic growth as driven by agents' intertemporally optimized investment decisions. Examples include the RICE/DICE family of models (Nordhaus 1994, Nordhaus and Yang 1996), and its modifications such as FEEM-RICE (Bosetti et al. 2004) or ENTICE (Popp 2004), as well as the MIND (Edenhofer et al. 2005) and DEMETER (Gerlagh 2006) models.

Two main aspects justify the use of intertemporal optimization in the context of climate policy: First, Edenhofer et al. (2006) argue that this framework is appropriate whenever the research question requires an economic model to be run over long time horizons and to capture structural changes. Indeed, inertia in the climate system requires to adopt time horizons of more than a century. Second, Turnovsky (1997, pp. 3), arguing from a more theoretical point of view, backs the intertemporal utility maximization of a representative agent as the preferred way to give macroeconomic models a firm micro-foundation and make them suitable for welfare analysis. Although critics point to the fact that assumptions such as perfect foresight and strict rationality are actually at odds with reality, results from such models retain their usefulness (at least) in terms of a first-best benchmark.

To come closer to the political reality of a world consisting of self-interested and sovereign nation states, optimal growth models, just like other IAMs, have over

[72] Chapter based on the homonymous article by Lessmann, Marschinski, and Edenhofer published in *Economic Modelling* 26(3):641-49, 2009. Being there multiple authors, the text uses the plural 'we'.

[73] See, for example, Kypreos and Bahn (2003), Barker et al. (2006), Crassous et al. (2006), Bosetti et al. (2006).

time passed from a uni-regional world[74] representation to a decentralized multi-regional[75] formulation. Unfortunately, even the sole introduction of emissions trade comes at the cost of a substantial aggravation of the numerics required to compute competitive equilibria. The calculation of trade flows and price vectors would in principle be straightforward with Negishi's (1960) algorithm. But in the presence of an externality like the climate feedback, an appropriate modification of the algorithm is required.[76] The additional effort is, of course, justified by the need to estimate the regional distribution of climate damages and mitigation costs, as well as by the new possibility to compute scenarios in which only a group of nations—a 'climate coalition'—decides to cooperate on climate change.

In our work we follow the multi-regional modeling approach and formally extend it in two ways: first, international trade in goods is introduced by dropping the common assumption[77] that all countries produce the same perfectly substitutable good; instead we assume that goods are differentiated according to their place of origin.[78] This approach—sometimes referred to as Armington assumption—is often encountered[79] in CGE modeling and allows to reproduce international cost spillovers from mitigation policies.[80] Second, we introduce another feature that is incompatible with the basic Negishi approach, namely a tax distortion in form of a punitive tariff duty.

The first part of the paper emphasizes the formal aspects of solving such a model structure for a competitive equilibrium. We describe our solution approach that draws on work by Kehoe et al. (1992) and Leimbach and Edenhofer (2007), and illustrate how a validation of the competitive equilibrium is obtained.

To demonstrate the usefulness of the model set-up, an application to a current issue in climate policy is presented in the second part of the paper. Namely, we analyze the scope for regional cooperation—that is the viability of a 'climate coalition'—and investigate whether tariffs can help to increase participation in such a coalition.

This question seems timely in view of the currently meager prospects for full international cooperation after the expiry of the Kyoto Protocol in 2012. Indeed,

[74] E.g. DICE (Nordhaus 1994) and MIND (Edenhofer et al. 2005).
[75] E.g. RICE (Nordhaus and Yang 1996) and WITCH (Bosetti et al. 2006).
[76] Implementing trade in these models is challenging (Nordhaus and Yang 1996, Eyckmans and Tulkens 2003). Nordhaus and Yang (1996) mention that "a major cause of the long gestation period of this research has been the difficulty in finding a satisfactory algorithm for solving the intertemporal general equilibrium."
[77] E.g. in the RICE (Nordhaus and Yang 1996) and WITCH (Bosetti et al. 2006) models.
[78] This model of international trade is discussed, e.g., in Feenstra et al. (2001).
[79] E.g. Bernstein et al. (1999), Kemfert (2002).
[80] In models without trade, one country's carbon constraint bears no economic consequences for other countries. This seems contradictory when thinking of shifts in competitive advantage and specialization ('carbon leakage'), as well as of the negative consequences for some countries if fossil fuel demand plunges.

a lively debate has emerged on the scope for regional cooperation, and various supportive policy instruments have been brought up in the literature, such as R&D protocols (Barrett 2003, Buchner et al. 2005), a technology fund (Benedick 2001), a Marshall Plan (Schelling 2002), and, last but not least, trade sanctions (e.g. Aldy et al. 2001).

The use of trade restricting tariff duties has been proposed in the form of energy or CO_2 border tax adjustments, with the double objective to deter free-riding and to ease the loss of competitiveness for coalition members. The debate has so far focused on the question of whether tariffs are feasible under legal (Biermann and Brohm 2005) and implementation (Ismer and Neuhoff 2007) aspects. However, another question is whether their employment would be credible, given that orthodox economic theory suggests that the distortionary effects of tariffs would be welfare depressing for all parties.

More specifically, Stiglitz (2006) proposes to raise participation in a climate treaty by imposing trade sanctions against non-signatories. He argues that this is possible and even required in the legal framework of the World Trade Organization (WTO): products from countries that allow unconstrained emissions are implicitly subsidized which warrants to prohibit or tariff the import of such products. Perez (2005) gives a detailed analysis of the legal implications of such a proposal concluding that recent precedents (the so-called "shrimp decision") suggest that the WTO will not interfere with such tariffs. Similar to these trade sanctions, Nordhaus (1998) proposes border tax adjustments to enforce compliance with harmonized carbon taxes.

The effects of trade sanctions on coalition formation have also been analyzed within formal models (Barrett 1997, Finus and Rundshagen 2000), albeit to lesser extent. As mentioned before, the widely used optimal growth models do not naturally accommodate trade in goods (other than emissions trade), and are therefore normally unsuitable for an analysis of the effects of tariffs. Thus, existing formal studies of trade sanctions and international cooperation either utilize a static modeling framework (Barrett 1997) or Computable General Equilibrium (CGE) models (Kemfert 2004).

For the purpose of this study, we apply the model in a stylized—i.e. not empirically calibrated—form in order to explore the scope for tariffs in international cooperation. We find that under the assumption of price- as well as tariff-taking behavior of all countries, the imposition of tariffs on non-coalition members unequivocally raises the scope for international cooperation. However, the coalition's welfare gains start to decline once the tariffs go beyond a certain threshold, and—at a still higher level—tariffs actually become welfare decreasing and thus lose credibility. We interpret the observed effects as a consequence of the model's representation of international trade: when each country's representative output good can only be imperfectly substituted by goods from other countries, but all countries must behave as price-takers, then

the tariff constitutes an indirect price setting mechanism, which helps coalition countries to capitalize on their implicit market power and increase their terms-of-trade. However, similar to an optimum tariff rate or monopoly price, the benefits from this increase start to vanish once the tariff exceeds a certain level.

In line with economic theory our model shows that the introduction of tariffs distorts the otherwise efficient markets, and hence, global welfare would be higher without tariffs. We find, however that these losses are easily offset by the gains of increased cooperation that are induced by these tariffs. With respect to environmental effectiveness, we find that in our model carbon leakage is small, i.e. emission increases in free-riding countries do not outweigh the abatement effort of the coalition.

Although we employ the model and the algorithm in an exemplary way in order to explore the scope for tariffs in coalition formation, it can be easily extended to other research questions, e.g. to investigate the effects of differentiated border tax adjustments (BTA) on coalition formation, or to analyze the long-term structural effects of different (optimal, non-optimal) carbon taxes.

The remaining part of this chapter is organized as follows: The next section presents the model; Section 4.3 explains the solution algorithm. In Section 4.4, we discuss its application to coalition stability in a model with import tariffs, and Section 4.5 concludes.

4.2 Model Structure

We begin by stating the problem: we introduce a multi-actor growth model with climate change damages and tariffs on trade flows.

4.2.1 Preferences

Each region i is modeled following Ramsey (1928), i.e. the maximization of discounted utility endogenously determines the intertemporal consumption-investment pattern.

$$welfare_i = \int_0^\infty e^{-\rho t}\, l_{it}\, U\left(c_{it} / l_{it}\right) dt \tag{4.1}$$

Instantaneous utility U is an increasing and concave function of per capita consumption c/l. It is weighted with the region's total population l and discounted with a rate of pure time preference ρ.

In a world where goods from different countries are imperfect substitutes, utility depends on the consumption of both domestic c^{dom} and foreign goods c^{for}, which are combined into a so-called Armington aggregate via a CES (Constant Elasticity of Substitution) function.

$$c_{it} = \left[s^{dom} \left(c_{it}^{dom} \right)^{\rho^A} + \sum_j s_j^{for} \left(c_{ijt}^{for} \right)^{\rho^A} \right]^{\left(1/\rho^A\right)} \tag{4.2}$$

The elasticity σ^A>0 is determined by the parameter $\rho^A \in (0,1)$ according to σ^A = 1/(1 - ρ^A). Share parameters s^{dom} and s_j^{for} characterize the relative preference for domestic and foreign goods and add up to one.

4.2.2 Technology

We assume a macroeconomic production function F of the Cobb-Douglas form that depends on two input factors, capital stock k and labor supply l.

$$F\left(k_{it}, l_{it}\right) = \left(k_{it}\right)^{\beta} \left(a_{it} l_{it}\right)^{(1-\beta)} \tag{4.3}$$

Hence, technology is constant-returns-to-scale and with decreasing marginal productivity in both factors. The productivity parameter a grows exogenously at the constant rate gr and thus incorporates labor-augmenting technological progress.

$$\frac{d}{dt} a_{it} = gr \cdot a_{it} \tag{4.4}$$

While labor is given exogenously, capital can be accumulated by investment:

$$\frac{d}{dt} k_{it} = in_{it} \quad . \tag{4.5}$$

4.2.3 Climate Dynamics

Greenhouse gas emissions e are generated as a byproduct of production. The autonomous decrease of emission intensity at a constant rate ν may be enhanced by investments im in abatement capital km. Parameter $iekm$ determines the investments' efficiency.

$$e_{it} = \sigma_{it} \; y_{it} \; \exp\left(-\nu t\right) \tag{4.6}$$

$$\sigma_{it} = \left(1 + km_{it}\right)^{-\psi} \tag{4.7}$$

$$\frac{d}{dt} km_{it} = iekm \cdot im_{it} \tag{4.8}$$

The climate system is represented in a stylized way based on Petschel-Held et al. (1999). The total stock of atmospheric greenhouse gases ce grows due to the instantaneous emissions of all countries

$$\frac{d}{dt} ce_t = \sum e_{jt} \tag{4.9}$$

and is linked to the greenhouse gas concentration *conc* according to

$$\frac{d}{dt} conc_t = B\ ce + \beta^P \sum e_{jt} - \sigma^P \left(conc_t - conc_0 \right) \tag{4.10}$$

The concentration, in turn, determines the change of global mean temperature *temp* by

$$\frac{d}{dt} temp_t = \mu \log\left(conc_t / conc_0 \right) - \alpha^P \left(temp_t - temp_0 \right) \tag{4.11}$$

Similar to Nordhaus and Yang (1996), temperature changes cause climate change damages, destroying a fraction 1-Ω of economic output:

$$\Omega_{it} = 1 / \left(1 + dam1_i \left(temp_t \right)^{dam2_i} \right) \tag{4.12}$$

$$y_{it} = \Omega_{it}\ F\left(k_{it}, l_{it} \right) \tag{4.13}$$

4.2.4 Trade and Tariffs

We impose an intertemporal budget constraint enforcing that export value and import value are ultimately balanced.

$$\int_0^\infty \sum_j p_{ijt}^m\ m_{ijt}\ dt = \int_0^\infty \sum_j p_{ijt}^x\ x_{ijt}\ dt \tag{4.14}$$

Imports received by i from j are denoted by m_{ij}, exports from i to j by x_{ij}. Naturally, imports and exports that describe the same trade flow must be the same, hence $m_{ijt} = x_{jit}$. Imports become foreign consumption goods after import tariffs—if any—have been deducted in the form of iceberg costs.

$$c_{ijt}^{for} = \left(1 - \tau_{ij} \right) m_{ijt} \tag{4.15}$$

$$tr_{ijt} = \tau_{ij} m_{ijt} \tag{4.16}$$

Tariff revenues *tr* are recycled without the consumer realizing the origin of the revenues. We close the economy by stating the physical budget constraint, which balances the available economic output with consumption, both investment options, and exports to the rest of the world.

$$y_{it} = c_{it} + in_{it} + im_{it} + \sum_j x_{ijt} \tag{4.17}$$

Finally, we need to update the Armington equation (Equation 4.2) to incorporate the tariff revenue *tr*.

$$c_{it} = \left[s^{dom} \left(c_{it}^{dom} \right)^{\rho^A} + \sum_j s_j^{for} \left(c_{ijt}^{for} + tr_{ijt} \right)^{\rho^A} \right]^{\left(1/\rho^A \right)} \tag{4.18}$$

4.3 Solving for a Nash-Equilibrium

The model features two distortions preventing that competitive equilibrium and social planner solution coincide: climate change damages caused by emissions, and import tariffs. In this section, we describe an algorithm that finds a Nash equilibrium for such models.

Our approach to compute a competitive equilibrium builds on Negishi (1960), Kehoe et al. (1992), and Leimbach and Edenhofer (2007). For a discussion of algorithmic alternatives we refer to Leimbach and Edenhofer (2007). Negishi (1960) shows that a competitive equilibrium maximizes a particular social welfare function which is a weighted sum of the utility functions of the individual consumers. Hence maximization of such a social welfare function may be used to compute a competitive equilibrium. Similarly, Kehoe et al. (1992) use joint maximization to compute competitive equilibria but extend the scope to economies with externalities. They analytically demonstrate the equivalence of a set of optimization problems and the competitive equilibrium.

To find an equilibrium, we iterate individual welfare maximization for all players in addition to a maximization of aggregate social welfare, an approach similar to the one proposed by Leimbach and Edenhofer (2007). We do so by fixing variables of the optimization problems at previously determined levels.

4.3.1 Finding a Nash Equilibrium

To solve our model for a Nash equilibrium, we repeat the following three steps until convergence is reached.

- *Step 1*

  We start by finding a Nash equilibrium in emissions $e=\{e_t\}$, $e_t=(e_{1t}, ..., e_{Nt})$ which are determined by the investment decisions in production capital in and abatement capital im, i.e. we solve a fix point problem $e=G(e)$ where G is the self-interested response of players to other players' emission trajectories. We compute G by solving

$$\forall_i \quad \max_{\{in_{it}, im_{it}\}} welfare_i$$

$$\text{subject to} \quad \text{Equations } 4.1 - 4.13, 4.15 - 4.18$$

$$\text{and } m_{ijt} = \overline{m_{ijt}},\ x_{ijt} = \overline{x_{ijt}},\ e_{kt} = \overline{e_{kt}} \text{ for } k \neq i$$

  with trade flows m_{ijt} and x_{ijt} and other players' emissions e_{kt} fixed to their previous levels, as indicated by the bars.

- *Step 2*

  Next, we search for a competitive equilibrium in trade flows (m,x) with m={m_t}, m_t=(m_{ijt}) and x={x_t}, x_t=(x_{ijt}), while keeping the emission externality fixed at the level $\bar{e}$ found in Step 1. This is done by solving the fix point problem tr=H(tr), with tr={tr_t}, tr_t=(tr_{ijt}), and H the response of the social planner to a given tariff revenue constraint $\overline{tr}$. H is computed by solving the joint optimization

  $$\max_{\{in_{it}, im_{it}, m_{ijt}, x_{ijt}\}} \sum \delta_i \; welfare_i$$

  $$\text{subject to} \quad \text{Equations } 4.1 - 4.13, 4.15, 4.17 - 4.18$$

  $$\text{and } e_{it} = \overline{e_{it}}, tr = \overline{tr}$$

  The parameters δ_i represent the regions' weights within the joined social welfare function, and are also referred to as Pareto or Negishi weights.

- *Step 3*

  By using price information derived from the Lagrange multipliers of the maximization problem, we determine deficits and surpluses in the intertemporal budget constraints (Equation 4.14). We balance the budgets by adjusting the welfare weights δ_i and repeating steps 1-3.

Convergence is reached when the intertemporal budget is in balance and the fix point equations in steps 1 and 2 are satisfied.

4.3.2 Numerical Verification of the Nash Equilibrium

We verify the resulting 'candidate' Nash equilibrium strategies in emissions and trade numerically by comparing them to the results of the following maximization problems:

$$\forall_i \quad \max_{\{in_{it}, im_{it}, m_{ijt}, x_{ijt}\}} welfare_i$$

$$\text{subject to} \quad \text{Equations } 4.1 - 4.18$$

$$\text{and prices } p^m_{ijt}, p^x_{ijt}$$

which include the budget equation Eq.(4.14) with market prices from the final model solution. Deviations of this model from our solution should be within the order of magnitude of numerical accuracy only, which is what we find (not

shown). In particular, simultaneous clearance of all international markets confirms the Nash equilibrium in international trade.[81]

4.3.3 Partial Agreement Nash Equilibria

For the application of this algorithm to self-enforcing International Environmental Agreements (IEA), we need to extend the algorithm from plain Nash equilibrium to Partial Agreement Nash Equilibrium (PANE). Whereas in the Nash equilibrium there is no cooperation, PANE defines partial cooperation as socially optimal behavior among a subset of players (the coalition). PANE is a Nash equilibrium of the coalition (acting as one player) and all non-members. Within the coalition, a utilitarian social welfare function, i.e. the equally weighted sum of all individual welfare functions, is maximized.

4.4 Application to International Cooperation on Climate Change

In this section we apply our model to the analysis of import tariffs as a trade sanction against non-signatories of an International Environmental Agreement (IEA). Following the literature on self-enforcing IEA (e.g. Carraro and Siniscalco 1993, Barrett 1994), we consider coalitions that are internally and externally stable, i.e. members of the coalition cannot improve their situation by leaving the coalition and joining the group of non-members which free-ride on the effort of the remaining coalition, and neither do non-members have an incentive to join the coalition.

To avoid the black-box effect and to facilitate an interpretation of the qualitative effects produced by the model, we restrict the following analysis to the symmetric case of nine perfectly identical countries.

4.4.1 Results

Tariff's Influence on Participation

Our model confirms that tariffs are potentially an effective instrument to increase the scope for international cooperation: participation in the coalition becomes unambiguously higher when a tariff on imports from non-member countries is applied. This result is illustrated in Figure 4.1: in the absence of tariffs, the largest stable coalition has only three or four members, while a tariff rate between 1.5 to 4 percent is sufficient to induce full cooperation.

[81] Note that we do not attempt to show uniqueness of the identified equilibrium. Indeed, Kehoe et al. (1992) demonstrate how general equilibrium models are prone to multiplicity in the presence of externalities. However, they also show that this occurs when the externality is rather large. In our case, where tariffs and climate damages are on the scale of percents and ten percent, respectively, we assume that the issue of multiple equilibria is still negligible. This is corroborated by the fact that our numerical simulations produced robust results without indication of multiple equilibria.

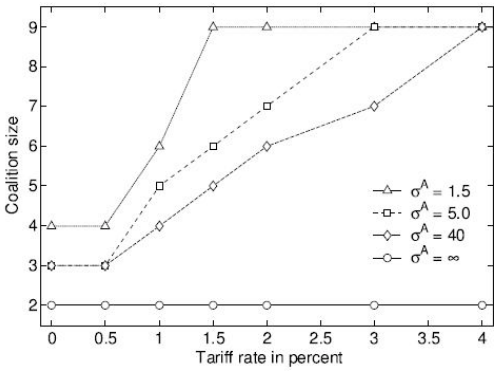

Figure 4.1: Largest stable coalitions for a given tariff.

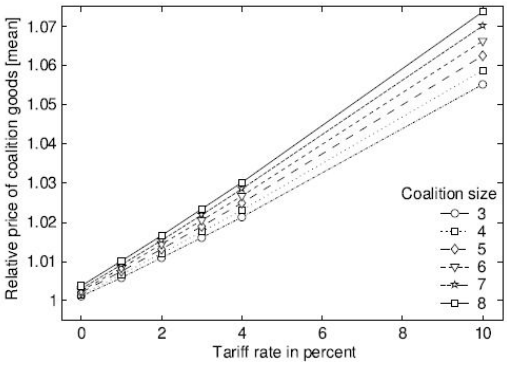

Figure 4.2: Relative price of coaltion good.

This effect can be understood in the light of the model's representation of international trade, in which each region produces an imperfectly substitutable good and hence disposes—not at the firm, but at the country level—of some market power.[82] In effect, a small tariff on imports from non coalition-members exploits this market power and leads to a rise in the relative price of goods produced by coalition members (see Figure 4.2). The latter obtain a net benefit from this positive terms-of-trade effect, similar in its mechanics to what is known from the analysis of optimal tariffs or monopolistic pricing. Since by assumption only coalition members can apply such a tariff, it constitutes an incentive to join the coalition.

Note that the relative price of coalition goods also rises just as a function of the size of the coalition, even in the absence of any tariff (Figure 4.2 at $\tau = 0$). This happens because the emission cuts realized by coalition countries diminish their output, and hence there is—with respect to the business-as-usual—a reduced supply of coalition goods. If demand is inelastic ($\sigma^A < \infty$), the relative price must consequently go up. In fact, the possibility to pass on mitigation costs to free-riders via such terms-of-trade effects also explains how larger coalitions can be 'stabilized' even without tariffs by simply decreasing the elasticity of substitution to a sufficiently low level, as seen in Figure 4.1 at $\tau = 0$.

The graph in Figure 4.1 also shows that the effectiveness of tariffs is reduced in the presence of higher elasticities of substitution. For example, a tariff of 1 percent induces a stable coalition with six out of nine member countries when $\sigma^A = 1.5$, five members when $\sigma^A = 5$ and four members when $\sigma^A = 40$. Since a higher elasticity implies higher substitutability and hence lower market power,

[82] In this context, market power is to be understood as an aggregate property of whole countries, and is due to the fact that each country's representative output bundle is somewhat different. However, there is no monopolistic market structure as such, since the firms making up each country's economy always behave competitively. In fact, *all* Nash equilibria in this study represent competitive equilibria based on price-taking behavior.

this behavior is fully consistent with our explanation. Indeed, in case all goods are perfect substitutes ($\sigma^A = \infty$), the tariff loses its clout entirely, as expected.

