CLIMATE CHANGE

Scientific Assessment and Policy Analysis

WAB 500102 029

# Balancing the carbon market

## Overview of carbon price estimates

CLIMATE CHANGE

SCIENTIFIC ASSESSMENT AND POLICY ANALYSIS

# BALANCING THE CARBON MARKET

## Overview of carbon price estimates

**Report**
500102 029
ECN-B--09-007

**Author**
T. Bole

**March 2009**

This study has been performed within the framework of the Netherlands Research Programme on Scientific Assessment and Policy Analysis for Climate Change (WAB), Balancing the Carbon Market

## Wetenschappelijke Assessment en Beleidsanalyse (WAB) Klimaatverandering

Het programma Wetenschappelijke Assessment en Beleidsanalyse Klimaatverandering in opdracht van het ministerie van VROM heeft tot doel:

- Het bijeenbrengen en evalueren van relevante wetenschappelijke informatie ten behoeve van beleidsontwikkeling en besluitvorming op het terrein van klimaatverandering;
- Het analyseren van voornemens en besluiten in het kader van de internationale klimaatonderhandelingen op hun consequenties.

De analyses en assessments beogen een gebalanceerde beoordeling te geven van de stand van de kennis ten behoeve van de onderbouwing van beleidsmatige keuzes. De activiteiten hebben een looptijd van enkele maanden tot maximaal ca. een jaar, afhankelijk van de complexiteit en de urgentie van de beleidsvraag. Per onderwerp wordt een assessment team samengesteld bestaande uit de beste Nederlandse en zonodig buitenlandse experts. Het gaat om incidenteel en additioneel gefinancierde werkzaamheden, te onderscheiden van de reguliere, structureel gefinancierde activiteiten van de deelnemers van het consortium op het gebied van klimaatonderzoek. Er dient steeds te worden uitgegaan van de actuele stand der wetenschap. Doelgroepen zijn de NMP-departementen, met VROM in een coördinerende rol, maar tevens maatschappelijke groeperingen die een belangrijke rol spelen bij de besluitvorming over en uitvoering van het klimaatbeleid. De verantwoordelijkheid voor de uitvoering berust bij een consortium bestaande uit PBL, KNMI, CCB Wageningen-UR, ECN, Vrije Universiteit/CCVUA, UM/ICIS en UU/Copernicus Instituut. Het PBL is hoofdaannemer en fungeert als voorzitter van de Stuurgroep.

## Scientific Assessment and Policy Analysis (WAB) Climate Change

The Netherlands Programme on Scientific Assessment and Policy Analysis Climate Change (WAB) has the following objectives:

- Collection and evaluation of relevant scientific information for policy development and decision–making in the field of climate change;
- Analysis of resolutions and decisions in the framework of international climate negotiations and their implications.

WAB conducts analyses and assessments intended for a balanced evaluation of the state-of-the-art for underpinning policy choices. These analyses and assessment activities are carried out in periods of several months to a maximum of one year, depending on the complexity and the urgency of the policy issue. Assessment teams organised to handle the various topics consist of the best Dutch experts in their fields. Teams work on incidental and additionally financed activities, as opposed to the regular, structurally financed activities of the climate research consortium. The work should reflect the current state of science on the relevant topic.

The main commissioning bodies are the National Environmental Policy Plan departments, with the Ministry of Housing, Spatial Planning and the Environment assuming a coordinating role. Work is also commissioned by organisations in society playing an important role in the decision-making process concerned with and the implementation of the climate policy. A consortium consisting of the Netherlands Environmental Assessment Agency (PBL), the Royal Dutch Meteorological Institute, the Climate Change and Biosphere Research Centre (CCB) of Wageningen University and Research Centre (WUR), the Energy research Centre of the Netherlands (ECN), the Netherlands Research Programme on Climate Change Centre at the VU University of Amsterdam (CCVUA), the International Centre for Integrative Studies of the University of Maastricht (UM/ICIS) and the Copernicus Institute at Utrecht University (UU) is responsible for the implementation. The Netherlands Environmental Assessment Agency (PBL), as the main contracting body, is chairing the Steering Committee.