Environmental Effectiveness of Cooperation

A common argument brought forward against climate coalitions with incomplete membership is the leakage problem: the effectiveness of any collective effort by the coalition could be undermined, if not annihilated, by free-riders who increase their emissions in response to the coalition's reductions. As Figure 4.3 illustrates, the extreme case of 100 percent leakage rate is not present in our model. Instead we observe that an increase in the coalition size unambiguously results in a reduction of cumulative global emissions. Free-riding does cause some leakage, but the extent is limited and would not warrant the discouragement of cooperation between a subset of countries (Figure 4.4).

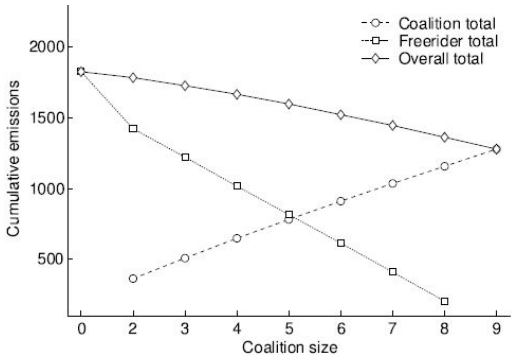

Figure 4.3: Effect of coalition formation on cumulative emissions.

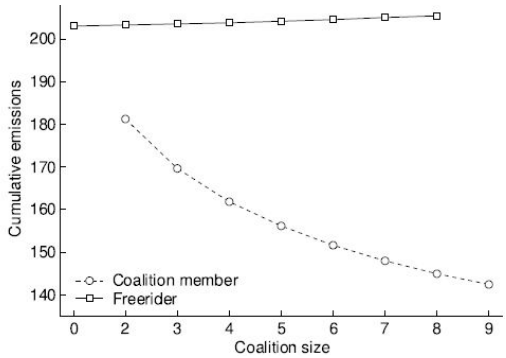

Figure 4.4: Average free-rider and coalition member emissions as function of coaltion size.

The missing indication of the parameter values for τ and σ^A in Figures 4.3 and 4.4 hints at another behavioral characteristic of the model: emission trajectories are fully determined by the coalition size, and do not depend on the Armington elasticities or the tariff rate.[83] Perhaps counterintuitive, this observation is actually in line with the model assumptions: we defined utility as the logarithm of a linearly homogeneous function, which, by using the indirect utility function and an exact price index, can be rewritten as a sum of two terms, the first related to the output level, and the second to the relative prices and the elasticity of substitution. Price changes induced by a tariff or a change in σ^A have an influence only on the latter, but do not change the optimal capital accumulation and, as a direct consequence, output levels and emissions remain the same.

[83] The coalitions' stability of course depends on their value.

Credibility of Tariffs

Threatening to impose tariffs is only credible if the coalition is better off with than without tariffs.[84] Within our model characterized by national product differentiation, tariffs provide an indirect means for coalition countries to exploit their implicit market power. Thus, a tariff should be beneficial as long as it is not too high, the limit depending on the elasticity of substitution. This intuition is confirmed in Figure 4.5, which shows how a coalition's welfare changes with increasing tariffs.

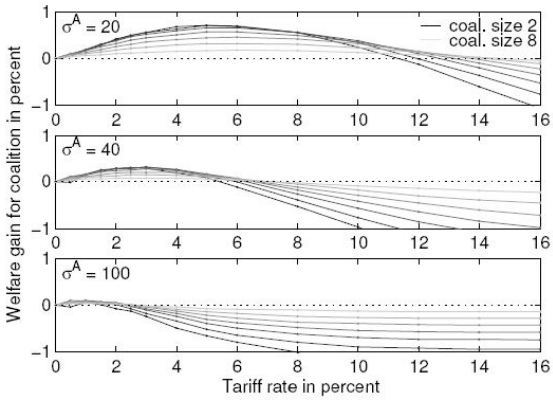

Figure 4.5: Credibility of imposing tariffs.

As expected, welfare initially increases, but starts to decline after reaching a maximum value and eventually drops below zero. The threshold value at which the welfare effect becomes negative marks the maximum tariff rate that is still credible.

Although the observed qualitative pattern is robust with respect to parameter changes, the specific value of the maximum tariff as well as the potential welfare gain depend on the elasticity of substitution σ^A and on the coalition size: both increase with lower elasticities and smaller coalition sizes. For example, at $\sigma^A = 20$ tariff rates of less than 10 percent are credible for any coalition size, while at $\sigma^A = 100$ the cut-off is already at about 2 percent. This dependence on σ^A can again be explained in terms of the greater market influence that can be realized with a lower elasticity. The observable higher welfare gain for *smaller* coalitions is a consequence of higher tariff revenues: in the presence of large coalitions, there are only few free-riders left whose goods are actually subject to tariff duties, while there are payments from almost all trading partners if the coalition has only two members.

[84] This concept of credibility is rather shortsighted: when considering only the welfare effects of tariffs on themselves, coalition members ignore that tariffs may increase participation and thus bring about net positive welfare effects even when 'incredible' according to this concept. This shortsightedness is, however, consistent with the employed shortsighted concept of stability.

Welfare Implications of Tariffs

Tariffs have an ambiguous effect on global welfare: on the one hand they can increase global welfare because they enhance the scope for cooperation. On the other hand—as free trade advocates might object—they distort free trade and thus undermine global efficiency, which ought to cause a loss of welfare which could in the worst case outweigh the gains. We compare the two opposing effects in Figures 4.6 and 4.7.

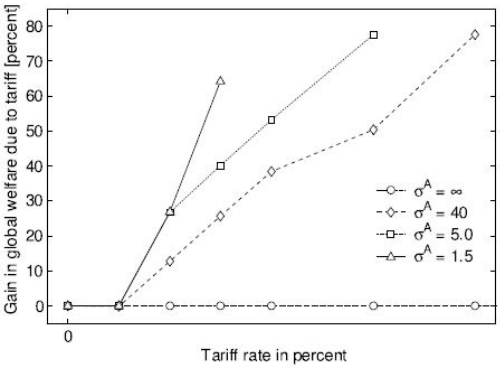

Figure 4.6: Gains in global welfare due to tariffs.

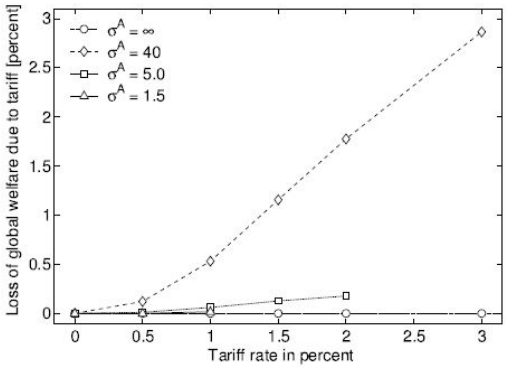

Figure 4.7: Losses in global welfare due to tariffs.

Figure 4.6 shows gains induced by tariffs measured as the difference in global welfare between the largest stable coalition with a given tariff rate and the largest stable coalition in the absence of tariffs.[85] As can be seen, the welfare gains are quite significant and reach up to 65 to 80 percent for full cooperation, depending on the coalition size and corresponding welfare levels without tariffs (see Figure 4.1).

In contrast, the welfare losses caused by the distortionary effects of tariffs are shown in Figure 4.7. They are measured by taking the largest stable coalition at each tariff rate and computing the increase in global welfare achieved by dropping all tariffs (ignoring that the coalition may not be stable anymore). In agreement with standard economic theory the graph shows welfare losses that increase steadily with the tariff rate. However, the welfare losses due to the trade distortion are one order of magnitude smaller than the gains achieved by furthering cooperation. In normative terms, this suggests that the trade distorting effect of tariffs should be an acceptable price to pay in exchange for more inclusive climate coalitions.[86]

[85] Normalized (in both figures) to the scale defined by the welfare gap between the Nash equilibrium and social optimum.

[86] It might seem counterintuitive that welfare losses in Figure 4.8 are higher when goods are better substitutes, especially since in the limit case $\sigma^A \to \infty$ tariffs become ineffective and hence welfare losses drop to zero. The intuition behind this effect is as follows: Tariffs have two effects, an income effect and a substitution effect. The income effect (due to the price increase of coalition

4.4.2 Sensitivity Analysis

A central result in the previous section was that a tariff levied on imports from free-rider countries in the order of magnitude of a few percent sustains full cooperation on emissions reduction. In this section, we explore in how far this result continues to hold when the values of the model's key input parameters are systematically changed to *high value* and *low value* estimates. In order to keep the computational costs manageable, we stick to an exploration of local sensitivities.[87]

Figure 4.8 reports sensitivities obtained from the variation of nine parameters. Indicated are the lowest tariff rates that still support full cooperation for the chosen parameter values. The numerical values for high and low are reported next to the data-point, while the parameters' name and default value is given at the bottom of the figure. The results show that for all parameter variations, full cooperation can still be achieved by adjusting the tariff rate. Furthermore, the required tariff rate does not exceed five percent for our selection of low and high values.

Barrett's (1994) conclusion that cooperation is harder to achieve when it is most needed helps to understand the sensitivities. The largest impact is exerted by the rate of pure time preference ρ, which is known to have a strong impact on growth and the (associated) emissions: patience boosts savings leading to more production. Additionally, the weight of future damages is increased. Varying parameters of the damage function immediately lessens or exacerbates the need for coordinated mitigation. Also the next two most sensitive parameters, the exogenous rates of decarbonization ν and productivity growth gr are again closely related to emissions and economic growth, and therefore the urgency of environmental cooperation.

In addition to the local sensitivity analysis, we also explore the consequences of a structural change in the model: in Eq.(4.4) we assumed exogenous technological progress, at the constant rate gr. Alternatively, we might follow the concept of Jones and Williams (1998) and depict the productivity parameter a as a knowledge stock that evolves endogenously according to

goods) is predominantly of distributional nature, leaving global welfare largely unaffected. The substitution effect, on the other hand, causes a decline in the total volume of world trade, which bears welfare costs for all countries. This deviation from the socially optimal trade volume increases with higher elasticities of substitution, and thus becomes more pronounced for large values of σ^A.

[87] Our approach is similar–albeit much more concise–to the sensitivity analysis of the DICE model in Nordhaus (1994, Ch. 4). Parameter variations leading to Nordhaus' alternative high values are comparable to ours. Moreover, five of the eight identified most sensitive parameters have counterparts in our analysis. As one difference, in our study the uncertainty of climate dynamics is solely assessed by varying the damage function.

$$\frac{d}{dt}a_{it} = gr\left(iea \cdot ia_{it}\right)^{\lambda}\left(a_{it}\right)^{\varphi} \tag{4.19}$$

The new control variable *ia* represents R&D investments[88], *iea* their efficiency, and λ and ϕ parameters for "stepping on toes" and "standing on shoulders" effects, respectively.[89] To test the influence of endogenous technological change, we choose *iea* = 1.7e3, λ = 0.15, and ϕ = 0.2, which reproduces the average growth rate of the default model with exogenous technological change. The latter case is recovered from Eq.(4.19) by setting λ = 0, ϕ = 1. The impact of this structural change is no larger than the parameter variations (see last column in Figure 4.8).

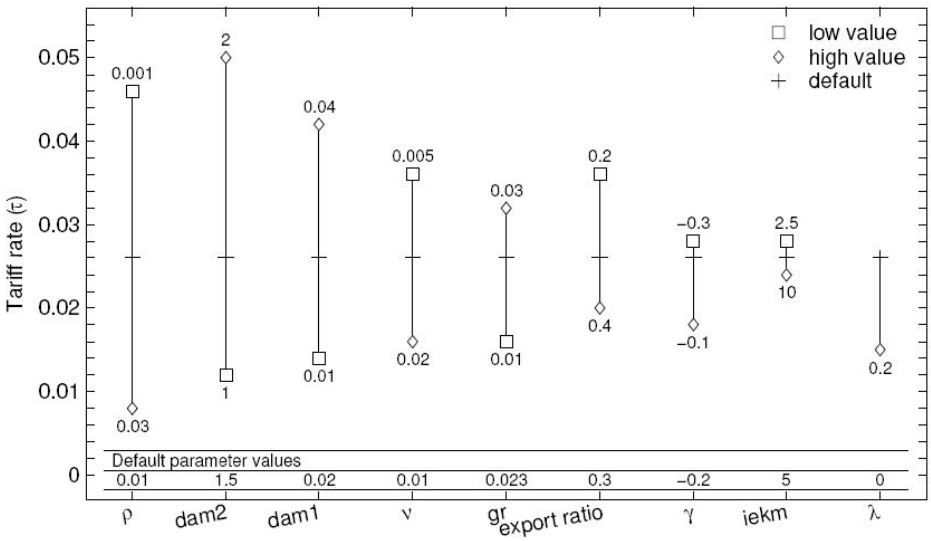

Figure 4.8: Local sensitivity analysis. The figure shows how the tariff rate necessary to induce full cooperation changes when key input paramters are replaced by lower or higher values.

In the main part of this study, we restrict the analysis to symmetric regions. This greatly reduces the number of computations needed to determine the largest stable coalition: for *n* symmetric regions, *n* model evaluations suffice (in our case 9), whereas *n* heterogeneous regions require 2^n-*n* model runs (in our case 503). In Table 4.1 we take one step towards heterogeneous regions by exploring the impact of "stylized" heterogeneity. To this end, we define three different scenarios with heterogeneous parameters.

First, scenario 1 (row 4) incorporates heterogeneity by assigning all regions different amounts of initial capital k_0. As can be seen, even though the poorest and richest regions differ by a factor 20, the effect on the tariff rate needed to induce full cooperation is all but negligible. Indeed, cooperation becomes a little easier.

[88] Of course, these investments need to be deducted from the budget in Eq.(4.15).
[89] See Jones and Williams (1998) for a detailed discussion of the equation.

		Region									Tariff
Parameter	Scenario	1	2	3	4	5	6	7	8	9	τ
dam2		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	
iekm	*default*	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	0.028
k0		34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	
k0	*1*	3.4	11.1	18.7	26.4	34	41.7	49.3	57.0	64.6	0.026
dam2	*2*	1.75	1.69	1.63	1.56	1.5	1.44	1.36	1.31	1.25	0.034
iekm		4.0	4.25	4.5	4.75	5	5.25	5.5	5.75	6	
dam2	*3*	2	1.88	1.75	1.63	1.5	1.38	1.25	1.13	1.0	0.042
iekm		3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	

Table 4.1: Impact of heterogeneity. The last column shows the smallest tariff rate τ that is sufficient to induce full cooperation; τ was varied between 0.01 and 0.05 using a step size of 0.002. Only parameter values that differ from their defaults in rows 1-3 are listed, i.e. scenario 1 shows a variation of initial capital k_0, scenarios 2 and 3 show experiments that effect mitigation costs (via iekm) and climate change damages (via dam2).

Heterogeneity should constitute a more serious obstacle to cooperation when there are some regions with high damages and high mitigation costs (high interest in cooperation) and some with low damages and low mitigation costs (low interest in cooperation). This hypothesis is tested in scenarios 2 and 3, shown in rows 5-6 (moderate heterogeneity) and 7-8 (strong heterogeneity), where the damage and mitigation cost parameters have were set accordingly.

We find that this type of heterogeneity does not prevent full cooperation either, even though higher tariff rates are necessary. Whether the increased level of tariffs is due to heterogeneity remains an open question: both the damages and mitigation costs are determined through nonlinear functions. Hence, even though we varied the parameters such that their average value across all countries remains the same, average damages and average mitigation costs may well have changed due to the introduction of heterogeneity.

4.5 Conclusions

This study makes a methodological and a policy contribution to the integrated assessment modeling of climate change. We present a model in the tradition of multi-regional optimal growth models that includes trade relationships between regions. Including climate damages and punitive tariffs introduces two external effects into the model. Thus the competitive equilibrium will fail to be socially

optimal and a more elaborate approach than social welfare maximization is necessary to find an equilibrium solution.

We address this challenge by presenting an algorithmic extension to the approaches by Negishi (1960) and Kehoe et al. (1992). We illustrate model and algorithm by applying the model to the current issue of trade sanctions as an instrument to foster participation in an international environmental agreement. We find:

- When the coalition imposes tariffs on imports from free-riding regions, participation in the coalition rises. Global social welfare rises along with participation despite small welfare losses due to the distortion caused by the tariff instrument.
- To threaten non-members with trade sanctions is credible as long as the tariff rate is small, where 'small' depends on the Armington elasticity. For large tariff rates coalition members would be better off not to sanction trade.
- Non-members respond to emission cuts on the part of the coalition by raising their own emissions, but we find this leakage effect to be small.

These results are comprehensible in light of the underlying theoretical model of international trade: following the concept of national product differentiation, goods produced by different regions are assumed to be imperfect substitutes among each other. Yet all countries act as price takers in a competitive equilibrium. Introducing tariffs in this context allows coalition members to capitalize on their potential market power. The elasticity of substitution between goods determines the ease with which non-members can avoid coalition goods, and hence puts a limit on the potential clout of the tariff instrument.

The application of the model nevertheless identifies some robust qualitative relationships and clearly demonstrates the usefulness of the algorithm. In fact, the treatment of externalities sketched in this chapter can easily be transferred to similar dynamic games with externalities. Finally, in order to put numbers on the identified qualitative effects, heterogeneous regions should be introduced and be calibrated to real world regions. This would further enhance the policy relevance of the model results.

4.6 Appendix: Parameter Choices

Table 4.2 lists our choice of parameters. We restrict this study to the case of symmetric players, hence a calibration to real world regions is out of question. Nevertheless we selected a set of parameters such as to produce a scenario that appears plausible. This appendix lists the assumptions we made.

The choice of the pure rate of time preference has received much attention since Stern (2007) suggested a significantly lower value (0.001) than earlier studies, e.g. 0.03 in Nordhaus (1996). We strike middle ground by selecting $\rho = 0.01$, but explore both Stern's and Nordhaus' choices in our sensitivity analysis.

We chose the rate of exogenous labor enhancing technological change *gr* such that long term economic growth averages at 2.1 percent per year, which is within the range of the IPCC SRES family of development scenarios (IPCC 2000).

Parameter	Symbol	Value
Pure rate of time preference	ρ	*0.01*
Income share capital	β	*0.35*
Labor productivity growth	gr	*0.023*
Rate of autonomous emission intensity reduction	ν	*0.01*
Initial labor	l_0	*1*
Initial labor productivity	a_0	*1*
Initial capital stock	k_0	*34*
Share parameter, domestic	s^{dom}	*see text*
Share parameter, foreign	s^{for}	*see text*
Armington elasticity of substitution	ρ^A	*0.975*
Effectiveness of investments in *km*	$iekm$	*5.0*
Abatement cost exponent	ψ	*0.2*
Ocean biosphere as CO_2 source	β^P	*0.47*
Atmospheric retention factor	B	*1.51e-3*
Radiative temperature driving factor	μ	*8.7e-2*
Temperature damping factor	α^P	*1.7e-2*
Ocean biosphere as CO_2 sink	σ^P	*2.15e-2*
Initial concentration	$conc_0$	*377*
Initial temperature	$temp_0$	*0.41*
Initial cumulative emissions	$cume_0$	*501*
Damage function coefficient	$dam1$	*0.02*
Damage function exponent	$dam2$	*1.5*

Table 4.2: Parameter values.

With initial labor and labor productivity at 1.0, we chose initial capital such that the savings rate is approximately constant at 23 percent during the first decades, i.e. the economy is on a balanced growth path. This figure corresponds

to the world's empirical average of 23 percent between 1990 and 2002 (Bank for International Settlements 2004, 28).

We frequently vary the Armington parameter σ^A that determines the elasticity of substitution in our experiments using values between 1.5 and 40. We compare these result to the limit case of an infinite σ^A and explore the transition to the limit using a high value of $\sigma^A = 100$. In calibrated real-world models these elasticities typically lie between 1 and 8 (Bernstein et al. 1999). To enhance the comparability of calculations with different ρ^A we selected the share parameters s^{dom} and s^{for} such that for all ρ^A the export ratio is about 30 percent in the Nash equilibrium. For 2005, the WTO has estimated the ratio of exports in goods and commercial services to GDP as 29 percent (WTO 2007, 30).

Parameters in the climate module are based on literature values, giving us a 3°C temperature increase by 2100, and a 7.5°C increase by 2200 in the business as usual, i.e. without climate change damages and without any cooperation between regions. Nordhaus and Yang (1996) estimate a similar temperature increase of 3.06°C in 2100 for their market scenario.

The damage function was chosen such that in Nash equilibrium damages in 2100 are 6 percent. We chose this relatively high value (compared to damages ranging from 0 to about 5.5 percent across regions in RICE with a global average of about 3 percent) to account for Stern's (2007) estimation that "[business as usual] climate change will reduce welfare by an amount equivalent to a reduction in consumption per head of between 5 and 20 percent."

Within the mitigation option, parameters ψ and *iekm* were selected such that optimal abatement (the social planner solution) reduces the temperature increase in 2100 by 0.6°C. In Nordhaus and Yang (1996), cooperative behavior reduces global temperature in 2100 by 0.22°C.

Chapter 5

Revisiting the Case for Intensity Targets: Better Incentives and Less Uncertainty for Developing Countries?[90]

5.1 Introduction

What kind of follow-up agreement should or could succeed the United Nation's Kyoto Protocol, due to expire in 2012, is currently the central question in international climate policy (e.g. Aldy and Stavins 2007, Bodansky 2004). Among the various issues, one aspect regards the mechanism by which emission control is to be implemented. On the one hand there are *absolute* targets, which require future emissions not to exceed a certain amount of CO_2 (or CO_2 equivalents). Such targets, also referred to as caps, were adopted by most industrialized countries under the Kyoto Protocol. On the other hand, so called *intensity* targets[91] set an upper limit on the ratio of emissions to output, expressed in CO_2 per GDP. As a prominent example, the U.S. administration announced such a target in 2002, pledging to reduce greenhouse gas emissions relative to GDP by 18% over a ten year period.92 Recently, the approach received a boost when Canada (Government of Canada 2007) and China[93] expressed their intention to implement intensity targets in the coming years. It was also suggested to devise such targets only for some sectors of major developing economies, in order for them to participate in international permit trade (Schmidt et al. 2006).

The strong emphasis on mechanisms capable to facilitate the participation of developing countries in climate change mitigation (Kim and Baumert 2002) reflects the insight that without their contribution, avoiding dangerous climate change will hardly be feasible and–in any case–definitely not cost-effective. However, developing countries have so far remained hesitant, fearing that any type of binding emission restriction would be in conflict with their development objectives.

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[90] Chapter based on the homonymous article by Marschinski and Edenhofer published in *Energy Policy* 38(9):5048-58, 2010. Being there multiple authors, the text employs of the plural 'we'.
[91] Also called dynamic (e.g. IEA 2003) or indexed (e.g. Newell and Pizer 2008) targets.
[92] See White House news release 2002/02 on climate change.
[93] See, e.g., the speech of President Hu at the UN general assembly on 22 September 2009.

Against this backdrop, intensity targets have been characterized as a more acceptable type of commitment for developing countries, as they can "alleviate developing countries' concerns about constraining their development" (Philibert and Pershing 2001) by reducing cost-uncertainty and offering a way to contribute to international mitigation efforts while retaining some scope for emissions growth, which–in face of their growth ambitions–seems unavoidable in the near term (Pizer 2005). By creating the right type of incentive, they would foster "clean growth" and help to put development countries on "low-emissions pathways" (Herzog et al. 2006). Moreover, they are expected to alleviate 'hot air' (Philibert and Pershing 2001) and may readily be integrated in international emissions trading (IEA 2003).[94]

However, few of these prospective benefits of the intensity target have undergone formal analysis, and if so–as in the case of uncertainty reduction (e.g. Sue Wing et al. 2009)–not within a comprehensive assessment that compares and weighs the results for all the different aspects. It is this gap that the present chapter wants to address, by presenting a formal assessment of five potential merits of the intensity target.

First, the question of cost-uncertainty is briefly revisited, showing that whether or not an intensity target leads to less uncertainty than a cap depends on (potentially uncertain) parameter values. Second, a short analysis yields the result that the same also holds with respect to the reduction of 'hot air'. Third, emissions trading between a country with absolute and one with intensity target is investigated, demonstrating that this leads to inefficient allocations and to an expansion of global emissions whenever the country with intensity target is a net importer of permits. Forth, the hypothesis that an intensity target creates a stronger incentive for a systematic decarbonization of the energy system is assessed. By means of an exemplary analysis of abatement through intensity reduction versus end-of-pipe abatement (interpretable as carbon capturing and sequestration), it is shown that the incentive to reduce emission intensity is not necessarily weaker under an absolute cap. Fifth, the question of whether an intensity target could act as a substitute for a banking/borrowing mechanism is explored. It results to be the case only to a limited extent, i.e. an absolute cap with banking/borrowing will likely constitute a better way for reducing the fluctuation of abatement over time. In conclusion it is argued that absolute caps represent the more robust policy choice, given the doubts or at least uncertainties on several issues about the effective benefits of an intensity target.

The remaining part of this chapter is organized as follows: the next section reviews related literature on the subject. Section 5.3 defines the two types of targets. Section 5.4 addresses cost-uncertainty, Section 5.5 'hot air'. Section 5.6

[94] An often-mentioned drawback of the intensity target consists of its reduced environmental effectiveness, i.e. its outcome in terms of emission control is uncertain. However, over multiple time periods this uncertainty should average out (Jotzo and Pezzey 2007).

discusses the efficiency of emissions trading, and Section 5.7 the incentives for decarbonization. Section 5.8 analyzes banking/borrowing, and Section 5.9 concludes.

5.2 Related Literature

The early literature dealt with the basic properties of the intensity target and highlighted its potential to reduce cost-uncertainty, using both qualitative (Frankel 1999, Philibert and Pershing 2001, IEA 2003) and quantitative approaches based on the (exemplary) use of GDP and emissions data (Kim and Baumert 2002). More formal analytical treatments of the question of uncertainty were offered by Kolstad (2005) and Ellerman and Sue Wing (2003): starting from slightly different assumptions on the link between GDP, emissions, and abatement costs, the former shows intensity targets to always reduce uncertainty, while the latter find that they are superior only if "generalized growth-indexed" targets are employed, which allow to tie emissions to GDP with an elasticity of less than unity. Following up on this, Sue Wing et al. (2009) present a comprehensive formal analysis of the abatement uncertainty (taken as proxy for cost-uncertainty) under absolute and intensity target, establishing the formal condition to be discussed later in Section 5.4. Although they also included a formal comparison of "temporal stability" of abatement under the two types of targets, they did not, however, extend the analysis to cover banking and borrowing.

The possibility that–due to reduced cost-uncertainty–intensity targets could offer a more acceptable type of commitment for developing countries was emphasized, among others, by Frankel (1999), Philibert and Pershing (2001), and Lisowski (2002). This conclusion is shared by Pizer (2005), but for slightly different reasons, namely on the grounds that intensity targets offer a better way of framing mitigation policy when absolute emission levels of developing countries are destined to rise, at least in the near term.

A different strand of literature follows the tradition of Weitzmann's (1974) analysis of price versus quantity regulation, and includes the benefits of abatement in order to evaluate the general welfare implications of the intensity target. Based on an analytical approach, Quirion (2005) finds that in most cases either an emission tax or an absolute cap is preferred to the intensity target, but that in climate change policy the latter could be a second-best solution if the first-best, an emission tax, cannot be implemented for political reasons. This result is in essence confirmed and further elaborated by Newell and Pizer (2008), who confront their findings with empirical data to show that indeed indexed quantities would be second-best for about half of the considered countries.

The welfare implications of the intensity target were also assessed within empirically calibrated model simulations. In an 18-region global cap-and-trade model, Jotzo and Pezzey (2007) find that standard intensity targets have an overall positive impact, but not for every single country, since GDP-induced shocks on emissions tend to be "systematically over- or undercompensated". Tian and Whalley (2009) use a multi-regional model with a 30 and 50 years horizon with explicit disutility from rising global temperatures. By constructing plausible cases in which all countries prefer absolute over intensity targets, they illustrate that the ranking of targets is significantly influenced by model assumptions, in their case in particular on how growth rate uncertainty is specified.

Overall, the existing literature shows a focus on the intensity target's performance under uncertainty, be it in terms of expected abatement costs or net benefits. An exception with relevance for the present contribution is Fischer (2003): motivated by a similar question as the one addressed in Section 5.6, she examines trade of emission permits between a cap-and-trade and tradable performance standard program. However, despite a certain resemblance, the latter is actually different from an intensity target, as it is defined not at the national but sectoral level, and sets a limit on emissions per unit of physical output. Accordingly, her analysis adopts a micro-view and explicitly models the behavior of competitive firms in two sectors. Partially in line with the findings of Section 5.6, she finds that in the absence of cross-price effects permit trade always leads to an expansion of combined emissions, but then goes on to concentrate on the identification of suitable countermeasures.

5.3 Definition of Intensity and Absolute Target

Consider a closed economy, and let Y be future economic output and E future emissions. Throughout this chapter, a subscript zero is used for denoting the deterministic value of variables, i.e. the value they would take on in the absence of uncertainty. For symmetric uncertainty distributions, the expected (or mean) value coincides with the deterministic value: $\langle Y \rangle = Y_0$ and $\langle E \rangle = E_0$. Finally, let γ be defined as the emission intensity of output E/Y, which in the absence of uncertainty is given by $\gamma_0 = E_0/Y_0$.

Two types of emission reductions will be considered: absolute targets (in short also 'caps'), which constrain emissions to a given level $\overline{E}$, and intensity targets, which set a maximum intensity of $\overline{\gamma}$. In a deterministic setting, absolute and intensity targets are equivalent instruments for the purpose of emission control, since any absolute target can be implemented through an intensity target (Ellerman and Sue Wing 2003), where $\overline{\gamma} = \overline{E}/Y_0$ denotes what shall be called the equivalent intensity target.

5.4 Reduction of Cost-Uncertainty

In the literature, advocates of the intensity target argue that it reduces cost-uncertainty in the face of unknown–but GDP sensitive–business-as-usual emissions (Frankel 1999, Kolstad, 2005, Strachan 2007). In fact, when a country accepts an emission target, the incurred costs are uncertain for two reasons: first, in the face of unknown future baseline emissions the amount of abatement needed for meeting the target is uncertain; and, second, because of marginal abatement cost (MAC) uncertainty, i.e. the a priori unknown costs for reducing emissions by a given amount. Nevertheless, in what follows we abstract from MAC uncertainty, assuming that it would affect both types of targets equally, and hence that differences in cost-uncertainty are essentially driven by differences in the uncertainty about the required amount of abatement.

In formal terms, the overall reduction burden is given by the difference between baseline emissions E and the emissions target T (be it absolute or relative), and will be denoted by R. The associated level of uncertainty, expressed in terms of the variance σ_R^2, is given by[95]

$$\sigma_R^2 = <(E-T)^2> - <(E-T)>^2 = \sigma_E^2 - 2\left(<ET> - <E><T>\right) + \sigma_T^2 \quad . \tag{5.1}$$

For an absolute target, T becomes a fixed emission level $\overline{E}$, meaning that all terms except the first one cancel out, leaving only the uncertainty about future baseline emissions:

$$\sigma_{R\_Cap}^2 = \sigma_E^2 \quad . \tag{5.2}$$

For an intensity target, T is given by the fixed emission intensity $\overline{\gamma}$ multiplied by economic output Y. The associated reduction uncertainty now becomes a function of the coefficient of correlation ρ, which captures the relationship between shocks in baseline emissions and output with respect to their expected values:

$$\sigma_{R\_Int}^2 = \sigma_E^2 - 2\overline{\gamma}\,\sigma_E\sigma_Y\rho + \overline{\gamma}^2\,\sigma_Y^2 = \sigma_E^2\left(1 - \overline{\gamma}\frac{\sigma_Y}{\sigma_E}\left(2\rho - \overline{\gamma}\frac{\sigma_Y}{\sigma_E}\right)\right) \quad . \tag{5.3}$$

Comparison with Eq.(5.2) directly leads to the previously noted result that the intensity target reduces uncertainty only if the correlation ρ is higher than a parameter-dependent threshold value ρ_{min} (Sue Wing et al. 2009, Jotzo and Pezzey 2007):

$$\sigma_{R\_Int} < \sigma_{R\_Cap} \quad \Leftrightarrow \quad \rho > \frac{1}{2}\,\frac{\overline{\gamma}}{\left(E_0/Y_0\right)}\,\frac{\sigma_Y/Y_0}{\sigma_E/E_0} =: \rho_{\min} \quad . \tag{5.4}$$

[95] Note that uncertainty is represented solely through the second moment, i.e. the standard deviation, which is equivalent to assuming the underlying distribution to be normal.

It is intuitive that the intensity target does not always reduce uncertainty: if the uncertainty about future GDP is much higher than the uncertainty about future emissions, then a coupling of the target to GDP will introduce more new uncertainty than can be reduced.

The fraction $(\sigma_Y/Y_0)/(\sigma_E/E_0)$ in Eq.(5.4) can be interpreted as the ratio of the average (normalized) forecast errors for GDP and emissions, which has been estimated to be roughly around one (Marschinski and Lecocq 2006). The other term is the ratio between target and BAU emission intensity–generally a value between zero and one. Thus, the equation implies that a significant positive correlation between shocks in E and Y is necessary in order for the intensity target to reduce cost uncertainty, and that a simple rule of thumb could be given by $\rho>0.5$ (see also Höhne and Harnisch 2002).[96]

This condition might not appear very demanding at first sight, given that the raw series of E and Y are indeed often strongly correlated (Peterson 2008). However, it should be checked carefully, since the deviations from expected values (shocks, or forecast errors) do not always seem to be highly correlated, or, at a minimum, are difficult to estimate with high confidence. For instance, Newell and Pizer (2006, 2008) employ a vector forecasting model to compute ρ for 19 high-emitting countries, and find a wide range of values between 0.01 and 0.74, broadly in line with similar results reported by Marschinski and Lecocq (2006). Relatively low values for ρ seem plausible if, e.g., agriculture plays a strong role in a country's economy, or when electricity production is dominated by nuclear energy, as in France. Intuitively, shocks in emissions can also be related to non-economic factors, such as weather conditions, e.g. when a series of years with particularly cold winters causes higher energy consumption. However, a robust estimation of ρ is difficult not only because of data limitations, but also due to non-stationarity, i.e. structural changes occurring when countries pass from one stage of development to another (Höhne and Harnisch 2002, Peterson 2008).

As a short illustration, let us consider the hypothetical case of what would have happened if in the year 2000 China, India, and Russia had adopted a business-as-usual CO_2 target for 2010, and compare the outcome for an absolute and intensity target. To do so, we let the 2010 forecast of the 1999 International Energy Outlook (EIA 1999) define the BAU target, which is then confronted

[96] It is a conventional assumption to let the cost function depend on the nominal amount of abatement. However, though seemingly appropriate for end-of-pipe abatement such as CCS, where high variable costs dominate, it seems less justifiable for other abatement options. E.g. when switching to natural gas or nuclear power, upfront fixed costs make up a significant part, and the achieved abatement will also depend on energy consumption, and thus be related to (uncertain) output. For such abatement options, modeling costs as a function of the percentage reduction with respect to BAU might be preferable. In this case, the minimal ρ from Eq.(5.4) turns out to be higher, as it becomes multiplied by the inverse target intensity. In reality, the cost function probably depends on both the nominal and relative percentage reduction.

with actual values.[97] As Table 5.1 shows, for China both emissions and GDP were grossly underestimated, which would have resulted in an unexpected reduction burden of more than 2GtCO_2 under an absolute target, whereas the originally intended reduction–namely zero–would have been preserved almost perfectly under an intensity target. This is, of course, due to the fact that the forecast errors for CO_2 and GDP are nearly equal for China. However, the figures for India illustrate that this not always so: while GDP was also underestimated, India's emissions were in fact overestimated. The case is similar for Russia, where both were underestimated, but GDP much more than emissions. As a consequence, India and Russia would be facing a small amount of 'hot air' and a modest reduction requirement, respectively, under an absolute target, while they would have received massive amounts of 'hot air' in case of an intensity target. Although 'hot air' might not be perceived as bad as a high unexpected reduction burden, this–admittedly exemplary–illustration shows how the intensity target does not lead to the hoped-for results when forecast errors are not well-correlated.

	1999 IEO forecast error 2010		**Implied 2010 reduction under BAU target**			
	CO_2	*GDP*	*Absolute cap*		*Intensity*	
Country	%	%	[Mio tCO2]	% reduct.	[Mio tCO2]	% reduct.
China	-29%	-30%	2122	29%	-62	-1%
India	4%	-21%	-49	-4%	-433	-32%
Russia	-10%	-42%	187	10%	-1000	-55%

Table 5.1: Implications of a hypothetical business-as-usual target for 2010.

In fact, under such conditions the costs of being wrong could be quite high: the variance may easily double when an intensity target is adopted although the actual value of ρ is approximately zero, as shown by Eq.(5.3). Severe consequences can ensue, e.g. when a country with intensity target suffers from an economic downturn and there is no accompanying drop in emissions; in the face of such a double burden non-compliance could become the preferred option for the country, possibly leading to a destabilization of the entire system. On the other side, the same equation implies that even in the most favorable cases (in terms of parameter values for γ, σ_E, and σ_Y), the reduction of uncertainty is bounded by $\sqrt{1-\rho^2}$, meaning that correlations of ½, 3/5, and ¾ allow *at best* to reduce uncertainty by 13%, 20%, and 34%, respectively.

5.5 Reduction of 'Hot Air'

Another benefit claimed for the intensity target is its presumed ability to reduce the incidence of 'hot air' (Philibert and Pershing 2001), i.e. the unintended over-

[97] For lack of data proxied by the 2010 forecast of the current 2009 issue (EIA 2009).

allocation occurring when a country's baseline emissions turn out to be lower than its target. The undesirable effect of 'hot air' is that it allows selling permits that are not backed by actual abatement.[98] As the following formal analysis shows, the intensity target's capacity to reduce the likelihood of 'hot air' is again contingent on parameter values; namely, the linear correlation ρ between GDP and emission shocks has to be high enough to satisfy Eq.(5.4), the condition which determined whether or not the intensity target lowers reduction uncertainty.[99]

The likelihood for a given emission target T to lead to a 'hot air' allocation is equal to the probability of the uncertain variable E to stay below T. Suppose future emissions E can be represented as $E=E_0 + \varepsilon$, with ε as zero-mean stochastic error term. For an absolute cap $\overline{E}$, the probability of hot air occurrence can then be expressed as

$$\text{Prob}[E < T] = \text{Prob}[\varepsilon < \overline{E} - < E >] = \text{Prob}[\varepsilon < -R_0] \quad , \tag{5.5}$$

which corresponds to the cumulative distribution function of ε, evaluated at the negative expected reduction amount, $-R_0$. For instance, in case of a BAU level target ($<R>= R_0=0$) the likelihood of 'hot air' amounts to 50%. In general, when ε is given by a normal distribution with standard deviation σ_E, the last expression is equal (up to normalization) to the error function.

For an intensity target, on the other side, the probability of 'hot air' occurrence is given by

$$\text{Prob}[E < \bar{\gamma} Y] = \text{Prob}[\varepsilon < \bar{\gamma} < Y > + \bar{\gamma}\eta - < E >] = \text{Prob}[\varepsilon - \bar{\gamma}\eta < -R_0] \quad , \tag{5.6}$$

where future economic output Y is represented as a random variable in the same manner as emissions. In contrast to the absolute target, the probability now depends on the cumulative distribution of the convolution of ε and $\bar{\gamma}\eta$. If ε and η are characterized by a linear correlation ρ, then the term $\varepsilon - \bar{\gamma}\eta$ is again distributed normally, with zero mean and variance $\sigma_E^2 + \bar{\gamma}^2 \sigma_Y^2 - 2\bar{\gamma}\sigma_E\sigma_Y\rho$.

For negative arguments (i.e. a positive $<R>$, corresponding to a target below BAU) the cumulative distribution of a zero mean normal is an increasing function of the variance. Thus, the probability of 'hot air' is larger for the target that exhibits the higher variance. As in the case of reduction uncertainty, the expression for the intensity target Eq.(5.3) is smaller than the corresponding variance σ_E^2 of the absolute target if the condition in Eq.(5.4) is met.[100]

[98] A case in point is Russia's allowance for the Kyoto Protocol's first commitment period.
[99] This result is nicely illustrated by the hypothetical cases of India and Russia shown in Table 5.1.
[100] Note that the condition becomes likelier to hold, the more stringent the envisaged reduction of intensity is; however, the absolute level of probability of hot air then becomes a priori extremely low for both types of targets.

5.6 Compatibility with International Emissions Trading

Parallel to the negotiations on a follow-up agreement to the Kyoto Protocol, a number of national and regional emissions trading systems, e.g. in Europe, the US, and New Zealand, have been installed or are currently emerging (Flachsland et al. 2008). Although absolute targets prevail, some systems contemplate the adoption of intensity targets (Government of Canada 2007, Schmidt et al. 2006). As a consequence, a fragmented regime with one group of countries adopting the former and another group of countries the latter could become reality. The question then arises whether it is generally true that "emissions trading may also be easily accommodated within a dynamic target regime" (IEA 2003). In other words, does emissions trading between countries that are not subject to the same type of emissions constraint lead to an efficient outcome? In fact, the trade of permits at the company level across such independent regional systems–the so-called 'linking'–has lately been described as a promising option (Jaffe and Stavins 2007, Flachsland et al. 2009a). However, before a common permit market is established, the implications of regulatory differences across systems should be carefully assessed.

For a formal analysis, consider a country with an absolute cap $\overline{E}$, and let $C(A)$ denote the convex aggregate cost function for abating an amount A. In autarky, the country faces costs of $C(E_0 - \overline{E})$, where E_0 denote the expected business-as-usual emissions.[101] The government may implement its international obligation by means of a domestic ETS, distributing $Q = \overline{E}$ permits across all emitting agents in its economy. Under perfect market conditions, the resulting equilibrium permit price within the ETS will coincide with the economy's aggregate marginal abatement costs, i.e. $C'(E_0 - \overline{E})$.

In the presence of inter-governmental emissions trading, such as under the Kyoto Protocol, with an expected permit price of p, a cost-minimizing and price-taking government solves

$$\min_{Q} C(E_0 - Q) + p(Q - \overline{E}) \quad , \tag{5.7}$$

implying the standard efficiency condition $C' = p$ and thus $Q^* = E_0 - C'^{inv}(p)$. In other words, domestic abatement is carried out up to the level $A = C'^{inv}(p)$, at which marginal abatement costs reach the permit price level, whereas the remaining reduction gap (or surplus) $Q^* - \overline{E}$ is met by acquiring (or selling) permits from other countries.

If international permit trading is devolved directly to companies, such as would be the case if different ETS were linked, the government simply sets the cap of

[101] For the purpose of this section perfect foresight is assumed, although in reality both E_0 and the function C are not perfectly known.

its domestic ETS at the internationally agreed level, i.e. $Q=\overline{E}$. Firms receive Q in the form of permits, and by minimizing the costs of meeting their reduction gap, will again satisfy the efficiency condition $C' = p$. In fact, whether governments or firms buy permits on the international market makes in principle no difference (assuming competitive behavior). If firms import Π permits, their emissions rise accordingly. Compliance at the country level is ensured as long as actual emissions correspond to the sum of the initial national allocation and the additional permits, i.e. if $E = \overline{E} + \Pi$.