**For further information:**

Netherlands Environmental Assessment Agency PBL, WAB Secretariat (ipc 90), P.O. Box 303, 3720 AH Bilthoven, the Netherlands, tel. +31 30 274 3728 or email: wab-info@pbl.nl.
This report in pdf-format is available at www.pbl.nl

# Preface

This report was commissioned by the Netherlands Programme on Scientific Assessment and Policy Analysis (WAB) Climate Change. This report has been written by the Energy research Centre of the Netherlands (ECN), as a deliverable of the WAB project 'Balancing the carbon market'. The steering committee of this project consisted of Gerie Jonk (Ministry of Environment), Marcel Berk (Ministry of Environment), Joelle Rekers (Ministry of Economic affairs), Maurits Blanson Henkemans (Ministry of Economic Affairs), Bas Clabbers (Ministry of Agriculture), Remco vd Molen (Ministry of Finance) and Leo Meyer (PBL).

The author acknowledges receiving helpful comments from Michel den Elzen (PBL) and Jos Sijm (ECN).

**This report has been produced by:**

Tjaša Bole
Energy research Centre of the Netherlands (ECN)

**Name, address of corresponding author:**
Tjaša Bole
Energy research Centre of the Netherlands (ECN)
Unit Policy Studies
P.O. Box 56890
1040 AW Amsterdam, The Netherlands
http://www.ecn.nl
E-mail: bole@ecn.nl

**Disclaimer**

Statements of views, facts and opinions as described in this report are the responsibility of the author.

# Contents

***List of Tables***

***List of Figures***

# Executive Summary

The costs associated with climate policy are of high interest to both governments and economic agents in developed and in developing countries. When a clear climate target is set, the carbon price should reflect the marginal costs associated with implementing the mitigation measures that will stabilize the concentration of GHG to the level specified by the target.

For this report, we performed a literature review of scientific models that calculate a global carbon price. The search ultimately yielded thirty studies presenting results from twenty-seven different scientific models for a total of seventy-six observations and six projections from private actors on the carbon market.

The below table summarizes the outcomes of the literature review of scientific models assuming global cooperation in GHG mitigation. It presents the basic statistics of carbon price projections for different stabilization levels:

*Table ES.1 Summary statistics of model-based projections of 2020 carbon prices (\$2008/t$CO_2$)*

| | All estimates | $CO_2$eq stabilization at 450 ppm | $CO_2$eq stabilization at 550 ppm | $CO_2$eq stabilization at 650 ppm |
|---|---|---|---|---|
| Min | 0.6 | 31.4 | 2.6 | 0.6 |
| Max | 234.6 | 76.6 | 234.6 | 63.5 |
| Average | 33.6 | 52.1 | 48.2 | 17.3 |
| St. dev | 36.4 | 19.2 | 48.2 | 13.5 |
| No of observ. | 64 | 5 | 25 | 33 |

One of the main conclusions stemming from the literature overview is that very little modelling work has been done on low stabilization levels of GHG concentration, which is of most relevance for climate policy. The few studies that do address the implications of achieving low stabilization levels (around 450 ppmv $CO_2$eq), on average estimate a carbon price of 52 \$/t$CO_2$, while those analyzing the costs of stabilization around 550 ppm $CO_2$eq come to an average figure of 48 \$/t$CO_2$. The high standard deviation around the average estimate testifies to the large model and parameter uncertainties inherent to the modelling process and calls for cautious interpretation of modelling results, both when comparing the outcomes of different models and in their individual use.

Most models assume optimal abatement policies with full *when* and *where* flexibility, meaning that abatement can happen whenever and wherever it is cheapest globally. The related carbon credit prices are thus global carbon prices set on a single global carbon market and equal the marginal abatement cost of the last option in the least-cost abatement mix required to achieve a pre-determined climate target. This is of course not the case on the actual carbon market.

There are only a few exceptions found in the literature. Those studies explore the effect of delayed developing countries participation on the carbon market. The outcomes of those studies set carbon prices in 2020 to be in the range from a few \$/t$CO_2$ to several hundred \$/t$CO_2$, depending on the climate target and the date of entry of developing countries into a global climate coalition. Because of the small number of such studies, the different assumptions they use on the date of entry of developing countries into a global climate coalition and the different GHG constraints they apply in their models, it is very difficult to draw any robust conclusions on the cost of global climate policy under imperfect cooperation.

The same reasons make it also difficult to compare the estimates of carbon prices under full and imperfect cooperation. Although the average projected carbon price in studies assuming full global cooperation is indeed lower than the average estimate of studies assuming imperfect cooperation, because of the small number of latter, such comparisons are of limited value.

An altogether different approach is followed by private sector players on the carbon market. They mainly focus on a particular type of carbon credit and because the EU ETS is the largest segment of the carbon market, we collected their estimates on the price of the EUAs in the third commitment period, from 2013 to 2020. Their estimates vary from 33 €/t$CO_2$ to 48 €/t$CO_2$.