Consider now the case in which the same country has instead adopted an equivalent intensity target $\overline{\gamma}$, defined by

$$\overline{\gamma} = \frac{\overline{E}}{Y(\overline{E})} = \frac{\overline{E}}{Y_0 - C(E_0 - \overline{E})} \quad . \tag{5.8}$$

Without international emissions trade, the regulator allocates $Q = \overline{E}$ permits to the domestic ETS, just as under the absolute target. With Kyoto-style intergovernmental permit trade, the cost minimizing domestic allowance Q^* is determined according to[102]

$$\min_{Q} C[E_0 - Q] + p \cdot (Q - \overline{\gamma}\, Y) \quad \Rightarrow \quad -C'[E_0 - Q^*] + p \cdot \left(1 - \overline{\gamma}\, dY/dQ\right) = 0 \ , \tag{5.9}$$

where the term dY/dQ represents the reduction of economic output (with respect to BAU) implied by the emission constraint Q: $Y(Q) = Y_0 - C(E_0\text{-}Q)$ and thus $dY/dQ = C'$. Substituting back one obtains

$$C'(E_0 - Q^*) = \frac{p}{(1 + p\overline{\gamma})} \quad \Rightarrow \quad Q^* = E_0 - C'^{inv}\left[\frac{p}{(1 + p\overline{\gamma})}\right] \quad . \tag{5.10}$$

Domestic abatement is thus carried out up to the level $C'^{inv}\left[p/(1 + p\overline{\gamma})\right]$, which is *less* than what was found for an absolute cap. Likewise, the price leading to a zero-trade equilibrium is given by $p=C'$ for the absolute target, but $p = C'/(1 - \overline{\gamma}\, C')$–i.e. somewhat higher–for the intensity target.

The interpretation of this result is as follows: acquiring an international permit of one ton of CO_2 allows expanding emissions by just one ton in a country constrained by an absolute target, with an according increase of output. Under an intensity target the acquired permit also allows an initial increase of emissions by one unit, but the resulting increase in output has the 'secondary' effect of also increasing the allowed level of emissions $\overline{\gamma}\, Y$. In other words, the admissible total expansion of output is larger than it would be under an absolute target, and, as a consequence, the regulator of an intensity constrained country

[102] Where brackets are used to emphasize arguments of functions.

is willing to pay more for an emission permit than his counterpart implementing an absolute target.[103]

This characteristic property of the intensity target bears two implications regarding the efficiency and effectiveness of emissions trading between countries with absolute and with intensity targets. To develop an intuition, consider the simple comparison from before, but let there now be two copies of the same country, one with absolute and one with the equivalent intensity target. By definition, both countries have the same emissions level in autarky. Since they are identical, there are no gains-from-trade to be realized, and hence the situation is Pareto optimal. However, if the two countries open up to government-level emissions trading, trade would occur since–as was just shown–their domestic permit price actually differs. More specifically, the intensity constrained country, having the higher price, will buy permits from the other country until the permit price p reaches an equilibrium within the interval $C' < p < C'/(1-\bar{\gamma}C')$. As a consequence, efficiency must break down, since an efficient allocation for two identical countries with convex abatement costs cannot but have the same level of emissions in both countries.

Naturally, permit trade remains mutually beneficial in purely economic terms (otherwise it would not occur), i.e. it raises income in both countries. But it carries a cost in terms of environmental effectiveness: suppose the country with absolute emission cap has sold an amount of Π permits, which are used by the intensity constrained country to expand its output by an amount ΔY. However, compared to the pre-trade state, i.e. $\bar{E}$, the latter's emissions constraint is increased by more than Π, namely by $\Pi + \bar{\gamma}\,\Delta Y$. In other words, the combined total emissions of the two countries experience a net increase of $\bar{\gamma}\,\Delta Y$ due to the distorted emissions trading.

As demonstrated in Appendix 5.10.1 and 5.10.2, these arguments hold even in the completely general case of heterogeneous countries with differently stringent reduction targets: free permit trade between countries with absolute and intensity target always leads to an inefficient international allocation of emissions, and net imports (exports) of permits by intensity constrained countries always lead to an increase (decrease) of total combined emissions.

Would the same effect occur if permit trade was devolved to the company level, as suggested by the idea of directly linking different ETS? In this case a country with a national intensity target would initially issue $Q = \bar{E}$ permits to firms by means of, e.g., grandfathering. Firms then face the same incentive-structure as

[103] These results do not depend on whether the emission policy is implemented by a quantity (cap) or price instrument (tax). The optimal domestic emission tax under an intensity target would be distorted just in the same way as the domestic emission price under a cap. For the intensity target's distortionary effect it also makes no difference whether permit trade takes place during or only directly after the commitment period (ex-post trading), as long as it is anticipated by the regulator.

in the absolute cap case, i.e. domestic abatement A will be carried out until $C'(A) = p$, while for the remaining gap, E_0-Q-A, permits Π will be acquired on the joint ETS market. At the end of the commitment period, the country's compliance with its international obligation will be verified by comparing its intensity-based regular allowance plus acquired permits, i.e.

$$\bar{\gamma} Y + \Pi = \bar{\gamma}(Y_0 - C[E_0 - \bar{E} - \Pi]) + \Pi = \bar{E} + \Pi(1 + \bar{\gamma}\ \widetilde{C}') \ , \tag{5.11}$$

where $\widetilde{C}'$ is the average marginal abatement cost within the interval $[E_0 - \bar{E} - \Pi,\ E_0 - \bar{E}]$, with the actual emissions level, $\bar{E} + \Pi$.[104] Because the former is evidently larger than the later, the regulator has an incentive to allocate $\bar{\gamma}\ \Pi\ \widetilde{C}'$ additional permits within the domestic ETS before the commitment period ends.[105] Thus, the mechanism at work remains the same: by importing permits, the economy expands, and hence increases its regular emission allowance (and vice-versa).

In sum, although both types of targets are equally well equipped to control emissions in autarky, the 'mechanical' differences between the two instruments cause efficiency to break down in the presence of free permit trade between the two systems. Moreover, if the intensity based regime is a net buyer of permits, global emissions are inflated as a consequence of the trading. A possible solution that restores Pareto efficiency, as demonstrated in Appendix 5.10.3, is to subject governments or firms of countries with intensity target to a specific tax τ on traded permits, namely

$$\tau = p\bar{\gamma}/(1 - p\bar{\gamma}) \qquad . \tag{5.12}$$

However, this approach would need the approval of the countries in question; otherwise the group of countries with absolute target would have to implement this solution self-handedly by levying a tax-equivalent tariff.

5.7 Incentive to Decouple Carbon and Economic Output

For developing countries, compatibility with high economic growth is a condition *sine qua non* for engaging in any form of international mitigation effort. Against this backdrop, some authors argue that the intensity target is better suited to accommodate "the need for economic growth" (Herzog et al. 2006), and praise its focus on "decoupling economic growth and emissions growth" (Kim and Baumert

[104] Arguably, one could subtract the term '$- p\ \Pi$' from ex-post output Y, though this would turn Y into a measure of national income rather than GDP, as it is mostly intended. In any case (because $p < \widetilde{C}'$), the implications of the above equation still hold.

[105] The option of issuing additional permits must necessarily be part of an intensity target based ETS, since the main justification for an intensity target is the possibility to allow for more emissions in cases of unforeseen high growth. It would not be necessary for a tax based regulation, but then emissions trade would–if any–be implemented at the government level.

2002). Accordingly, it would provide a stronger incentive for the "development of clean energy technologies" (Herzog et al. 2006) and the "uptake of low-carbon energy and fuels" (ibid.), thereby helping to bring developing countries on a path of "clean growth" (ibid.).

This section discusses whether and how the choice of abatement investment strategies may depend on the type of the adopted emission target. In an exemplary illustration, the relative preference for abatement by intensity-reducing 'decarbonization' versus 'end-of-pipe' (e.g. CCS) is investigated by means of a formal model. Intuitively, an intensity target seems to set a stronger incentive for decoupling growth and emissions because it allows the regulator to focus on the technological transformation of the energy system without having to worry too much about breaching a given absolute emissions ceiling. However, this does not imply that under an absolute cap the incentive to do so is necessarily lower. In fact, it is well established that in a deterministic setting intensity and absolute targets are perfectly equivalent (Ellerman and Sue Wing 2003), meaning that in such circumstances all incentives and technology choices would be identical.[106]

Therefore, a necessary condition for breaking the symmetry between the two types of targets is the presence of uncertainty. With an intensity target, abatement uncertainty may under some conditions be reduced (see Section 4), but would this also lead to a different–namely 'greener'–abatement strategy? Such a question has been addressed by Krysiak (2008), who formally analyzed the influence of uncertainty on the technology choice at the firm level. He considered a linear marginal abatement cost curve, and assumed two different investment options for lowering abatement costs: reducing the curve's slope and reducing its overall level (i.e. the intercept). For his model, he proposed to interpret the first option as end-of-pipe measures like CCS, which provides a flexible abatement with approximately constant–albeit potentially high–marginal costs, and the latter as investments into renewable or nuclear energy options, characterized by higher upfront costs and inelastic–albeit potentially cheaper–abatement supply.

If one generalizes Krysiak's results and interprets the curve as the economy's aggregate abatement cost function, it can be used to evaluate how uncertainty affects the choice between the two options. Namely, with an analogous and straightforward calculation it can be shown that in the cost-minimizing strategy, investments of the second type (renewables, nuclear) only depend on the mean expected abatement, while investments of the first type (like CCS) are in addition positively correlated to the uncertainty on the expected abatement. In other words, CCS-like investments will be higher for the target with higher

[106] This equivalence also implies that absolute and intensity targets are equally suitable to define targets with room for some emission growth, as expected–at least in the near term–to be necessary for developing countries.

uncertainty. This is an intuitive result: a flexible technology with relatively flat marginal costs becomes more valuable the higher the uncertainty about the required abatement. Therefore, within the framework proposed by this model, the intensity target would be a better promoter of a thorough decarbonization of the energy system than the absolute cap only if it actually reduces uncertainty vis-à-vis the latter, i.e. if Eq.(5.4) holds.

However, a significant shortcoming of the previous analysis is that it abstracts from the specific properties of the two targets by merely considering the different levels of abatement uncertainty they imply. For a more specific analysis, their particular coupling to emissions and GDP should be taken explicitly into account. To illustrate this point, let us consider the following formal analysis of the relative employment of the abatement strategies 'reduction of emission intensity' and 'end-of-pipe measures' under intensity and absolute target, where only the first is taken to represent real 'decarbonization'.

Specifically, let the total costs for lowering the economy's BAU emission intensity γ by a percentage s be given by the convex function *C[s]*, while constant marginal costs x are assumed for the end-of-pipe abatement. The former is a common assumption (e.g. Nordhaus 1993) justified, e.g., by the need to use ever less suitable sites for renewable energy production (wind, solar) and the associated increasing integration and storage costs. The latter is a simplifying assumption, which would be fully valid only if x is interpreted as the price of an emission permit on the international market.[107] To a lesser extent, it can also be viewed as a representation of CCS, which–in comparison to renewable or nuclear energy–is characterized by relatively high operational costs, provoking a switch-off if the price of carbon falls below a certain threshold or would be suspended completely.[108]

In formal terms, total abatement costs for a given emissions target T can then be expressed as (*E[s]* denoting emission as function of the intensity parameter s)

$$TC[T] = x\big(E[s] - T\big) + C[s] = x\big(Y\,\gamma\,(1-s) - T\big) + C[s] = x\big(E\,(1-s) - T\big) + C[s] \quad (5.13)$$

where the target T is equal to $\overline{E}$ for an absolute and $\bar{\gamma}\,Y$ for an (equivalent) intensity target. For a regulator with risk aversion, here incorporated through a parameter $\lambda>0$ the optimal choice for s may be determined by

$$\min_{S} < TC > + \lambda\,\sigma_{TC} \quad . \qquad (5.14)$$

The average costs are the same for both targets, but the uncertainty of costs (σ_{TC}) depends on the abatement uncertainty, which is generally not the same.

[107] Within this interpretation, the present analysis would asses in how far the intensity sets a stronger incentive for domestic abatement (versus buying one's way out) than an absolute target.
[108] According to study by McKinsey (2008), total costs for CCS in 2030 could be between 30€ and 45€ per ton, of which around 50% are variable costs that could be saved by switching-off the CCS process.

Namely, computing the standard deviation of Eq.(5.13) shows that $\sigma_{TC}=x\sigma_A$, where σ_A is the target-specific abatement uncertainty, which depends on the degree of intensity reduction *s*. As shown in Appendix 5.10.4, reducing the emission intensity γ produces a stronger reduction of cost uncertainty under an absolute than under an intensity target, which leads to the result that the optimal reduction of intensity is in fact higher under an absolute target.

The underlying intuition is the following: reducing the emission intensity by a percentage *s* leads to a decrease in the variability of emissions by a factor *(1-s)*, which has an unambiguously positive (i.e. decreasing) effect on the abatement and (thus) cost-uncertainty under a cap. However, under an intensity target the abatement uncertainty comprises (see Eq.(5.3)) two additional terms, which dampen the effect of a reduced emission variability. This is due to the specific mechanics of the intensity target, which performs best if the variability of emissions is not too low, as can be seen by considering the limit case with constant known emissions ($\sigma_E=0$): an absolute cap then implies zero abatement uncertainty ($\sigma_{A\_Cap}=0$), whereas uncertainty would remain finite ($\sigma_{A\_Int}=\bar{\gamma}\,\sigma_Y$) for the intensity target, due to its coupling to uncertain economic output.

In sum, it was shown that in the presence of uncertainty, the incentive to implement one or the other abatement measure may indeed differ for the two types of emission targets. However, the intuitive idea that intensity targets generally provide a stronger incentive for the decoupling of growth and emissions was rebutted exemplarily in an analysis of intensity-oriented versus end-of-pipe abatement, where the incentive to pursue the first was shown to be stronger for the absolute target. However, due to its stylized character the analysis should be understood as a starting point for further investigations on whether intensity and absolute targets could–in models with different sectors and abatement technologies–lead to different domestic outcomes in terms of technology choices. All the more so since the existing arguments with regard to the intensity target's incentive towards 'decoupling' have been based on an intuitive and therefore rather vague reasoning, without giving formal definitions (e.g. meaning of 'clean growth') that would have allowed a more rigorous assessment of their merit.

5.8 A Substitute for Banking and Borrowing?

An intuitive appeal of the intensity target is its 'smoothing over time' effect: a country can retain a higher share of emissions in higher-than-expected growth periods, since (supposedly) these will be offset by lower emission allowances in subsequent lower-than-expected growth periods. Based on this idea, Sue Wing et al. (2009) compare intensity and absolute targets with respect to their "temporal stability"–i.e. volatility of abatement over time–and find a higher stability for the intensity target if, again, the condition of Eq.(5.4) is met. A natural

extension of their analysis is the question of whether the intensity target could reduce volatility to the extent of becoming a viable substitute for a banking and borrowing ('banking' for short) scheme. The latter is known to enhance dynamic efficiency (Bosetti et al. 2009), but policy makers tend to be cautious especially with unfettered borrowing, fearing a destabilization of the whole system when uncontrollable amounts of debt accumulate (Boemare and Quirion 2002). Hence, the question of this section is whether the same level of abatement volatility of an absolute target with banking and borrowing can be reached by just employing a plain intensity target.

To derive how banking reduces fluctuations under an absolute target, consider a two-period model, where emissions of period one and two are assumed to behave according to

$$\begin{aligned} E_1 &= E_0 + \varepsilon_1 \\ E_2\big|_{E_1} &= E_0 + \beta\left(E_1 - E_0\right) + \varepsilon_2\sqrt{1-\beta^2} \end{aligned} \tag{5.15}$$

Here, $.|_E$ denotes the conditional value operator, and the ε_i are independent and identically distributed random variables with zero mean and standard deviation σ_E, while β is a parameter with $|\beta|<1$. This set-up conveniently implies $\sigma_{E1}=\sigma_{E2}=\sigma_E$ for the individual standard deviations, and a temporal correlation of β between E_1 and E_2. The latter can be used to capture the influence of business-cycle dynamics on emissions, e.g., with a negative value for β higher-than-expected emissions in a first commitment period will likely be followed by lower-than-expected emissions in the next period.[109]

Under an absolute cap $\overline{E} < E_0$, the optimal amount of banking B–once first period emissions E_1 have realized–can be derived by requiring the expected period two abatement effort A_2 to be equal to the one of the first period[110]

$$< A_2 >\big|_{E_1} = < E_2 >\big|_{E_1} - \overline{E} + B \overset{!}{=} A_1 = E_1 - \overline{E} - B \quad . \tag{5.16}$$

This yields the following expression for the optimal amount of banking in period one: $B = \frac{1}{2}\left(E_1 - < E_2 >\big|_{E_1}\right) = \frac{1}{2}(E_1 - E_0)(1-\beta)$. (5.17)

The result follows intuition: with perfect temporal correlation ($\beta=1$), emissions are a priori constant over time, leaving no scope for banking. In the opposite case ($\beta=-1$), the entire period one deviation from the expected value E_0 is banked, as it is always followed by an equal–but opposite direction–deviation in the next

[109] Implicitly, such an argument is based on the assumption that countries adopt reduction obligations that–unlike in the Kyoto Protocol–span over more than one commitment period. There is indeed a strong case to do so, e.g. to stabilize long-term expectations of private investors (Blyth et al. 2007).

[110] As implied by the efficiency condition of constant marginal costs, if the abatement cost function is time invariant.

period. Without any temporal correlation ($\beta=0$), half of the difference with respect to the expected value is banked.

When this strategy is pursued, the resulting abatement volatility for the first and second period can be computed (shown in Appendix 5.10.5) to

$$\sigma_{A1} = \sigma_E \left(\frac{1+\beta}{2} \right)$$
$$\sigma_{A2} = \frac{\sigma_E}{2} \sqrt{3(1+\beta)(5/3-\beta)} \tag{5.18}$$

As expected, no 'smoothing' effect would occur for a temporal correlation of one, whereas in the opposite case ($\beta=-1$) volatility of abatement could be eliminated completely, i.e. $\sigma_{A1}=\sigma_{A2}=0$. With negligible temporal correlation ($\beta=0$), it is still reduced by 50% vis-à-vis the no-banking case in the first period, but only at the cost of an increase of 12% in the second period. The latter, however, is mostly due to the short time horizon, which necessitates the settling of the 'account' in period two; this effect would thus be (much) smaller for longer-term targets with several commitment periods.

Therefore, banking always decreases the abatement volatility of the first period, whereas in the second period this is only the case if there is a cyclical behavior with sufficiently negative temporal correlation ($\beta<-1/3$). The net effect, i.e. the sum of the change over both periods, is always to reduce volatility. For instance, with a weakly cyclical behavior of $\beta=-0.1$ one obtains a change in variability of -55% and +9% for the first and second period, respectively, corresponding to an average net effect of –23%.

This can now be compared to the level of volatility that is achieved with a plain intensity target. Without banking, cyclical behavior must not be taken into account, and the average reduction with respect to an absolute targets thus follows Eq.(5.3). Accordingly, in order for the intensity target to reduce volatility by 50%, a very high correlation between emission and GDP shocks of at least $\rho=0.87$ would be needed, and–in the most favorable case with regard to the parameter values of $\bar{\gamma}\,\sigma_Y / \sigma_E$ –at least $\rho=0.6$ for an average reduction of 20%.

With the latter, the reduction would be comparable in size to the effect of banking under an absolute target, and since the value $\rho=0.6$ is not completely implausible, the intensity target can indeed be seen as a possibility to substitute banking and borrowing to some extent – conditional on suitable parameter values and in reference to a very short two-period framework. Said differently, an intensity target with proven and significant ability to reduce uncertainty lowers the need to employ banking for an intertemporal smoothing of the abatement effort. Naturally, the converse also holds: when banking provisions are already put in place, the added value of an intensity target becomes much lower.

But as long as the intensity target's effect is itself somewhat undetermined, i.e. whether and by how much it decreases uncertainty is only imperfectly known due to uncertain parameter values, an absolute cap with banking provisions–even limited ones–appears preferable, since it always leads to a net reduction of abatement volatility. Moreover, the intensity target can never substitute explicit banking when it comes to setting an incentive for early abatement, a policy objective in its own right (Bosetti et al. 2009).

5.9 Conclusion

Intensity targets are often portrayed as an attractive alternative to Kyoto-style absolute emission caps, especially for developing countries. Amongst others, China recently announced that it intends to implement such a target.[111] In this chapter, five policy relevant properties that could–and have been–associated with the intensity target are discussed and formally assessed by means of simple analytical models.

First, the conditions under which an intensity target lowers cost-uncertainty–with reduction uncertainty taken as proxy–were revisited. In autarky, this is only the case when parameter values fulfill conditions that do not self-evidently hold nor are easily verifiable by empirical analysis. Moreover, even in favorable cases would the potential gain–in terms of uncertainty reduction–likely remain modest. Last but not least, any potential decrease in uncertainty becomes less significant when considering that cost-uncertainty can be reduced to some extent also for absolute targets by participation in international emissions trading.

Second, whether or not an intensity target lowers the incidence of hot air is shown to depend on the same formal condition as the reduction of cost-uncertainty. Therefore, the same doubts about the outcome–due to uncertain parameter estimates–persist.

Third, an analysis of emissions trading between countries with absolute and intensity target was carried out. The relevance of this question is underpinned by the currently observable tendency towards fragmentation in international climate policy (Victor 2007). Within a two-country model, the intensity target is shown to create an upward distortion in the permit price, i.e. the price becomes higher than actual marginal abatement costs. Two implications arise: first, due to the 'mechanical' differences between the two targets, efficiency breaks down if permits are traded freely between the two systems, leading to allocations not satisfying Pareto efficiency. Second, emissions trading between the two systems increases (decreases) global emissions whenever the country with intensity target is a net buyer (seller) of permits.

[111] See also the article "U.S. and China to Go to Talks With Emissions Targets" in the New York Times, appeared online on 26 September 2009.

Forth, it was argued and shown exemplarily that the incentive for a lasting transformation of the energy system by means of low-emission technology ('decarbonization') is not necessarily stronger under an intensity than under an absolute target. In the chosen analytical model this is due to the fact that a reduction of emission intensity also implies a reduction of emission uncertainty, which always has a positive impact under an absolute cap, but an ambiguous one under the intensity target. In fact, the latter–in order to work well–does not require the lowest possible emissions uncertainty, but one that is well-balanced with the uncertainty of output.

Fifth, the intensity target's potential to act as a substitute for banking and borrowing was assessed. The possibility of doing so is suggested by the way it adjusts the emission allowance to unexpected high or low growth, similar to a buffer-mechanism against business-cycle induced fluctuations. It was shown that banking and borrowing under an absolute cap unambiguously reduces abatement volatility, especially when emission targets extend over multiple commitment periods. Intensity targets without banking can also decrease volatility, but the magnitude will even in favorable cases (in terms of parameters) not exceed the lower end of what can be achieved by borrowing and banking.

In sum, three out of five potential benefits of the intensity target are linked to uncertainty and were found to be contingent upon the values of parameters, in particular the correlation ρ between shocks in future emissions and future economic output. There is little doubt that the stability and predictability of abatement commitments has a significant influence on the acceptability and stringency of emission targets proposed to developing countries (IEA 2003) – e.g., in a world without uncertainty a BAU target on emissions would represent a no-regret option. However, as the analysis in this chapter has shown, even though the intensity target can reduce uncertainty under some conditions and for some countries, the contingency of its performance on the new and difficult to estimate parameter ρ (among others) introduces new uncertainty, which in a real-world application might turn the potential benefit into a liability.

This is further aggravated when taking into account alternative measures that can be implemented under absolute caps–like international emission trading and banking/borrowing provisions–which are guaranteed to reduce uncertainty and at the same time come without the potential pitfalls of the intensity target. To increase developing countries' incentive to join international mitigation efforts, they could be endowed with–at least initially–generous emission allocations, so as to ensure they become permit sellers. Theoretically, such measures are feasible also under an intensity target – but in this case their implementation would be less straightforward and could require additional

provisions to ensure efficiency, as the analysis of international emissions trading has shown.[112]

Finally, a robust advantage of the intensity target in terms of the generated incentives for decarbonization could not be verified. Although intuitively appealing, the actual incentive for adopting one or the other abatement strategy may depend on techno-economic details, not warranting a general conclusion that lowering the emissions intensity by means such as renewable energy and fuel-switching is always more appealing under an intensity than under an absolute target. Admittedly, the analysis presented here represents only the first step, while for a definite answer more research on the specific cost-structures and macroeconomic links of the various abatement technologies is needed.[113] However, for the time being absolute caps represent the more robust target choice, not least because of their simplicity and high transparency.

5.10 Appendix

5.10.1 Proof that emissions trading between a country with absolute and one with intensity target always leads to an inefficient allocation of emissions.

For an arbitrary pair of countries, with subscript 'A' for absolute target and 'I' for intensity constrained, an efficient after-trade emission allocation requires the equalization of marginal abatement costs, i.e.

$$C_A^{'}[E_{A0} - \overline{E} + \Pi] = C_I^{'}[E_{I0} - \overline{\gamma}\, Y - \Pi] \quad . \tag{5.A1}$$

Following the cost-minimization rationale of Eq.(5.7) and Eq.(5.9), the implicit permit demand functions of each regulator (assuming 'Kyoto-style' trade at government level), for a given permit price p, are, respectively

$$-C_A^{'}[E_{A0} - Q_A^{*}] + p = 0 \tag{5.A2}$$

$$-C_I^{'}[E_{I0} - Q_I^{*}] + p \cdot \left(1 - \overline{\gamma}\, dY_I / dQ_I\right) = 0 \tag{5.A3}$$

Note that the arguments (in brackets) correspond to the amount of net domestic abatement, just as in Eq.(5.A1). Imposing market clearance by equating the price p yields

[112] Other 'technicalities' potentially complicating the implementation of an intensity target include the question of MER vs. PPP measurement of output, and the fact that with an intensity target the actual emission allowance is only known with a considerable time delay, when official GDP statistics are released (see Herzog et al. 2006).

[113] For a different aspect, however, the incentive structure of the intensity target could be questioned: namely, it could be used to justify an unduly low abatement effort, when political leaders cling to an upwardly biased GDP expectation (or ambition), which–for them–implies a generous emissions allowance and, consequently, less need for abatement.

$$C_A^{'}[E_{A0} - Q_A^*] = \frac{C_I^{'}[E_{I0} - Q_I^*]}{\left(1 - \bar{\gamma}\, dY_I / dQ_I\right)} \quad , \tag{5.A4}$$

which evidently contradicts the efficiency condition given in Eq.(5.A1) since $C_A^{'} > C_I^{'}$. □

In other words, the last equation shows that in equilibrium marginal abatement costs in the country with absolute target are too high with respect to the efficient level.

5.10.2 Proof that emission trading between an arbitrary pair of countries with different types of targets leads to an increase in combined emissions if the country with absolute target is a net seller and to a decrease if it is a net buyer of permits.

Suppose in the trade equilibrium the country with absolute cap sells an amount (positive or negative) of Π permits to the country with intensity target. In the pre-trade state, the latter's emissions constraint was implemented by means of an ETS with a total allowance volume Q, satisfying

$$Q = \bar{\gamma}\ Y(Q) \quad . \tag{5.A5}$$

After trading the Π permits, the regulator adjusts the number of allowances in his domestic ETS, to be in line with the new constraint

$$Q + \Delta Q = \bar{\gamma}\, Y(Q + \Delta Q) + \Pi \quad . \tag{5.A6}$$

For the combined emissions to stay constant, the change ΔQ must coincide with Π. However, assuming positive abatement costs and focusing on the case of permit import ($\Pi>0$), one immediately obtains

$$\bar{\gamma}\, Y(Q + \Delta Q) + \Pi > \bar{\gamma}\, Y(Q) + \Pi = Q + \Pi \quad \Rightarrow \quad \Delta Q > \Pi \quad , \tag{5.A7}$$

and the case $\Pi<0 \Rightarrow \Delta Q<\Pi$ accordingly. □

5.10.3 Application of Tax as Corrective Policy Measure

Since the distorted permit price lies at the heart of the trade incompatibility between regions with absolute and intensity based targets, it seems natural to impose a tax on permit trade with the intensity constrained country. To reflect the true marginal productivity of emissions, an *ad valorem* tax τ of $\tau = p\bar{\gamma}/(1 - p\bar{\gamma})$ on traded permits must be accepted by the country with the intensity target or, alternatively, imposed on it from the outside in form of a tariff (within government-level AAU trade à la Kyoto). To see this, consider again how the government in the intensity-constrained country determines its

demand for international permits by minimizing total compliance costs as expressed in Eq.(5.9), now modified by the tax τ

$$\min_{Q} C[E_0 - Q] + p \cdot (1+\tau)\ (Q - \bar{\gamma}\, Y) \ \Rightarrow\ p \cdot (1+\tau)\ \left(1 - \bar{\gamma}\, dY/dQ\right) = C'[E_0 - Q] \,. \quad (5.A8)$$

Using $Y(Q) = Y_0 - C[E_0 - Q]$ and the above definition for τ, one immediately obtains $p = C'$, i.e. the desired efficiency condition of price = marginal abatement costs. □

In effect, the tax modifies the permit price p by letting it appear somewhat higher.

5.10.4 Optimal Reduction *s* of Emission Intensity under Absolute and Intensity Target

Computing the standard deviation of Eq.(5.13) is straightforward for the absolute cap and yields

$$\sigma_{TC\_Cap} = x\,(1-s)\,\sigma_E \quad , \qquad (5.A9)$$

where σ_E is the standard deviation of BAU emissions. With average costs of $< TC >= x\left(E_0\,(1-s) - \bar{E}\right) + C[s]$ for both targets, substituting back in Eq.(5.14) and taking the first derivative yields a simple first-order condition for the optimal percentage reduction s under the absolute target

$$C'[s] = x\left(E_0 + \lambda\sigma_E\right) \ . \qquad (5.A10)$$

Since the cost function C is convex, this determines a unique value for s. In case of the intensity target, average costs do not change, but their standard deviation becomes

$$\sigma_{TC\_Int} = x\sqrt{(1-s)^2\ \sigma_E^2 + \bar{\gamma}^2\sigma_Y^2 - 2\bar{\gamma}(1-s)\rho\sigma_E\sigma_Y} = x\sigma_{A\_Int} \quad . \qquad (5.A11)$$

For the corresponding first-order condition of the objective function one obtains

$$C'[s] = x\left(E_0 + \lambda\sigma_E\,\frac{((1-s)\sigma_E - \bar{\gamma}\rho\sigma_Y)}{\sigma_{A\_Int}}\right) \quad . \qquad (5.A12)$$

For any s within the unit interval, and any $|\rho|<1$, the right hand side of this equation is always smaller than the corresponding value for the absolute target, Eq.(5.A10). To see this, consider the fraction part from the last equation, written as a square root

$$\sqrt{\frac{((1-s)\sigma_E - \bar{\gamma}\rho\sigma_Y)^2}{\sigma_{A\_Int}^2}} = \sqrt{\frac{(1-s)^2\sigma_E^2 + \rho^2\bar{\gamma}^2\sigma_Y^2 - 2\bar{\gamma}(1-s)\rho\sigma_Y\sigma_E}{(1-s)^2\sigma_E^2 + \bar{\gamma}^2\sigma_Y^2 - 2\bar{\gamma}(1-s)\rho\sigma_E\sigma_Y}} < 1\,, \qquad (5.A13)$$

where the expression for abatement uncertainty σ_{A_Int} from Eq.(5.A11) was used. The numerator in Eq.(5.A12) can become negative, but in this case the claim still holds.

If the right-hand-side of Eq.(5.A12) is always smaller than the one of Eq.(5.A10), it follows by the convexity of C that the optimal s under an intensity target must always be lower than under an absolute cap. The potentially negative numerator in Eq.(5.A12) corresponds to the case in which an increase of s has a counterproductive effect, i.e. it leads to an increase in cost uncertainty. Note that this will always be the case for sufficiently high s.

5.10.5 Computation of the volatility of abatement for period one and two with an absolute cap $\overline{E}$ and optimal banking B.

Given the definition of emissions in period one and two from Eq.(5.15), and the expression for the optimal banking in Eq.(5.17), it follows for the average abatement in the first period

$$< A_1 >=< E_1 > -Q- < B >= E_0 - Q \equiv A_0 \quad , \tag{5.A14}$$

while the average for the squared abatement is

$$\begin{aligned} &< A_1^2 >=< (E_1 - Q - B)^2 >=< (A_0 + \varepsilon_1 - B)^2 >= \\ &= < A_0^2 > + < \varepsilon_1^2 > + \frac{(1-\beta)^2}{4} < \varepsilon_1^2 > +2A_0 < \varepsilon_1 > -2A_0 < B > - < \varepsilon_1(\varepsilon_1)(1-\beta) > \\ &= A_0^2 + \left(1 + \frac{(1-\beta)^2}{4} - (1-\beta)\right)\sigma_E^2 = A_0^2 + (1+\beta)^2 \frac{\sigma_E^2}{4} \end{aligned} \tag{5.A15}$$

This gives the desired result for the first period standard deviation in the actual abatement:

$$\sigma_{A1} = \sigma_E \left(\frac{1+\beta}{2}\right) \quad . \tag{5.A16}$$

The average abatement in the second period is again A_0

$$< A_2 >=< E_2 > -Q+ < B >= E_0 - Q = A_0 \quad . \tag{5.A17}$$

For the average of the squared abatement in period two one computes

$$\begin{aligned} &< A_2^2 >=< (E_2 - Q + B)^2 >= < E_2^2 > +Q^2 + < B^2 > -2QE_0 + 2 < BE_2 > \\ &= \sigma_E^2 + A_0^2 + \frac{1}{4}(1-\beta)^2\sigma_E^2 + (1-\beta) < \varepsilon_1 \left(E_0 + \beta\,\varepsilon_1 + \varepsilon_2\sqrt{1-\beta^2}\right) > \\ &= \sigma_E^2 + A_0^2 + \frac{1}{4}(1-\beta)^2\sigma_E^2 + \beta(1-\beta)\sigma_E^2 = A_0^2 + \frac{\sigma_E^2}{4}\left(5 + 2\beta - 3\beta^2\right) \end{aligned} \tag{5.A18}$$

which allows to obtain the desired expression for the standard deviation

$$\sigma_{A2} = \frac{\sigma_E}{2}\sqrt{5 + 2\beta - 3\beta^2} = \frac{\sigma_E}{2}\sqrt{3(1+\beta)(5/3-\beta)} \quad . \tag{5.A19}$$

Chapter 6

Do Intensity Targets Control Uncertainty Better than Quotas? Conditions, Calibrations and Caveats[114]

6.1 Introduction

With the entry into force of the Kyoto Protocol, the design of the climate regime beyond 2012 is now a central issue on the international negotiation agenda. A lively debate has emerged on the form that the future regime should take to facilitate the participation of the U.S. and, in the medium term, of major emitters among developing countries (see, e.g., Bodansky 2004 and Aldy et al. 2003 for reviews).

The 'acceptability' of a regime obviously depends on the global mitigation effort that is requested, and on the way this effort is shared among parties. In the case of climate change, however, this problem is compounded by the fact that decisions are made "in a sea of uncertainty" (Lave 1991): future business-as-usual (BAU) emissions are very uncertain, and so are current—let alone future—costs of mitigating greenhouse gas (GHG) emissions.

No regime will eliminate uncertainty altogether. However, different instruments (e.g., caps, coordinated taxes or intensity targets) will allocate uncertainty very differently among the key variables that parties focus on when negotiating future climate policies. For example, a quota system implies with near certainty that a predetermined level of emissions is not exceeded,[115] but the costs of abatement (whether measured at the margin, globally, or as a share of GDP) are very uncertain. Conversely, a coordinated tax system would provide certainty as to the marginal cost of abatement, but would leave ex post emissions or total costs uncertain.

The objective of this chapter is to examine how different policy instruments distribute uncertainty to key variables for decision-makers, including marginal costs of abatement (the price of carbon), total costs of abatement, and effective emissions, when future GDP, BAU emissions and marginal abatement costs are uncertain. We focus on two main instruments, absolute quotas and intensity

[114] Chapter based on the homonymous article by Marschinski and Lecocq published as *World Bank Policy Research Working Paper* 4033 (2006), and presented at the 2006 World Congress of Environmental and Resource Economists in Kyoto. With two authors, the text uses the plural 'we'.
[115] Barring non-compliance of course.

targets, i.e., emissions quotas indexed on economic output. This choice is motivated by the fact that intensity targets have often been proposed as an alternative to the continuation of the current absolute quota approach embedded in the Kyoto Protocol, notably on the grounds that they would reduce uncertainty.

Since various forms of intensity targets have been proposed in the literature and in policy circles—e.g., linear dependence of the emissions ceiling on GDP by the US administration,[116] or square-root dependence by Argentina[117]—, we consider in this study both a linear intensity target, in which the quota depends linearly on GDP, and a 'general' intensity target with a power-law indexing.

The chapter is organized as follows. After reviewing the literature (Section 6.2), we build a simple but general model of the uncertainties associated with BAU emissions, future GDP and future abatement costs (Section 6.3). On this basis, we derive explicit conditions under which intensity targets reduce uncertainty on key policy variables—namely effective emissions, reduction effort, marginal costs, and total costs relative to GDP—with respect to quotas (Section 6.4). We then estimate ranges of values for the parameters of our model (Section 6.5). On this basis, we discuss how, in practice, different instruments compare with regard to uncertainty (Section 6.6). Section 6.7 concludes.

6.2 Literature Review

Two related strands of literature compare the performances of economic instruments under uncertainty. One stems from Martin Weitzman's (1974) paper on "Prices vs. Quantities". Here, 'performance' is measured in terms of the welfare implications of each instrument, given assumptions about the marginal costs of abatement, about the marginal benefits of depollution, and about the uncertainty surrounding these costs and benefits. Pizer (1999) and Newell and Pizer (2003) apply this approach to the problem of climate change and show that, in the short run at least, a tax dominates a cap approach because the slope of the marginal damage curve is likely to be flat relative to the slope of the marginal abatement cost curve. Using the same approach, Quirion (2005) finds that (linear) intensity targets are dominated by either tax or fixed quota approaches for a wide range of parameters—even though in his model there is no uncertainty on future GDP. Quirion also points out that the result of the comparison may depend on whether abatement costs depend on the absolute amount of abatement, or on the percentage of abatement relative to the baseline.

[116] In February 2002, the U.S. government announced a plan to reduce national greenhouse gas emissions relative to GDP by 18% by 2012 compared with 2002 (http://www.whitehouse.gov/news/releases/2002/02/climatechange.html).

[117] The Government of Argentina proposed in 1998 to adopt an intensity target such that the quota would be a function of the square root of GDP (Barros and Grand 2002).

The above approach is comprehensive because the performance indicator is welfare. However, it requires detailed knowledge about the shape of the damage function, which remains highly controversial (Ambrosi et al. 2003). In addition, it does not provide decision-makers with information about the way different economic instruments reduce or increase the uncertainty on key decision variables, such as effective (ex post) emissions, marginal abatement costs (the price of carbon), or total costs. For this reason a second—and more recent—strand of literature analyzes how the choice of a tax, a quota, or an intensity target impacts on the variance of these variables. The papers in this group differ in the way they model uncertainty on input variables (future GDP, future baseline emissions, etc.), and in the policy variables they analyze.

The idea that intensity targets would reduce uncertainty on abatement costs relative to a quota system seems rather intuitive, and is often mentioned among the arguments in support of the adoption of such an instrument. For example, Frankel (1999) argues that intensity targets will, among others, "moderate the effects of uncertainty". Kim and Baumert (2002) suggest that intensity targets could "reduce economic uncertainty". Similarly, Strachan (2007) finds that "using GHG intensities reduces baseline uncertainty". The first detailed discussion of this argument is, to our knowledge, provided by Höhne and Harnisch (2002), who compare intensity targets and caps with regard to the amount of emissions that is abated relative to the baseline—a proxy for abatement costs. They find that a general intensity target dominates a cap when the elasticity of emissions with regard to GDP is high enough, and superior to 0.5 in the case of a linear intensity target. They note, however, that the elasticity of emissions with regard to GDP is difficult to estimate from historical data.

In a broad paper aimed at exploring the negotiation spaces provided by various policy instruments in a multi-region model, Jotzo and Pezzey (2004) provide—in passing—the first analytical treatment of the performance of a general intensity target under uncertainty, and derive an optimal calibration that depends on the stringency of the reduction target and the strength of the GDP-emissions nexus. In their model, the marginal abatement cost functions are assumed certain and linear in the abatement level. The level of future business-as-usual GDP and the emissions intensity of GDP are independent random variables. In a subsequent paper (Jotzo and Pezzey 2007), the authors derive an explicit expression for the variance of the required abatement effort and show that, with a set of parameters calibrated on historical time series, a linear intensity target does not necessarily dominate a quota, but that an optimally indexed general intensity target can always reduce the variance of marginal abatement costs relative to a cap.

Sue Wing et al. (2009) derive an explicit analytical condition under which a general intensity target yields a lower variance of the expected abatement effort

than a cap. In their model, both BAU emissions and future GDP are random variables. They find that a linear intensity target is preferred to a cap unless the correlation between emissions and GDP is very low, or the uncertainty about future GDP is much larger than the uncertainty about future emissions. They also find that a partial intensity target, defined as a weighted average of a cap and an intensity target, can always outperform a cap when the weights are set correctly. Testing their results empirically, they suggest that intensity targets are clearly preferred to caps for developing countries, while the result is more ambiguous for developed countries.

Finally, Kolstad (2005) develops a model where both abatement costs and output are uncertain. Within his framework, he shows that under a linear intensity target, total costs of abatement relative to GDP are only sensitive to the uncertainty on abatement costs, and not to the uncertainty on output. This result, however, rests on the assumption made in the paper that abatement costs depend only on output and on emissions intensity, and not on the level of emissions *per se*.

The present study is attached to the second strand of literature. It adds to this literature in three ways. First, it models abatement costs in a very general way, and explicitly represents the uncertainty on abatement costs as a separate source of uncertainty. Since abating greenhouse gas emissions has virtually never been experienced before, uncertainty on abatement costs is very large (Hourcade et al. 2001), and plays a prominent role in the public debate on climate policies. From an analytical perspective, introducing uncertainty on abatement costs allows us to address two questions raised in the literature: (i) whether uncertainty on marginal abatement costs can indeed be proxied by the uncertainty on the reduction effort, and (ii), following Quirion (2005), whether the fact that abatement costs depend on the absolute level of abatement, on the relative level of abatement, or on some combination thereof, matters for the relative performances of intensity targets and quotas.

Second, our study provides an explicit comparison of the 'performance' of a cap and a general intensity target for four policy relevant variables: effective (*ex post*) level of emissions, abatement effort, marginal cost of abatement (the price of carbon), and total costs of abatement relative to GDP. This point is important because different stakeholders will likely relate differently to these variables. For example, environmental NGOs might be more sensitive to the effective level of emissions, industries might look carefully at the price of carbon, while governments may be particularly interested in the total costs of abatement relative to GDP. Finding common ground on climate policies between stakeholders thus requires considering all these variables.

Third, our study is the first to explicitly take into account the risk that BAU emissions may be below the emissions ceiling if the target (quota or intensity) is not too strict. This risk is not purely theoretical, as exemplified by the amount of

'hot air' in Russia and other transition economies under the Kyoto Protocol. In addition, a compromise with developing countries might well involve targets that are not too far off projected BAU emissions, at least initially. In the analytical part, we need to make the assumption that the target is stringent enough so that this risk can be considered negligible. But in the numerical computations, we explicitly go back to the 'full' model, and assess the validity of our analytical results.

6.3 Model Description

6.3.1 Definitions: Quota, Linear Intensity Target, and General Intensity Target

We assume a unique region, and compare three possible climate policy instruments for a future 'commitment period' of arbitrary but fixed and finite length: an emissions quota, a linear intensity target, and a general intensity target. Let E be the expected emissions of the region in the BAU scenario, and $\overline{E}$ be the effective (i.e., after abatement) emissions during the same period. If the region adopts an *emissions quota* Q, its effective emissions $\overline{E}$ are constrained as follows:

$$\overline{E} = \begin{cases} Q & \text{if } Q \leq E \\ E & \text{otherwise} \end{cases} . \tag{6.1}$$

Let Y be the economic output during the commitment period. An intensity target is defined as an emission quota indexed on Y. As noted above, several indexation methods have been proposed. In this chapter, we consider two variants. First, we consider a *linear intensity target* (LIT) such that, if q is the target GHG intensity (in volumes of emissions per unit of output), effective emissions $\overline{E}$ are constrained as follows:

$$\overline{E} = \begin{cases} qY & \text{if } q \leq E/Y \\ E & \text{otherwise} \end{cases} . \tag{6.2}$$

In addition, we consider a *general intensity target* (GIT) in which the relationship between the emissions quota and GDP is given by a power-law:

$$\overline{E} = \begin{cases} qY^m & \text{if } q \leq E/Y^m \\ E & \text{otherwise} \end{cases} . \tag{6.3}$$

A GIT with m=1 is equivalent to a linear intensity target, and a GIT with m=0 is equivalent to a quota.[118]

[118] Ellerman and Sue Wing (2003), and subsequently Jotzo and Pezzey (2004) and Sue Wing et al. (2009) consider a slightly different but essentially equivalent form of general intensity target, where the emissions target has a fixed part and a variable part that depends on future GDP (using our notations, $\overline{E} = (1-m)Q + mqY$.)