Finally, to develop an idea on the predictive power of model-based carbon price projections we compared older studies performed on the Kyoto-made carbon market and their projections on the carbon prices for the period 2008-2012 with the real forward carbon prices for the same period. We compare market CER price to the carbon price calculated by models assuming worldwide carbon trading and market ERU price to model-based carbon price estimates under the assumption of carbon trading being restricted to Annex B countries. We find that in the first case, the bias is mostly towards underestimation of the actual market price but can to a large extent be explained by the sales of 'hot air'. In the models, much more 'hot air' is assumed to reach the carbon market then actually has so far. If more excess AAUs were to be sold, they would depress the CER price closer to model-based estimates. The opposite is true for the case of ERUs, where most model-based carbon price estimates appear to be an upward bias and cannot be explained by sales of 'hot air'.

# Samenvatting

De kosten die verbonden zijn aan klimaatbeleid zijn van groot belang voor overheden en economische actoren in ontwikkelde landen en ontwikkelingslanden. Zodra een duidelijke klimaatdoelstelling is vastgesteld, zou de prijs van $CO_2$ duidelijk moeten weergeven welke marginale kosten verbonden zijn aan het implementeren van mitigatiemaatregelen die de concentratie van broeikasgassen stabiliseren op het niveau dat is vastgelegd in de doelstelling.

Voor dit rapport is een literatuurstudie gedaan naar wetenschappelijke modellen die de mondiale koolstofprijs berekenen. Het onderzoek bracht dertig studies naar voren waarin resultaten werden gepresenteerd van 27 verschillende wetenschappelijke modellen voor een totaal aantal van 76 wetenschappelijke rapporten en zes projecties van private actoren in de koolstofmarkt.

Tabel ES.1 geeft een samenvatting van de resultaten van de literatuurstudie van wetenschappelijke modellen waarbij wordt uitgegaan van wereldwijde samenwerking in broeikasgasmitigatie. Het geeft de basisstatistieken weer van $CO_2$-prijsprojecties voor verschillende stabilisatieniveaus:

*Tabel ES.1: Samenvatting van statistieken modelgebaseerde projecties van CO2-prijzen in 2020 (\$2008/t$CO_2$)*

| | Alle schattingen | $CO_2$eq stabilisatie op 450 ppm | $CO_2$eq stabilisatie op 550 ppm | $CO_2$eq stabilisatie op 650 ppm |
|---|---|---|---|---|
| Min | 0,6 | 31,4 | 2,6 | 0,6 |
| Max | 234,6 | 76,6 | 234,6 | 63,5 |
| Gemiddelde | 33,6 | 52,1 | 48,2 | 17,3 |
| Standaard. afwijking | 36,4 | 19,2 | 48,2 | 13,5 |
| Aantal observaties | 64 | 5 | 25 | 33 |

Een van de belangrijkste conclusies die getrokken kan worden uit het literatuuroverzicht is dat erg weinig modellenwerk is gedaan op het gebied van lage stabilisatieniveaus van broeikasgasconcentraties, iets wat juist zeer relevant is voor klimaatbeleid. De weinige studies die wel aandacht besteden aan de gevolgen van het behalen van lage stabilisatieniveaus (rond 450 ppm $CO_2$eq) komen uit op een gemiddelde schatting van een $CO_2$-prijs die 52 \$/t$CO_2$ bedraagt, terwijl diegenen die de kosten analyseren op een niveau van 550 ppm $CO_2$eq uitkomen op 48 \$/t$CO_2$. De hoge standaardafwijkingen benadrukken de grote model- en parameteronzekerheden die inherent zijn aan het modelleringproces en tonen de noodzaak aan van voorzichtige interpretatie van modelresultaten, zowel bij vergelijkingen tussen verschillende modellen als bij individueel gebruik van de modellen.

De meeste modellen gaan uit van flexibiliteit ten aanzien van *wanneer* en *waar*, wat inhoudt dat emissiereductie kan plaatsvinden wanneer en waar het wereldwijd gezien het goedkoopst is. Het daaruit voortvloeiende carbon credit prijzen zijn dus mondiale koolstofprijzen die zijn vastgesteld op een mondiale broeikasgasmarkt en gelijk zijn aan de marginale reductiekosten of de laagste–kosten-reductiemix die nodig is om een vastgestelde klimaatdoelstelling te behalen. Uiteraard is dit op de huidige koolstofmarkt niet het geval.