If future BAU emissions (E), future output (Y), and future costs of abatement were known with certainty, the implications of each instrument for all policy variables could be perfectly predicted *ex ante*. In particular, for any given emissions target $\overline{E}^*$, there would be a unique level of quota ($Q^* = \overline{E}^*$), and a unique level of intensity target ($q^* = \overline{E}^* / Y^m$) that would guarantee that the target is reached. In reality, future BAU emissions (E), future output (Y), and future costs of abatement are uncertain. But Q^* and q^* will be used as a benchmark throughout the text. Precisely, when comparing intensity targets with quotas, we will use an objective $q^*=Q^*/\langle Y\rangle^m$, so that the two instruments would lead to the same level of emissions in the certainty case ($\langle\cdot\rangle$ denotes the expected value operator).

6.3.2 Modelling Uncertainty on GDP and Emissions

Future BAU emissions and future output are not known with certainty, and there is no agreed-upon probability distribution for these variables. Many sets of projections are available in the literature for both variables. But in its Special Report on Emissions Scenarios (SRES) (Nakicenovic and Swart 2000), the Intergovernmental Panel on Climate Change (IPCC) has resisted to attach probabilities to these scenarios. To our knowledge, only Wigley and Raper (2001) have constructed a probability distribution function for cumulative emissions from 1990 to 2100, by considering each of the scenarios from Nakicenovic and Swart (2000) as equiprobable.

In this chapter, we assume that there are probability distribution functions that represent the possible values of E and Y, respectively, but we do not make specific assumptions about their functional forms. We simply assume that Y is a random variable of mean 1 (the central forecast value), and standard deviation σ_Y (the normalized mean square-root error). Similarly, we assume that E is a random variable of mean 1 and standard deviation σ_E. We denote by $\iota=Y-1$ the random perturbation of Y around its mean, and by $\varepsilon=E-1$ the random perturbation of E around its mean. By construction, ι has a mean of zero and a standard deviation of σ_Y, and ε has a mean of zero and a standard deviation of σ_E.

Future BAU emissions and future GDP are closely related, at least when considering CO_2 emissions from fossil-fuel combustion—a major component of total GHG emissions—and they usually move in the same direction. Cross-country panel data show a robust relationship between the two variables (Heil and Selden 2001, Ravallion et al. 2000), and country-level panel data tend to confirm this finding (Höhne and Harnisch 2002, Kim and Baumert 2002). However, since GDP and emissions time series are usually non-stationary (and often increasing), linear regressions over panel data capture only how the underlying trends correlate over time. They do not capture how, at each point in

time, a deviation of emissions with regard to its forecasted level is correlated with a deviation of GDP from its forecasted level.[119] In our model, it is the latter indicator that matters for comparing absolute and intensity targets. This indicator can be measured by the linear correlation coefficient ρ.

$$\rho = \frac{< EY > - < E >< Y >}{\sigma_E \sigma_Y} = \frac{< \varepsilon \iota >}{\sigma_E \sigma_Y} \quad . \tag{6.4}$$

6.3.3 Modelling Uncertainty on Marginal Abatement Costs

Marginal costs of abatement are modeled in many different ways in the literature. First, the argument of the cost function is sometimes the percentage of BAU emissions that has been abated (e.g., Nordhaus 1992), and sometimes the absolute amount of emissions abated (e.g., Ellerman and Decaux 1998). Second, marginal abatement costs are usually represented as an increasing and convex function of the level of abatement, but several functional forms have been used, including quadratic (Ellerman and Decaux 1998), exponential (such as GTEM curves in the CERT model by Grütter Consulting 2003) or general power-law functions (Ghersi 2003).

In this study, we adopt a general representation of costs. Marginal abatement costs are assumed to be a continuous, increasing and convex function of the abatement effort R, such that marginal abatement costs are zero when the effort is zero, and such that marginal costs remain finite for any finite value of $R \geq 0$. The abatement effort itself is expressed as a combination of a 'relative' and an 'absolute' effort, in the form

$$R = E^{\alpha - 1}(E - \overline{E}) \quad \text{where } 0 \leq \alpha \leq 1 \quad . \tag{6.5}$$

The index α characterizes the elasticity of the effort with respect to baseline emissions. When α=0, the marginal costs depend on the amount of abatement relative to BAU emissions, i.e. the reduction percentage. For example, consider a fleet of known size of identical cars. The marginal costs of reducing their emissions by a given percentage depend only on the unit cost of more fuel-efficient cars, and remain the same even if the emissions per car are higher or lower than expected. Conversely, when α=1, marginal costs depend on the absolute amount of emissions that is abated. For example, the marginal costs of sequestering carbon through plantations will depend on the total amount that is sequestered, rather than on the fraction of total baseline emissions that this amount represents. Economy-wide marginal abatement costs are likely to fall somewhere in between these two extremes.

[119] High linear correlation between time series does not necessarily imply a high correlation between residuals.

To model a general but simple uncertainty on marginal abatement costs we postulate that they take the form $aC(R)$, where a is a random variable of mean $<a>=1$ and of standard deviation σ_C. Again, it is useful to define $\kappa=a-1$, the random perturbation of a around its mean. κ has mean zero and a standard deviation of σ_C. We assume throughout this chapter that the variations of a are independent from the variations of E and Y, i.e. that κ is not correlated with ε or with ι.

6.3.4 Additional Assumptions: Tight Regime and Small Variances

We now have the mathematical framework in place to analyze the variances of key output variables such as the effective amount of emissions or the price of carbon under a quota, a LIT, and a GIT. But before we can proceed, two additional assumptions must be made.

First, a forthright analytical treatment is hampered by the fact that the constraint on the effective emissions of each instrument, as represented by Eqs.(6.1)-(6.3), is non-differentiable at the point where the BAU emissions are equal to emissions target. To avoid lengthy case differentiations (e.g., to avoid considering separately the cases $E<Q$ and $E>Q$ in the analysis of a quota), we restrict ourselves to quotas Q that are sufficiently small relative to $<E>-\sigma_E$ so that the probability of having $E<Q$ is very small. Similarly, we consider intensity targets q small enough so that the probability that $E/Y<q$ is negligible. In other words, our first assumption is to restrict our analysis to 'tight' regimes, in which the probability of 'compliance by chance' can be neglected.

Our second assumption is that the variances of E and Y are small enough so that the variations of output variables that depend on E and Y can be well approximated by a second-order Taylor expansion. Note that we do not need to make the same assumption for the variance of marginal abatement costs, since all policy variables that we analyze are linear in the random variable a.

Based on the two assumptions above, we can write the standard deviation σ_F of a generic function F of random variables E, Y, and a. Detailed calculations can be found in Appendix 6.8.1.

$$\sigma_F^2 \approx \sigma_C^2\left(\frac{\partial F}{\partial a}\right)^2 + \sigma_E^2\left(\frac{\partial F}{\partial E}\right)^2 + \sigma_Y^2\left(\frac{\partial F}{\partial Y}\right)^2 + 2\rho\sigma_E\sigma_y\frac{\partial F}{\partial E}\frac{\partial F}{\partial Y} \quad . \tag{6.6}$$

6.4 Intensity vs. Quota: Analytical Approach

In this section, we successively provide analytical expressions for the variances of four policy variables—effective emissions, abatement effort, marginal abatement costs and total abatement costs relative to GDP—under a quota, a LIT and GIT. We then compare these expressions to determine which

instrument dominates the other, i.e., leads to the lowest variance—and hence standard deviation—for the variable in question. Relying solely on variances is of course not sufficient to fully characterize the underlying probability density function. For example, the variance does not provide any indication on how symmetric or asymmetric a distribution is. But variance and standard deviation are sufficient to provide some valuable insights into the relative performance of quota, LIT and GIT vis-à-vis uncertainty.

6.4.1 Effective Emissions

The first policy variable we examine are the effective (i.e. after abatement) GHG emissions E. Table 6.1 lists the variances of $\overline{E}$ under a quota, a LIT and a GIT. These expressions are obtained by applying Eq.(6.6) to Eqs.(6.1), (6.2), and (6.3), respectively.

Instrument	**Emissions Variance** (σ_E^2)
Quota	*0*
Linear Intensity	$q^2\,\sigma_Y^2$
Gen. Intensity	$q^2\,\sigma_Y^2\,m^2$

Table 6.1: Variance of effective future emissions $\overline{E}$ under a quota, a linear intensity target and a general intensity target.

The results are intuitive. Since we assume that the quota is tight enough so that the probability of 'compliance by chance' is negligible, future emissions are equal to the quota with certainty and the variance is zero. Under a LIT or a GIT, on the other hand, the emissions ceiling and thus the effective emissions are uncertain because the ceiling is indexed on future GDP, which is itself uncertain. In fact, uncertainty on future GDP (σ_Y) is mapped one to one onto effective emissions in the LIT case (second line of Table 6.1). In other words, if the standard error of GDP forecasts is 10%, the corresponding standard error for effective emissions under a LIT is also 10%. This effect is attenuated under a GIT when m<1.

The comparison between instruments is straightforward: an intensity target (LIT or GIT) always increases the uncertainty on effective emissions relative to a quota.

6.4.2 Emissions Reduction Effort

The second policy variable we examine is the general abatement effort R. We compute the variance σ_R^2 of R under the three instruments by applying Eq.(6.6)

to R as defined in Eq.(6.5), where $\overline{E}$ is substituted by its values from Eqs.(6.1), (6.2), and (6.3), respectively. As discussed in Section 6.3.1, we compare the variances by setting $q<Y>=q=Q$ (i.e., in the certainty case all three instruments would yield the same outcome).

Table 6.2, where for convenience we have defined

$$q_\alpha := \alpha + q(1-\alpha) \quad . \tag{6.7}$$

gives the expression of σ_R^2 under each of the three instruments. The reader will easily check that in general all variances are positive. This is an obvious but important point that we will find again throughout the paper: a given instrument can control at most one output variable (effective emissions for a quota, emissions intensity of GDP for an intensity target, etc.), but it will in general leave all the other output variables uncertain.

Instrument	**Variance of Abatement Effort** (σ_R^2)
Quota	$q_\alpha^2\,\sigma_E^2$
Linear Intensity	$q_\alpha^2\,\sigma_E^2 + q^2\,\sigma_Y^2 - 2\,q\,q_\alpha\,\rho\,\sigma_E\,\sigma_Y$
Gen. Intensity	$q_\alpha^2\,\sigma_E^2 + q^2\,\sigma_Y^2\,m^2 - 2\,q\,q_\alpha\,\rho\,\sigma_E\,\sigma_Y\,m$

Table 6.2: Variance of general abatement effort R under a quota, a linear intensity target, and a general intensity target.

A second point worth noting is that all the variances depend on α, and thus on the type of abatement effort that is measured (absolute, relative, or in between the two). This translates the fact that, for any given objective Q or q, a 10% increase in baseline emissions E leads to a higher increase in absolute effort $E-Q$ than in relative effort $1-Q/E$. As a result, variations of E around its mean result in higher variations of R around its mean for absolute than for relative efforts. The difference between the relative and the absolute case might be quite significant for stringent targets. In the quota case for example, if the target is to reduce emissions by half relative to the baseline (namely $Q=q=0.5$), the standard deviation of the absolute effort is twice as high as the standard deviation of the relative effort.

Third, whereas in the quota case uncertainty on R stems only from uncertainty on BAU emissions E, two sources of uncertainty combine to make R uncertain under a LIT or a GIT: uncertainty on Y and uncertainty on E. If these random variables are uncorrelated (ρ=0), the two uncertainties just add up. But if Y and E are positively correlated, the two uncertainties partially cancel out. In fact, if Y and E are fully correlated (ρ=1), the two uncertainties might even completely cancel out.

The discussion above suggests that, if Y and E are sufficiently correlated, uncertainty on the abatement level might be lower in the intensity case than in the quota case. Precisely,

Proposition 6.1: *The variance of the general abatement effort R under a general intensity target with q>0 and m>0 is lower than the variance of the general abatement effort under a quota with Q=q if and only if:*

$$\rho > \frac{m}{2}\frac{q}{q_\alpha}\frac{\sigma_Y}{\sigma_E} \quad . \tag{6.8}$$

Proof: *Equation 6.8 is obtained by setting the third line of Table 6.2 to be greater than the first and solving for ρ.*

Condition (6.8) is a generalized version of the dominance condition obtained by Sue Wing et al. (2009) for the absolute abatement effort (α=1). We denote by ρ_{minR}:=$m/2\ q/q_\alpha\ \sigma_Y/\sigma_E$ the minimum value of ρ necessary for condition (6.8) to be met.

For a LIT (m=1), the condition cannot always be met, since ρ_{minR} becomes greater than unity if the standard deviation of Y is sufficiently larger than that of E. On the other hand, if σ_E=σ_Y, the condition becomes ρ>0.5 in the relative case (α=1), and ρ>$q/2$ in the absolute case (α=0).

With a GIT, on the other hand, regardless of the relative values of σ_Y and σ_E, and for any given value of ρ and q, condition (8) can always be met by choosing an exponent m that is small enough. In other words, by adequately choosing m, one can always ensure that the uncertainty on the reduction effort under a GIT is lower than the uncertainty on the reduction effort under a quota. And the reduction in variance can be maximized as follows:

Proposition 6.2: *The variance of the abatement effort under a GIT can be minimized by setting the parameter m to*

$$m_R^* = \rho\frac{q_\alpha}{q}\frac{\sigma_E}{\sigma_Y} \quad . \tag{6.9}$$

Condition (8) is then automatically met, and the remaining variance of the abatement effort is

$$\sigma_R^2 = q_\alpha^2\,\sigma_E^2\left(1-\rho^2\right) \quad . \tag{6.10}$$

Proof: *m_R^* is the zero of the derivative of σ_R (third line of Table 6.2) with regard to m. Since σ_R is a degree-2 polynomial function of m with a positive coefficient in m^2, m_R^* is unique and corresponds to a minimum. Eq.(10) gives the value of the extremum.*

Eq.(6.10) shows that when m is set to its optimal value m_R^*, the uncertainty on future GDP σ_Y is completely eliminated from the variance of the abatement

effort. Relative to the quota case, the variance of the abatement effort is then reduced by ρ^2 percent. The reduction of uncertainty is thus large when E and Y are well-correlated. In fact, uncertainty can even be eliminated completely if ρ=1. But the reduction of uncertainty diminishes rapidly as the degree of correlation between E and Y decreases. For example, if ρ=0.5, using an 'optimal' GIT reduces the standard deviation of the abatement effort relative to the quota case by 13%, a figure that becomes a mere 2% if ρ=0.2. In fact, when the degree of correlation between Y and E diminishes, Eq.(6.9) shows that m_R^* also diminishes. In other words, the optimal general intensity target gives less and less weight to GDP, and thus becomes closer and closer to an absolute target.

General intensity targets, however, are more difficult to apprehend and might be more difficult to negotiate. So what if a linear intensity target (m=1) is selected instead? If the correlation between Y and E is high, condition (6.8) is still likely to be met, at least as long as σ_Y is no more than twice as large as σ_E (this limit can even be relaxed when α=1). Whether the gain in uncertainty is maximal or not is determined by whether m_R^* is close to 1 or not. On the other hand, if ρ is small, then condition (6.8) is likely not to be met, and the uncertainty on the abatement effort under a LIT becomes higher than under a quota. The standard deviation of R might increase by a significant amount, for example by 63% if α=1, σ_Y=2σ_E, q=0.75 and ρ=0.2.

6.4.3 Price of Carbon

The third variable we consider is the marginal cost of abatement $aC(R)$, which can also be thought of as the price of carbon. Applying Eq.(6.6) to this variable, we can write the variance of the marginal cost of abatement σ_{MAC}^2 as a function of the variances of a and R. The expression below is valid for all instruments:

$$\sigma_{MAC}^2 \approx C_0^2\left(\sigma_C^2 + \left(\frac{C_0^{'}}{C_0}\right)^2 \sigma_R^2\right) \quad , \tag{6.11}$$

where

$$C_0 := C(1-q) \tag{6.12}$$

and

$$C_0^{'} := C'(1-q) \quad . \tag{6.13}$$

The variance of the marginal cost of abatement can thus be expressed as the sum of two terms: one related to the variance of marginal abatement costs, and the other related to the variance of the abatement effort R. Since the former does not depend on the instrument, the relative performances of a quota, a LIT or a GIT with regard to uncertainty on the price of carbon are the same as the

relative performances of a quota, a LIT or a GIT with regard to the uncertainty on the abatement effort. The analytical condition follows from the previous section.

Proposition 6.3: *Let R be the abatement effort that the marginal cost function C(R) takes as argument. A linear or general intensity target reduces the variance of marginal abatement costs relative to a quota, if and only if it also reduces the variance of the abatement effort R relative to a quota, and thus if and only if condition (6.8) is verified.*

In addition, the coefficient m of a general intensity target can be set in such a way that (i) condition (8) is met, and that (ii) the reduction of variance relative to the quota is maximized. This optimum coincides with m_R^* *from Eq.(6.9).*

Proof*: See proofs of Propositions 6.1 and 6.2.*

Much of the discussion regarding Eqs.(6.8) and (6.9) has already been conducted in the previous section. We simply make two additional remarks here. First, when ρ is between $1/2\ \sigma_Y/\sigma_E\ mq$ and $1/2\ \sigma_Y/\sigma_E\ m$, the relative performances of quota and GIT with regard to uncertainty on marginal abatement costs are determined by the value of α. We come back to this point in more detail in Section 6.6.5.

A second remark is that the reduction of uncertainty that one can achieve by selecting an optimal GIT (i.e., by setting $m = m_R^*$) is lower for marginal abatement costs than for the abatement effort. This is because the variance of marginal abatement costs is now given by the sum of two terms, one of which is unrelated to the uncertainty on R, and thus irreducible for all instruments.

6.4.4 Total Costs Relative to GDP

The fourth policy variable we examine is total costs of abatement relative to GDP (hereafter 'relative costs' or *RC*). We consider total costs relative to GDP as opposed to total costs because the intensity target, which is indexed on GDP, might presumably do a better job at controlling that particular variable. Also, total costs expressed as a fraction of GDP represent a better indicator for the effective impact of climate mitigation on a country's economy than absolute costs. Total costs relative to GDP are defined as

$$RC(R) = \frac{1}{Y}\int_{qY^m}^{E} a\,C\left(E^{\alpha} - e\,E^{\alpha-1}\right)de = \frac{a\,E^{1-\alpha}}{Y}\int_{0}^{R} C(r)\,dr \quad . \tag{6.14}$$

The term $E^{1-\alpha}$ in Eq.(6.14) translates the fact that the additional costs of abatement caused by an increase of the effort R by dR is the marginal cost of abatement at effort R, $C_0(R)$, times the additional amount of carbon that is

abated by increasing the effort by dR. Given the definition of R (Equation 6.5), that additional amount is equal to $E^{1-\alpha}\,dR$.

The variance of RC is given below. The equation is written for a GIT, but the quota case is easily obtained by setting m=0 and the LIT case by setting m=1. Detailed calculations can be found in Appendix 6.8.2.

$$\sigma_{RC}^2 \approx RC_0^2\left(\sigma_C^2+\sigma_E^2\,\Omega^2+\sigma_Y^2\left(1+q\,m\frac{C_0}{RC_0}\right)^2-2\,\rho\,\sigma_E\,\sigma_Y\,\Omega\left(1+q\,m\frac{C_0}{RC_0}\right)\right) \quad , \qquad (6.15)$$

where

$$\Omega := (1-\alpha)+\frac{C_0}{RC_0}q_\alpha \quad . \qquad (6.16)$$

and

$$RC_0 = \int_0^R C(r)\,dr \quad . \qquad (6.17)$$

From Eq.(6.15), the condition under which an intensity target reduces uncertainty on total relative costs vis-à-vis a quota follows:

Proposition 6.4: *A general intensity target qY^m with $m>0$ and $q>0$ leads to a lower variance of total abatement costs relative to GDP than a cap if and only if*

$$\rho > \frac{1}{2\Omega}\frac{\sigma_Y}{\sigma_E}\left(2+q\,m\frac{C_0(R)}{RC(R)}\right) =: \rho_{\min RC} \quad . \qquad (6.18)$$

Proof: *See Appendix 6.8.2.*

Condition (6.18) reveals three major differences between marginal abatement costs and total relative costs when it comes to uncertainty. First, unlike in the marginal abatement costs case, it is not always possible to find a positive value of m that will make the variance of total relative costs under a GIT lower than under a quota. In fact, ρ needs to fulfill condition (6.19) below to guarantee that such a value exists:

$$\rho > \frac{1}{\Omega}\frac{\sigma_Y}{\sigma_E} \quad . \qquad (6.19)$$

For example, if function C is quadratic, if we consider the relative case (α=0), and if the target is $q=0.5$, a quota always dominates a general intensity target with regard to uncertainty on total relative costs, regardless of the value of m, as soon as ρ is lower than $0.25\ \sigma_Y/\sigma_E$.

The second difference between marginal abatement costs and total relative costs vis-à-vis uncertainty is that $\rho_{minRC}>\rho_{minR}$ whenever $m<2$. In other words, a higher

degree of correlation between emissions and GDP is required for an intensity target to reduce uncertainty on relative costs relative to a quota.