Slechts enkele uitzonderingen zijn te vinden in de literatuur. Deze studies onderzoeken het effect van de vertraagde deelname van ontwikkelingslanden aan de koolstofmarkt. De uitkomsten van deze studies geven aan dat de $CO_2$-prijs in 2020 varieert van enkele tot enkele honderden \$/t$CO_2$, afhankelijk van de klimaatdoelstelling en het jaar waarop ontwikkelingslanden zijn toegetreden tot de mondiale klimaatcoalitie. Vanwege het beperkte aantal van dit soort studies, de verschillende toetredingsdata van ontwikkelingslanden tot de mondiale klimaatcoalitie die gehanteerd worden en de verschillende broeikasgasbeperkingen die toegepast worden in de modellen is het erg moeilijk om robuuste conclusies te trekken over de

$CO_2$-prijs of welvaartkosten van klimaatbeleid onder gebrekkige samenwerkingsomstandigheden.

Om dezelfde redenen is het ook moeilijk om de $CO_2$-prijsresultaten bij perfecte en imperfecte competitie te vergelijken. Hoewel de gemiddelde $CO_2$-prijs in studies die perfecte competitie aannemen lager is dan die in studies met imperfecte competitie is, is deze observatie van beperkte waarde door het kleine aantal studies onder zulke aannamen.

Een totaal andere aanpak wordt gevolgd door spelers op de $CO_2$-markt die afkomstig zijn uit de private sector. Zij concentreren zich vooral op een specifiek type carbon credit en omdat de EU ETS het grootste segment van de $CO_2$-markt beslaat hebben we hun schattingen verzameld ten aanzien van de prijs van de EUA's in de derde budgetperiode, welke loopt van 2013 tot 2020. Hun schattingen variëren van 33 €/t$CO_2$ tot 48 €/t$CO_2$.

Om tot slot ideeën te ontwikkelen over de voorspellende kracht van modelgebaseerde $CO_2$-prijsprojecties hebben we oudere studies over de door Kyoto gecreëerde koolstofmarkt en hun projecties ten aanzien van de $CO_2$-prijs in de periode 2008-2012 vergeleken met de echte termijnmarktkoers van $CO_2$-prijzen voor dezelfde periode. We vergelijken de CER-marktprijs met de $CO_2$-prijs berekend door modellen die uitgaan van wereldwijde emissiehandel en ERU-marktprijs tot model-gebaseerde koolstofprijsschattingen waarbij aangenomen wordt dat koolstofhandel beperkt wordt tot Annex-B landen. In het eerste geval blijkt er een neiging te bestaan tot onderschatting van de echte marktprijs, maar dit kan grotendeels worden verklaard door de verkoop van 'hot air'. In de modellen wordt aangenomen dat veel meer 'hot air' de markt zal bereiken dan tot nu toe is gebeurd. Als meer AAU's verkocht zouden worden zou dit de CER-prijs naar beneden drukken richting de schattingen op basis van de modellen. Het tegenovergestelde gebeurt bij ERU's, waarbij de $CO_2$-prijsschattingen op basis van modellen eerder een neiging tot overschatting tonen welke niet kan worden verklaard door de verkoop van 'hot air'.

# List of acronyms

| | |
|---|---|
| AI | Annex I |
| AAU | Assigned Amount Units |
| CCS | $CO_2$ capture and storage |
| CDM | Clean Development Mechanism |
| CER | Certified Emission Reduction |
| EUA | EU Allowance |
| ERU | Emission Reduction Unit |
| EU ETS | EU Emissions Trading Scheme |
| GDP | Gross Domestic Product |
| GHG | Greenhouse gas |
| IPCC | Intergovernmental Panel on Climate Change |
| JI | Joint Implementation |
| JRC | Joint Research Centre of the European Commission |
| NAI | Non-Annex I |
| OECD | Organisation for Economic Cooperation and Development |
| UNFCCC | United Nations Framework Convention on Climate Change |

# 1 Introduction

The costs associated with climate policy are of high interest to both governments and economic agents that would incur increased costs related to climate measures. When a clear climate target is set, the carbon price should reflect the costs associated with implementing the mitigation measures that will stabilize the concentration of GHG to the level specified by the target.

The most systematic attempt at quantifying the costs of climate policies is represented by a number of global models that produce estimates of future GHG emission levels, the abatement necessary to achieve a pre-determined stabilization level of GHG concentration and the related costs or welfare losses of achieving those climate goals. The type of models employed for such assessments are presented in section 2.