Third, the optimal calibration of the intensity target is generally different:

Proposition 6.5*: The value m^*_{RC} that maximizes the mitigation of uncertainty relative to the quota case for a given degree of correlation between E and Y is, when it exists, given by:*

$$m^*_{RC} = m^*_R + \frac{RC_0}{q\,C_0}\left(\rho\frac{\sigma_E}{\sigma_Y}(1-\alpha)-1\right) \quad . \tag{6.20}$$

Proof*: The result is obtained by finding the minimum of Eq.(6.15), and solving for m.*

Thus, in most cases, m^*_{RC} is smaller than m^*_R. This is true, in particular, when abatement costs depend on the absolute amount of emission reductions (α=1), and in a wide range of cases— e.g. for $\sigma_E \leq \sigma_Y$—when α=0. When m is set to m^*_{RC}, the uncertainty on GDP is completely eliminated (Eq. 6.21) and, if the correlation ρ is very high, σ^2_{RC} can even be reduced to an irreducible minimum $RC_0^2\,\sigma_C^2$. However, the reduction in variance—and even more so in standard deviation—will again by meager as long as ρ remains moderate.

$$\sigma^2_{RC}(m^*_{RC}) \approx RC_0^2\left[\sigma_C^2 + \sigma_E^2\,\Omega^2\left(1-\rho^2\right)\right] \quad , \tag{6.21}$$

On the other hand, choosing a linear intensity target in absence of an appreciable positive correlation between E and Y can lead to large uncertainties on total relative costs. For instance, for the absolute case and with a quadratic MAC function, a target reduction of *q=0.75* under a linear intensity target with ρ=0 yields a normalized variance, i.e. the variance divided by the square of the deterministic value of RC, RC_0, that is higher than the normalized variance for a quota by a margin of 99 times σ_Y^2.[120]

In sum, total relative costs are well-controlled neither by the cap nor by the intensity target. Since the effort is indexed on GDP, the intensity target might have been expected to perform better than the quota vis-à-vis uncertainty on relative costs. But the analysis demonstrates that this is not the case. In fact, intensity targets perform better than quotas vis-à-vis relative costs less often than they do vis-à-vis marginal abatement costs. And unlike in the marginal abatement cost case, general intensity targets can no longer automatically be

[120] Precisely, the normalized variance σ^2_{RC}/RC_0^2 under a LIT is $\sigma_C^2 + 144\sigma_E^2 + 100\sigma_Y^2$, while it is $\sigma_C^2 + 144\sigma_E^2 + \sigma_Y^2$ under a quota.

calibrated to perform better than quotas if the correlation between E and Y is not large enough.[121]

6.5 Estimation of Model Parameters

In this section, we estimate the parameters σ_E, σ_Y, σ_C and ρ. The commitment period we consider here is 2013-2017, because much of the current debate focuses on the post-Kyoto period. Ideally, one would like to estimate these parameters for individual countries because future targets, like those in the Kyoto Protocol, are likely to be adopted by individual countries. However, many of the GDP, emissions, and abatement cost projections on which we base our estimates are available only for regions, and not for individual countries. As a result, the uncertainties that we obtain with these aggregated data are likely to be smaller than the uncertainties that we would have obtained had we had country-level data.

6.5.1 Estimation of σ_E, σ_Y and ρ

Let us first recall that E and Y are uncertain because there is no single model that would accurately predict their value based on observables. The existing models that project future output and future emissions are themselves based on parameters that are unobservable and uncertain, such as the rate of autonomous technical change. In addition, there are competing models that project future output and future emissions.

To estimate σ_E, σ_Y and ρ, three main techniques are available. First, one can take sets of projections generated by one model (e.g. the scenarios of the US Energy Information Administration), and use the difference between the high and the low scenario as a proxy for uncertainty. Data points in this method are often too few to allow for the estimation of ρ. Second, one can compute the variance of projections originating from different models, as listed for example in the IPCC Special Report on Emissions Scenarios (Nakicenovic and Swart 2000). The internal consistency of the scenarios is lost because different models are involved, but larger data sets allow for the estimation of ρ. Finally, one can compute historical forecast errors, and take them as a proxy for the accuracy of today's forecasts for emissions and GDP during a post-Kyoto period.

Each approach has limitations. Using scenarios may lead to an overestimation of the actual variance because scenarios are often built to explore a wide range of plausible futures, and thus are not intended to be interpreted

[121] This result is not consistent with Kolstadt (2005), who shows that total relative costs are subject solely to cost function uncertainty under an intensity target. This is because, in his model, total abatement costs depend on emissions per unit of GDP ($\overline{E}/Y$). As a result, setting an intensity target, which is precisely setting a level of emissions per unit of GDP, automatically fixes total abatement costs, up to the uncertainty on the functional form itself.

probabilistically. Historical forecast errors, on theother hand, suffer from data scarcity, especially when considering long-range forecasts. In this method therefore, linear correlation coefficients can often be computed only from forecasts for the same time horizon, but for different countries (assuming forecasts as independent). This approach provides a cross-country average value for ρ, but individual countries may have higher or lower coefficients depending on their particular relationships between emissions and GDP.

In this study, we pursue all three approaches to make our estimates of the uncertainties as robust as possible. The upper section of Table 6.3 shows our estimates for the normalized standard deviation (also called coefficient of variation) of GDP and BAU CO_2 emissions in 2015, as inferred from the US Energy Information Administration's (EIA 2005) low, mid and high scenarios, assuming all three as equiprobable. We find relatively small values for both σ_Y (between *0.06* and *0.16*) and σ_E (between *0.03* and *0.10*). Uncertainty is in general higher for GDP than for emissions.

	World	US	Chn	Ind	Jap	WEU	EEU	FSU	LAM	MENA	SAFR
σ_Y	0.09	0.06	0.10	0.10	0.06	0.06	0.11	0.16	0.11	0.11	0.11
σ_E	0.06	0.04	0.07	0.06	0.03	0.04	0.06	0.07	0.10	0.08	0.06
σ_Y	0.07	0.07	0.15	0.25	0.12	0.06	0.17	0.16	0.12	0.12	0.17
σ_E	0.10	0.10	0.12	0.19	0.11	0.11	0.20	0.16	0.16	0.11	0.22
ρ	0.63	0.40	0.78	0.87	0.50	0.42	0.25	-0.12	-0.33	0.89	0.67

Table 6.3: Normalized standard deviations of the EIA (2005) scenarios for 2015 (top part), and normalized standard deviations and liner correlation coefficients of E and Y for 25 scenarios from various sources harmonized by Lecocq and Crassous (2003) (bottom part). Data refer to World, USA, China, India, Japan, Western Europe (WEU), Eastern Europe (EEU), Former Soviet Union (FSU), Latin America (LAM), Middle East and North Africa (MENA), and Sub- Saharan Africa (SAFR). For the EIA (2005), the latter two actually correspond to Middle East and Africa as a whole, respectively.

The bottom part of Table 6.3 presents estimates for the normalized standard deviation of cumulative GDP and BAU CO_2 emissions for the period 2013 to 2017, based on 25 scenarios from multiple sources (IPCC, IIASA and US EPA) harmonized by Lecocq and Crassous (2003) and assumed equiprobable. We find values of σ_Y between *0.06* for WEU and *0.25* for India, while values for σ_E lie in a slightly narrower band ranging from *0.10* (US) to *0.22* (SAFR). Uncertainty about E and Y, here, are of similar magnitude. Interestingly, parameter ρ can take a very wide range, from a negative *–0.33* for LAM to a strongly positive value of *0.89* for MENA, with most values, however, taking on positive values above or equal to *0.4*.

We also carried out a limited assessment of the accuracy of past emissions and GDP forecasts, similar to Lutter (2000). To this end, we compared the reference

7-year forecasts of the 1995 issue of the International Energy Outlook (EIA 1995) with actual data (EIA 2005), and likewise the 1994 8-year ahead WEO forecasts with current data (IEA 1994, 2002, 2004). Relative forecast errors are reported in Table 6.4.

IEO					**WEO**
Country or Region	CO_2 7 years	GDP 7 years	CO_2 8 years	GDP 8 years	Country or Region
World	4.4%	-6.6%	3.4%	-6.1%	World
Industrialized C.	3.1%	-1.3%	0.9%	-1.4%	Developing C.
Non-OECD Asia	-1.6%	-0.5%	-0.4%	-16.8%	US and Canada
United States	-2.6%	-7.8%	2.1%	38.3%	OECD Pacific
Canada	-1.4%	-7.4%	6.5%	-18.1%	China
Western Europe	14.0%	-1.4%	4.5%	66.9%	East Asia
Japan	4.1%	19.3%	-5.1%	-7.3%	South Asia
Former SU	30.8%	1.9%	-14.5%	-1.7%	Middle East
Eastern Europe	26.6%	-0.5%	-0.2%	19.6%	Latin America
Middle East	-13.9%	5.1%	0.2%	13.4%	Africa
Mexico	16.0%	5.3%			
China	4.8%	-13.3%			
Africa	1.1%	2.6%			
Latin America	-0.8%	12.7%			

Table 6.4: Historical forecast errors for CO2 emissions and GDP of the International Energy Outlook 1995 (EIA 1995) and the World Energy Outlook 1994 (IEA 1994). The WEO regions OECD and OECD Europe could not be considered, as their composition changed significantly during the 1990s. Likewise, we excluded South Korea from the OECD Pacific region.

As can be observed, forecast errors can be quite large (up to 67% for 8-year forecasts of East Asia's GDP).[122] Secondly, while for the IEO the average absolute error for emissions is larger than the one for GDP, the opposite is true for the WEO. Thus, as with the data in Table 6.3, it cannot be asserted that either type of uncertainty (emissions or output) is necessarily lower than the other. Third, when pooled over the different regions listed in Table 6.4, forecast errors of emissions and GDP do not show a strong correlation: the ρ corresponding to the two 'pairs' of forecasts from Table 6.4 is *-0.04* and *0.31*, respectively.[123]

Table 6.5 summarizes this section's findings. Four key conclusions can be drawn. First, σ_E and σ_Y are almost always found to be below 20%. Second, there is no obvious difference in patterns of uncertainties between developing and

[122] Our results are comparable to those of Lutter (2000), who finds that historical ten-year ahead emissions forecasts for the United States are subject to a 4.2% absolute error, and that 'simulated' forecasts for cumulative emissions of five-year periods are subject to errors between 5% and 25%, or even up to 37% (India), if the five-year period starts six or more years ahead in the future.
[123] To avoid double-counting, these linear correlation coefficients are computed by using only those individual regions and countries that do not overlap.

industrialized countries, except for an apparently lower emissions uncertainty for industrialized countries. Third, no robust statement can be made on the basis of the results above as to which uncertainty–emissions or output–is higher, even though for the limited data considered here, the average uncertainty on future GDP is somewhat higher than the average uncertainty on future emissions. This finding is significant because the ratio between the two variances plays a crucial role in the equations obtained in Section 6.4. Fourth, the most difficult parameter to estimate remains the correlation of forecast errors ρ. While the evaluation of the long-term scenarios led to a remarkably large range of values, the analysis of historical forecasts produced lower values not too far from zero. On the aggregated level values for ρ tend to be positive, around *0.25*, with a tendency to be higher in industrialized countries than in developing countries.

		Multi-Model Scenarios	IEO 2005	Forecast Errors IEO 1995	Forecast Errors WEO 1994	Weighted Mean $1:1:\frac{1}{2}:\frac{1}{2}$
	σ_E	15%	6%	11%	4%	9%
All	σ_Y	14%	10%	7%	23%	13%
Countr.	ρ	0.43	na	-0.04	0.31	0.28
	σ_E	17%	7%	13%	5%	11%
Develop.	σ_Y	16%	11%	6%	21%	14%
Countr.	ρ	0.43	na	-0.19	0.30	0.24
	σ_E	11%	4%	6%	1%	6%
Industr.	σ_Y	8%	6%	9%	28%	11%
Countr.	ρ	0.44	na	0.27	na	0.36

Table 6.5: Summary of parameter estimates for uncertainties σ_Y and σ_E, and for the linear correlation of forecast errors ρ. Note, however, that the latter has been derived with very few data points. Estimates derived from forecast errors represent the average of the absolute values of the relative forecast errors of GDP (respectively emissions) across all countries in Table 6.4 that are either in the developed or developing world. To avoid double-counting, aggregate regions such as 'World' were excluded in this calculation. Means (last column) are computed by taking the average of columns 2 to 5 with weights 1:1:1/2:1/2, so as to give equal weight to each of the three approaches.

6.5.2 Estimating Uncertainty about Marginal Abatement Costs

To estimate σ_c, one would need several estimates of the marginal abatement cost curve for the period 2013-2017, all with the same functional form. Such a set, however, is not readily available. Most of the marginal abatement cost curves currently available apply to the first commitment period only. In addition, available surveys of marginal abatement cost curves (e.g. Metz et al. 2001, Ghersi 2003) report only data points and not functional forms. Third, most available studies of abatement costs focus on developed countries only.

To get some insights into σ_C, we use a compilation of modeling results from Ghersi (2003), who reports two-point estimates for marginal abatement costs of 13 different models, both in terms of absolute and relative reductions. The marginal abatement costs are valid in 2010 for decisions made in 2000. For our study, we consider all these to represent random draws of the true cost function, and perform a least-square fit with an exponential and power-law function. Our estimate of σ_C is then the normalized standard deviation of the residuals, as reported in Table 6.6. Typical values are around *0.5* for the US, but significantly higher, between *0.6–0.9*, for other industrialized countries. Because of insufficient data, we cannot provide estimates for developing countries, but it seems reasonable—also for the very fact that no data is available—to assume even higher values for these less researched economies.

		US	Japan	EU 15	CANZ
Relative case	Exponential fit	52%	70%	85%	78%
	Power-law fit	54%	69%	81%	60%
Absolute case	Exponential fit	49%	80%	79%	97%
	Power-law fit	51%	74%	87%	62%

Table 6.6: Values for the MAC uncertainty σ_C, as derived from Ghersi (2003). Taking for each country/region the lower estimate leads to an overall average of 66%, and a range of 49%–81%, valid for both the absolute and relative case.

6.6 Intensity vs. Quota in a Real-World Setting

We now test whether an intensity target performs better than a cap vis-à-vis uncertainty on key policy variables, using the analytical conditions derived in Section 6.4 and the empirical values identified in Section 6.5.

6.6.1 Relative Performances of Quota, LIT and GIT with Regard to Abatement Effort and Price of Carbon

The condition under which a GIT reduces uncertainty on the abatement effort and the marginal abatement costs relative to a quota is given by Eq.(6.8). The key parameters in this equation are ρ, the ratio σ_Y / σ_E, q and α.

Section 6.5.1 provides a range of plausible values for ρ and σ_Y / σ_E. In Table 6.5, ρ ranges between *0.27* and *0.44*, and the ratio σ_Y / σ_E between *0.8* and *22* for developed countries (note that Table 6.5 shows rounded values). We limit the analysis to developed countries because there is less data on developing countries, and because the 'tight regime' assumption is more likely to be valid for industrialized countries, at least for the period 2013-2017.

We first discuss the relative performances of a quota and a linear intensity target. Figure 6.1 shows the area in the $(\log(\sigma_Y/\sigma_E),\rho)$ plane where a quota dominates a LIT in terms of uncertainty on abatement effort and marginal abatement costs. The box represents the range of plausible values as extracted from Table 6.5. In Figure 6.1, we set $q = 0.75$. This value is comparable to the Kyoto targets, under which the group of Annex B countries committed to limit emissions in 2010 to about 82% of the BAU level as it was projected in 1997 (EIA 1997). The value *0.75* is also in the range of targets that have been proposed in the literature for the second commitment period (see, e.g., Brouns and Ott 2005), at least for developed countries.

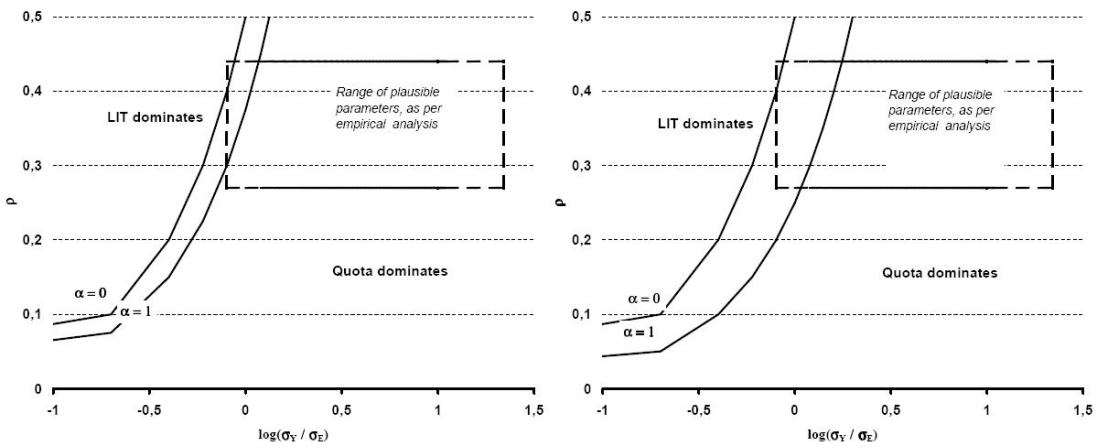

Figure 6.1: LIT vs. quota, for price of carbon, q=0.75 (Left). LIT vs. quota, for price of carbon, q=0.5 (Right).

Figure 6.1 (Left) shows that over most of the plausible values for ρ and σ_Y/σ_E, a quota dominates a LIT with regard to uncertainty on effort and marginal abatement costs. This result is valid regardless of the value of α since the frontier between the areas where LIT and quota dominate does not move much when α goes from 0 to 1.

With a more stringent target—i.e. a lower q—, the difference between the relative and the absolute cost functions becomes more acute. The frontier in the relative case (α=0) remains unchanged for any value of q because, when α=0, the term q/q_α in Eq.(6.8) is equal to one. But the frontier in the absolute case (α=1) becomes flatter and flatter as q diminishes because the term q/q_α is in this case equal to q. In other words, a more stringent target increases the 'gray area', where the relative performances of quota and LIT depend on α (Fig.6.1, Right).

Contrary to a linear intensity target, a general intensity target will always dominate a quota in terms of the uncertainty on abatement effort and marginal abatement costs, as long as m is well-chosen. However, when the ratio σ_Y/σ_E is large, a small value of m is necessary.

For example, Figure 6.2 (Left) shows that for *m=0.3*, a GIT dominates a quota for no more than half of the box of plausible parameter values. One would have to set *m=0.03* for a GIT to dominate over the entire range of plausible values. At this level, the GIT is very close to a cap, each additional point of GDP leading to a 0.05% increase in the emissions quota. And the gains in terms of the variance of the reduction effort σ_R are rather modest. In this case, numerical calculations show that the lowering of the standard deviation is 10% at most over the range of plausible values listed in Table 6.5.

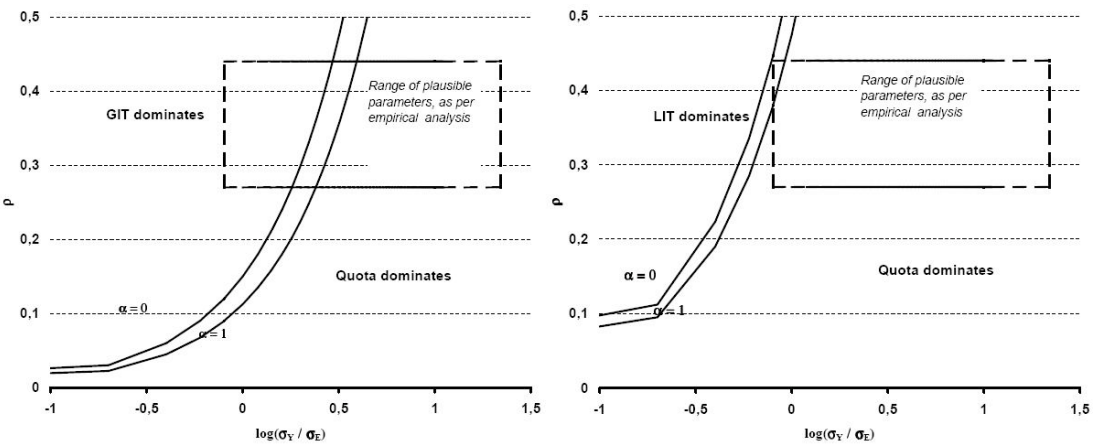

Figure 6.2: GIT vs. quota, for price of carbon, q=0.75, m=0.3 (Left). LIT vs. quota, for total costs relative to GDP, q=0.75 (Right).

Finally, it is interesting to note that the optimal parameter m_R^* that minimizes the variance takes a very wide range of values over the set of plausible values for ρ and σ_Y / σ_E: from 1 to *0.05* according to Eq.(6.9). This suggests that setting an optimal GIT cannot be done properly without first reducing the uncertainty on the values of ρ and σ_Y / σ_E.

6.6.2 Relative Performances of Quota, LIT and GIT with Regard to Total Relative Costs

The condition under which a GIT reduces uncertainty on the total costs per GDP relative to a quota is given in Eq.(6.18). We test this condition using the same ranges of parameter values as above. We use a power-law function for the marginal abatement cost function $C(R) = R^{\gamma}$, with γ>1. Under this assumption,

$$\frac{C_0}{RC_0} = \frac{\gamma + 1}{1 - q} \quad . \tag{6.22}$$

For exponents γ between 1 and 2, and for an effort $q=0.75$, C_0/RC_0 is thus between 8 and 12. This coefficient increases rapidly when the abatement effort becomes less stringent.

Figure 6.2 (Right) shows the area in the $(\log(\sigma_Y/\sigma_E),\rho)$ plane where a quota dominates a LIT in terms of the uncertainty on total relative costs, with $q=0.75$ and $\gamma=1.5$. Except for a small area in the upper left corner of the box, a quota dominates a linear intensity target for all of the plausible values for ρ and σ_Y/σ_E.

More stringent targets again increase the discrepancy between the relative and the absolute cost functions, and result in a larger area where the dominance of quota or LIT could be determined by α. Both frontiers move, but whereas the frontier for α=1 moves downward slightly, the frontier for α=0 moves upward significantly. This is because, in the relative case, q appears in the denominator of ρ_{minRC} in Eq.(6.18), whereas it appears only in the numerator in the absolute case. As a result, most of the box of plausible values remains dominated by the quota even when q is small (Figure 6.3, Left).

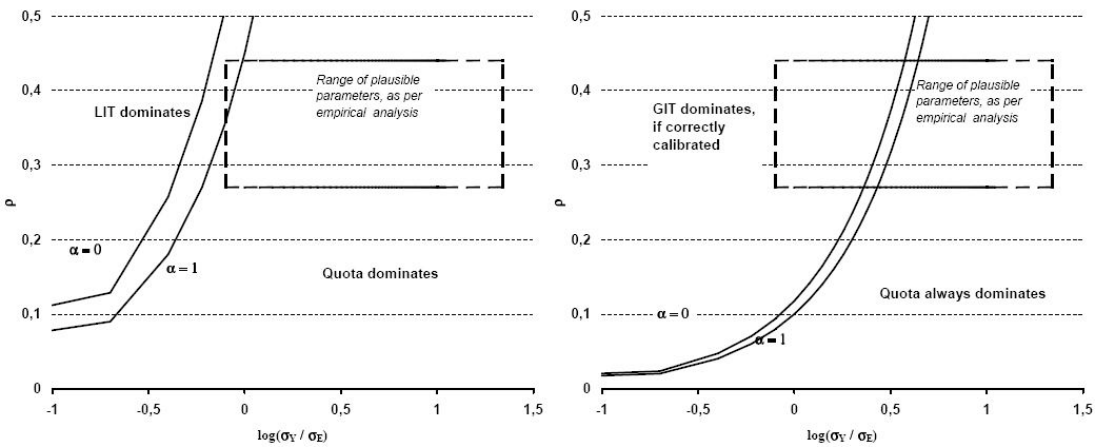

Figure 6.3: LIT vs. quota, for total costs relative to GDP, q=0.5 (Left). GIT vs. quota, for total costs relative to GDP, q=0.75 (Right).

Unlike in the case of marginal abatement costs, a general intensity target will not always dominate a quota with regard to the uncertainty on total abatement costs relative to GDP. Figure 6.3 (Right) shows the maximum area over which a GIT can dominate a quota. For $q=0.75$ and $\gamma=1.5$, this maximal area covers only about half of the range of plausible parameters reported in Table 6.5. It is important to note that in order to secure the dominance of the GIT across the entire rectangular area, parameter m must be very small, making the GIT very similar to an absolute quota.

Additionally, the figure indicates that the value of m needed to ensure that a GIT dominates a quota for relative costs is always lower than the one required for the marginal abatement costs. If we take again the previous example—

σ_Y/σ_E=*2* and ρ=*0.3*—, *m* needs to be lower than *0.075* for a GIT to dominate a quota vis-à-vis the uncertainty on total relative costs, to be compared with *0.3* when uncertainty on marginal abatement costs is considered.

Similarly, the optimal parameter m^*_{RC} that minimizes the variance, when it exists, takes a very wide range of values over the set of plausible values for ρ and σ_Y/σ_E: from 1 to nearly 0 according to Eq.(6.20). Thus, we find again that setting an optimal GIT cannot be done properly without first reducing the uncertainty on the values of ρ and σ_Y/σ_E.

6.6.3 Quantifying Uncertainty

In this section, we present numerical values for the absolute level of uncertainty on output parameters over our set of policy variables. To do so, we build three representative cases, the characteristics of which are summarized in Table 6.7. The first case ('average') is based on the average of the parameters for industrialized countries reported in Table 6.5. By contrast, the 'pro-intensity' case is constructed to be the most favorable for intensity targets, i.e., with the highest value of σ_E and ρ for industrialized countries from Table 6.5, the highest value for α and the lowest value for σ_Y. The 'pro-cap' case is the exact opposite. As in the previous section, we use *Q=q=0.75*.

Parameter	Case 1: Average of Industr. Countries	Case 2: Pro-Intensity	Case 3: Pro-Cap
σ_E	0.06	0.11	0.03
σ_Y	0.11	0.06	0.18
ρ	0.36	0.44	0.27
σ_C	0.66	0.66	0.66
α	0.5	1	0
$C_0(R)$	$R^{1.5}$	$R^{1.5}$	$R^{1.5}$
$Q = q$	0.75	0.75	0.75
ρ_{minR} (from Eq.8)	0.80	0.22	> 1
ρ_{minRC} (from Eq.18)	0.96	0.27	> 1
m^*_R (from Eq.9)	0.22	1.02	0.05
m^*_{RC} (from Eq.20)	0.10	0.89	< 0

Table 6.7: Definition and summary of the three representative cases.

Table 6.8 presents the normalized standard deviations for each output variable under each of the instruments—subject to the parameter values of one of the three cases. It shows that an intensity target (LIT or GIT) leads to non-negligible uncertainty on emissions, especially—by construction—in the pro-cap case (18%). The uncertainty on the abatement effort is larger, giving rise to very high uncertainties on marginal abatement costs, ranging from 68% (pro-cap case, GIT) to more than 100% (pro-cap case, LIT). Uncertainty on total relative

costs is higher still, with normalized standard deviations always higher than 72%.

Policy Variable		m	Average	Pro-Intensity	Pro-Cap
Emissions	Cap	0	0 (0.00)	0 (0.00)	0 (0.00)
	LIT	1	0.11 (0.11)	0.06 (0.06)	0.18 (0.18)
	GIT(1)	.5	0.05 (0.05)	0.03 (0.03)	0.09 (0.09)
Abatement Effort	Cap	0	0.21 (0.21)	0.42 (0.42)	0.10 (0.10)
	LIT	1	0.32 (0.32)	0.38 (0.38)	0.53 (0.52)
	GIT(2)	m^*_{R}	0.19 (0.19)	0.38 (0.38)	0.10 (0.10)
	GIT(3)	.22	0.19 (0.19)	0.41 (0.41)	0.14 (0.14)
Marginal Costs	Cap	0	0.73 (0.76)	0.92 (1.03)	0.68 (0.68)
	LIT	1	0.81 (0.89)	0.87 (0.97)	1.03 (1.19)
	GIT(2)	m^*_{R}	0.72 (0.75)	0.87 (0.97)	0.68 (0.68)
	GIT(3)	.22	0.72 (0.75)	0.90 (1.01)	0.69 (0.72)
Relative Costs	Cap	0	0.84 (0.95)	1.23 (1.65)	0.72 (0.79)
	LIT	1	1.11 (1.55)	1.16 (1.54)	1.64 (3.58)
	GIT(2)	m^*_{RC}	0.83 (0.95)	1.16 (1.54)	0.72 (0.75)
	GIT(3)	.10	0.83 (0.95)	1.21 (1.62)	0.76 (0.89)

Table 6.8: Normalized standard deviation for each policy variable and instrument, for each of the three representative cases, as derived from the analytical formulae, and computed by using a fully general numerical model (values in parenthesis). (1) m=0.5 for all cases. (2) GIT calibrated using optimal values for m for each representative case. (3) GIT calibrated using only one value for m, which corresponds to the optimal value for the 'average' case.

A robust pattern emerges: While the LIT outperforms the quota by a relatively small margin in the pro-intensity case (except of course on emissions), it leads to a medium-to-large increase of uncertainty in the other two cases. Therefore, Table 6.8 suggests again that adopting a LIT could introduce significant uncertainty into the system.

As expected, an optimal GIT dominates all other instruments on all policy indicators save emissions. Still, because the empirically found linear correlations ρ are not high, in particular always below 1/2, the impact of the GIT remains limited, and its performance is on the whole comparable to that of the cap. In addition, given that ρ and σ_Y / σ_E are uncertain, it is more realistic to assume that the GIT is calibrated for the central 'average' case (fourth line for each instrument), and not with the optimal m^* of each representative case. In that case, the GIT no longer outperforms the cap.

6.6.4 Validity of the 'Tight Regime' Assumption

Table 6.8 also provides some insights on the validity of the assumptions made in Section 6.3.4 in order to derive the analytical conditions, namely 'tight regime' and 'limited uncertainty' on future emissions and GDP. In each cell of the table,

the first value is computed based on the approximate analytical formulae derived in Section 6.4, while the second (between parenthesis) shows the actual value, as computed numerically with a bivariate normal distribution for E and Y, fully taking into account the possibility of 'compliance by chance'.

Table 6.8 confirms that our assumptions lead to acceptable results for a reduction target of –25% w.r.t. baseline emissions/intensity, at least for the three representative cases that we have selected. In fact, there are generally only modest deviations between the analytically approximated and rigorous numerical values, except for total relative costs, where analytical formulae systematically underestimate real uncertainty, sometimes by a wide margin.

Policy Variable	Target q	Ind.-Average analy.	Ind.-Average num.	Pro-Intensity analy.	Pro-Intensity num.	Pro-Cap analy.	Pro-Cap num.
Reduction	0.5	0.62	0.62	0.14	0.15	> 1	> 1
	0.75	0.80	0.80	0.22	0.22	> 1	> 1
	0.85	0.85	0.86	0.24	0.25	> 1	> 1
	0.95	0.91	0.94	0.27	0.28	> 1	> 1
Marg.Costs	0.5	0.62	0.67	0.14	0.15	> 1	> 1
	0.75	0.80	0.83	0.22	0.22	> 1	> 1
	0.85	0.85	0.89	0.24	0.25	> 1	> 1
	0.95	0.91	0.96	0.27	0.28	> 1	> 1
Rel.Costs	0.5	0.98	> 1	0.26	0.30	> 1	> 1
	0.75	0.96	> 1	0.27	0.32	> 1	> 1
	0.85	0.94	> 1	0.28	0.33	> 1	> 1
	0.95	0.93	> 1	0.28	0.34	> 1	> 1

Table 9: Validity of 'tight regime' assumption made for analytical calculation. We confront the analytically approximated and actual (numerical computations) threshold values for the linear correlation ρ above which a linear intensity target dominates the cap.

Since the main purpose of the paper is to examine dominance conditions, we also test the validity of the formulae for ρ_{minR} and ρ_{minRC}, the threshold values of ρ for marginal abatement costs and total relative costs, respectively. Table 6.9 shows that the approximations made at the beginning of the chapter do not lead to significant errors on the values of these parameters: the errors made on ρ_{minR} and ρ_{minRC} remain small compared with the range of uncertainty on the actual value of ρ.

6.6.5 Sensitivity to the MAC Function

In this final section, we come back to the uncertainty surrounding the argument (value of α) and the functional form of the MAC function. We have seen that there are realistic parameter configurations in which the choice between quota and LIT depends on α. However, numerical calculations (not shown here)

suggest that the stakes are not high, since the costs of an error in terms of additional uncertainty are relatively low.

The same applies for the curvature of the MAC function—which plays a role both through C_0/C_0' and through RC_0/C_0. C_0/C_0' influences the absolute amount of uncertainty on the marginal costs, but plays no role for the relative performances of the various instruments with regard to price uncertainty (Section 6.4.3). RC_0/C_0, on the other hand, influences both the level of uncertainty on total relative costs and the relative performance of cap and intensity target. However, numerical calculations (not shown) suggest again that the 'wrong' choice leads to very modest increases of uncertainty.

6.7 Conclusions

In this chapter, we have examined the relative performances of a quota, a linear intensity target, and a general intensity target with regard to uncertainty on four key variables for decisionmakers: emissions, abatement effort, price of carbon, and total costs of abatement relative to GDP. Assuming that the overall constraint on carbon is tight enough, and that the uncertainties surrounding future GDP and future business-as-usual emissions are not too large, we have derived analytical conditions of dominance for each instrument and for each output variable.

We have derived ranges of plausible values for the uncertainties on future GDP, future BAU emissions, and the linear correlation coefficient between the two, as well as for the uncertainty on future abatement costs. On this basis, we have examined which instrument is likely to dominate in practice. The range of plausible values that we have derived—even for developed countries where uncertainties appear lower—is so large that the result is ambiguous. However, a quota seems to dominate a linear intensity target over most of the plausible area of parameter values. A general intensity target can be constructed to dominate the quota, but in practice an optimal calibration of the GIT would most likely lead to a target that is only weakly dependent on GDP, and thus very similar to a quota. Therefore, the potential reduction of uncertainty on key output variables that could be achieved remains modest.

Three concluding remarks can be made based on these results. First, we find little evidence to support the adoption of a linear intensity target over a quota, at least on uncertainty grounds. There are clearly areas where a LIT dominates, but the overlap with the range of plausible values for the key parameters ρ and σ_Y/σ_E appears rather limited. More ambitious emission targets improve the performances of a LIT relative to those of a cap, but very stringent targets would be necessary—50% below BAU emissions or more—for the LIT to dominate a quota. Such levels appear beyond the range of plausible climate agreements, at least for the second commitment period.

Second, we confirm the finding of Jotzo and Pezzey (2004) and Sue Wing et al. (2009) that a well-calibrated general intensity target can always dominate a quota with regard to the uncertainty on marginal abatement costs. This result, however, is no longer valid for total costs relative to GDP. In addition, even when an optimal GIT can theoretically be constructed, given the wide range of plausible values for the key parameters ρ and σ_Y/σ_E, a very small value for m, the GIT's calibration parameter, has to be selected to limit the risk of error, in which case the GIT becomes basically equivalent to a cap. In other words, we do find support for a GIT, but only when it is calibrated to be close to a quota.

The two previous remarks stem from the fact that the range of plausible values that we have found in this study for ρ and σ_Y/σ_E is very large. Ultimately, these values translate beliefs about how the economy of a given country or group of country will behave over the next decade or so. If a policy-maker or an expert has a more precise view of those parameters, his or her selection of instruments might be different. But further analysis is necessary to provide hard data that could support such intuitions.

Finally, let us note that the 'tight regime' assumption we make in this paper is not necessarily valid in practice, as countries may negotiate targets that are close to their projected BAU emissions. In this case, the possibility that BAU emissions fall spontaneously below the target can no longer be sidestepped. Examining the relative performance of various instruments when the 'tight regime' assumption is relaxed is a subject for future research.

6.8 Appendix

6.8.1 Approximation of Mean and Variance

Let F be a function of future BAU emissions E, of future output Y, and of the slope of the marginal cost curve a. Since E, Y, and a are random variables, $F(E,Y,a)$ is also a random variable. Assuming that the fluctuations of E, Y, and a around their mean are small, we can approximate $F(E,Y,a) = F(\langle E\rangle+\varepsilon,\langle Y\rangle+\iota,\langle a\rangle+\kappa)$ by a Taylor expansion in the vicinity of its deterministic value $F(\langle E\rangle,\langle Y\rangle,\langle a\rangle)=F_0$. Precisely,

$$\begin{aligned} F(E,Y,a) &\approx F_0 + \left(\kappa\frac{\partial}{\partial a}+\varepsilon\frac{\partial}{\partial E}+\iota\frac{\partial}{\partial Y}\right)F + \frac{1}{2}\left(\kappa\frac{\partial}{\partial a}+\varepsilon\frac{\partial}{\partial E}+\iota\frac{\partial}{\partial Y}\right)^2 F \\ &= F_0 + \kappa\frac{\partial F}{\partial a}+\varepsilon\frac{\partial F}{\partial E}+\iota\frac{\partial F}{\partial Y}+\frac{\kappa^2}{2}\frac{\partial^2 F}{\partial a^2}+\frac{\varepsilon^2}{2}\frac{\partial^2 F}{\partial E^2}+\frac{\iota^2}{2}\frac{\partial^2 F}{\partial Y^2}+\rho\,\sigma_E\,\sigma_Y\frac{\partial^2 F}{\partial Y\partial E} \end{aligned} \quad , \quad (6.A23)$$

where all mixed derivatives except $\partial Y\partial E$ vanish because κ is independent from both ι and ε. The expected value $\langle F\rangle$ then follows:

$$\langle F(E,Y,a)\rangle \approx F_0 + \frac{\sigma_C^2}{2}\frac{\partial^2 F}{\partial a^2}+\frac{\sigma_E^2}{2}\frac{\partial^2 F}{\partial E^2}+\frac{\sigma_Y^2}{2}\frac{\partial^2 F}{\partial Y^2}+\rho\,\sigma_E\,\sigma_Y\frac{\partial^2 F}{\partial Y\partial E} \quad , \quad (6.A24)$$

where we have used the fact that, by definition, $<\kappa^2>=\sigma_C^2$, and so on. Finally, we obtain the variance by rewriting Eq.(6.A23) for the function F^2:

$$F^2(\varepsilon,\kappa,\iota) \approx F_0^2 + \left(\kappa\frac{\partial}{\partial a} + \varepsilon\frac{\partial}{\partial E} + \iota\frac{\partial}{\partial Y}\right)F^2 + \frac{1}{2}\left(\kappa\frac{\partial}{\partial a} + \varepsilon\frac{\partial}{\partial E} + \iota\frac{\partial}{\partial Y}\right)^2 F^2$$
$$= F_0^2 + 2F_0\left(\kappa\frac{\partial}{\partial a} + \varepsilon\frac{\partial}{\partial E} + \iota\frac{\partial}{\partial Y}\right)F + F_0\left(\kappa\frac{\partial}{\partial a} + \varepsilon\frac{\partial}{\partial E} + \iota\frac{\partial}{\partial Y}\right)^2 F + \left(\kappa\frac{\partial F}{\partial a} + \varepsilon\frac{\partial F}{\partial E} + \iota\frac{\partial F}{\partial Y}\right)^2, \tag{6.A25}$$

which yields an expected value of

$$\begin{aligned} <F^2> \approx\ & F_0^2 + 2F_0\left(\frac{\sigma_C^2}{2}\frac{\partial^2 F}{\partial a^2} + \frac{\sigma_E^2}{2}\frac{\partial^2 F}{\partial E^2} + \frac{\sigma_Y^2}{2}\frac{\partial^2 F}{\partial Y^2} + \rho\,\sigma_E\,\sigma_Y\frac{\partial^2 F}{\partial Y \partial E}\right) \\ & + \sigma_C^2\left(\frac{\partial F}{\partial a}\right)^2 + \sigma_E^2\left(\frac{\partial F}{\partial E}\right)^2 + \sigma_Y^2\left(\frac{\partial F}{\partial Y}\right)^2 + 2\rho\sigma_E\sigma_y\frac{\partial F}{\partial E}\frac{\partial F}{\partial Y} \end{aligned} \quad . \tag{6.A26}$$

Subtracting the square of Eq.(6.A24) from Eq.(6.A26) finally yields the variance of F

$$\sigma_F^2 \approx \sigma_C^2\left(\frac{\partial F}{\partial a}\right)^2 + \sigma_E^2\left(\frac{\partial F}{\partial E}\right)^2 + \sigma_Y^2\left(\frac{\partial F}{\partial Y}\right)^2 + 2\rho\sigma_E\sigma_y\frac{\partial F}{\partial E}\frac{\partial F}{\partial Y} \quad . \tag{6.A27}$$

6.8.2 Calculation of Variance of Total Relative Costs

Total relative costs of abatement are defined by Eq.(6.14)

$$RC(R) = \frac{1}{Y}\int_{qY^m}^{E} a\,C\left(E^{\alpha} - e\,E^{\alpha-1}\right)de = \frac{a\,E^{1-\alpha}}{Y}\int_0^R C(r)\,dr \quad . \tag{6.A28}$$

The variance is obtained by applying Eq.(6.6) to RC. Partial derivatives of RC are as follows:

$$\left(\frac{\partial RC}{\partial a}\right)^2 = RC_0^2 \tag{6.A29}$$

$$\left(\frac{\partial RC}{\partial E}\right)^2 = RC_0^2\left((1-\alpha) + \frac{C_0}{RC_0}\frac{\partial R}{\partial E}\right)^2 \tag{6.A30}$$

$$\left(\frac{\partial RC}{\partial Y}\right)^2 = RC_0^2\left(\frac{C_0}{RC_0}\frac{\partial R}{\partial Y} - 1\right)^2 \tag{6.A31}$$

$$\left(\frac{\partial RC}{\partial Y}\right)\left(\frac{\partial RC}{\partial E}\right) = RC_0^2\left((1-\alpha)+\frac{C_0}{RC_0}\frac{\partial R}{\partial E}\right)\left(\frac{C_0}{RC_0}\frac{\partial R}{\partial Y}-1\right)$$
$$= RC_0^2\left(\frac{C_0^2}{RC_0^2}\frac{\partial R}{\partial E}\frac{\partial R}{\partial Y}+\frac{C_0}{RC_0}\left((1-\alpha)\frac{\partial R}{\partial Y}-\frac{\partial R}{\partial E}\right)-(1-\alpha)\right) \quad . \tag{6.A32}$$

The variance is thus:

$$\sigma_{RC}^2 \approx RC_0^2\left[\sigma_C^2+\sigma_E^2\left((1-\alpha)+\frac{C_0}{RC_0}\frac{\partial R}{\partial E}\right)^2+\sigma_Y^2\left(1-\frac{C_0}{RC_0}\frac{\partial R}{\partial Y}\right)^2\right.$$
$$\left.+2\rho\sigma_E\sigma_Y\left((1-\alpha)+\frac{C_0}{RC_0}\frac{\partial R}{\partial E}\right)\left(\frac{C_0}{RC_0}\frac{\partial R}{\partial Y}-1\right)\right] \quad , \tag{6.A33}$$

For a quota, $\partial R/\partial Y$=0, and thus:

$$\sigma_{RC,Cap}^2 \approx RC_0^2\left[\sigma_C^2+\sigma_E^2\left((1-\alpha)+\frac{C_0}{RC_0}\frac{\partial R}{\partial E}\right)^2+\sigma_Y^2-2\rho\sigma_E\sigma_Y\left((1-\alpha)+\frac{C_0}{RC_0}\frac{\partial R}{\partial E}\right)\right] \tag{6.A34}$$

The condition under which the variance is lower under an intensity target than under a cap then becomes

$$\sigma_{RC,Int}^2 < \sigma_{RC,Cap}^2 \tag{6.A35}$$

$$\Leftrightarrow \quad \sigma_Y^2\left(1-\frac{C_0}{RC_0}\frac{\partial R}{\partial Y}\right)^2+2\rho\sigma_E\sigma_Y\left((1-\alpha)+\frac{C_0}{RC_0}\frac{\partial R}{\partial E}\right)\frac{C_0}{RC_0}\frac{\partial R}{\partial Y} < \sigma_Y^2 \tag{6.A36}$$

$$\Leftrightarrow \quad \frac{1}{2}\frac{\sigma_Y}{\sigma_E}\frac{\left(2-\frac{C_0}{RC_0}\frac{\partial R}{\partial Y}\right)}{\left(1-\alpha+\frac{C_0}{RC_0}\frac{\partial R}{\partial E}\right)} < \rho \tag{6.A37}$$

$$\Leftrightarrow \quad \frac{1}{2}\frac{\sigma_Y}{\sigma_E}\frac{\left(2+qm\frac{C_0}{RC_0}\right)}{\left(1-\alpha+\frac{C_0}{RC_0}\left(\alpha+q(1-\alpha)\right)\right)} < \rho \quad . \tag{6.A38}$$

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