The main aim of this report is to provide an overview of studies exploring the costs of climate policy and consider their main differences. Therefore, in section 3 we present carbon price projections for 2020 together with the main factors affecting the carbon price calculation. Those factors are crucial to a correct interpretation of the results of model-based studies estimating future carbon prices. Where available, we also present the related aggregate costs for the different regions in terms of loss/gain of welfare and the financial flows resulting from trading on the carbon market. The data allows for a systematic analysis on the current state-of-the-art climate policy modelling and some general conclusions on estimates provided by such models.
A rather different approach is followed by carbon market players from the private sector (banks, traders, consultants), who focus mainly on the segment of the carbon market that is relevant for their clients, but nevertheless offers valuable insights into future development of the carbon market. Because such commercial estimates are not built on the same assumptions as those in model-based studies, we cannot directly compare them.

There are large uncertainties that surround model-based projections on carbon prices, which call for caution in their interpretation and use in developing climate policies. Anyone wishing to use model predictions must be careful both when using any particular model as well as when comparing results from different models. Those uncertainties and limitations are discussed in section 4.

Nevertheless, if the relevant limitations are kept in mind, models can give a useful estimate of what would happen if a certain policy was to be implemented and if the assumptions made in the model proved to be correct. To assess to what extent that has happened so far, in section 5 of this report we compare older studies performed on the Kyoto-made carbon market and their projections on the carbon prices for the period 2008-2012 with the real forward carbon prices for the same period. In this way, we develop an idea on the predictive power of carbon price projections.

# 2 Methodology

## 2.1 Approach and inclusion criteria for literature overview

A literature review has been conducted to identify studies which use different types of models to assess the costs of stabilizing global GHG emissions at a pre-determined level. Only studies considering stabilization target categories I to IV as defined by the IPCC (Fisher & Nakicenovic, 2007) were included in the overview.

The search covered both scientific and commercial providers of carbon price estimates and was focused on the following sources:

- peer-reviewed journals,
- working papers from institutes developing such models,
- newsletters and reports of banks with carbon trading desks,
- newsletters and reports of carbon service consultants.

Initially, we have relied on the study by Kuik et al (2008) as a useful starting point offering a good overview of the different models that yield carbon prices and expanded on their work by including results from more studies focusing on lower stabilization levels.

The overview presented here includes results of studies from:

- The Energy Modelling Forum (EMF) of the Stanford University in the USA, which is the scientific forum where most such models are developed. Unfortunately, virtually all EMF studies focus on stabilization levels of 650 ppm $CO_2$eq (or 4,7 W/$m^2$) by 2100, which is a level widely regarded as insufficient to keep temperature rises below 2 degrees Celsius.
- The Innovation Modelling Comparison project (IMCP),[1] which brought together several modelling teams that analysed the cost stabilization level around 550 ppm $CO_2$eq.
- The studies for the category I stabilization scenario (400 – 490 ppm $CO_2$eq ) found in the IPCC FAR Chapter III (results from the MESSAGE and IMAGE models), which we complement with same-stabilization level results from the WIAGEM (Kemfert & Truong, 2007) and ENTICE-BR models (Popp, 2006). In general, very few studies focus on very low stabilization levels, something that IPCC (2007) already noted as well.
- Several other independently conducted studies not belonging to any particular scientific forum.
- A number of private actors on the carbon market.

The search ultimately yielded thirty studies presenting results from twenty-seven different scientific models for a total of seventy-six observations and six projections from private actors on the carbon market. It has to be noted immediately that the vast majority of scientific models calculate the price of a global carbon credit, while the commercial projections of carbon traders and consultants relate to a specific type of credit, in our case the European Emission Allowance (EUA), which is traded in the European carbon trading scheme (the EU-ETS) and thus cannot be directly compared.

The studies results are originally obtainable in different unit measures and different years of their monetary values. All results presented here are normalized to the unit US\$/t$CO_2$ by multiplying prices expressed in \$/tC by the conversion factor 12/44 after which all prices were brought to 2008 levels by using IMF world inflation figures (defined by changes in average

---

[1] The IMPCT represents a first systematic attempt to assess and compare the progress made through different modelling approaches (Edenhofer et a., 2006).

consumer prices)[2]. For prices expressed in EUR, the exchange rate of 1 EUR = 1,27 USD was used[3]. The 2020 carbon prices reported here are thus constant prices in 2008 US$.

## 2.2 Results presentation

We present the carbon price projections of the studies surveyed in two parts, depending on their assumption on the level of participation in a global climate coalition. In the first group, which includes the vast majority of studies, are those that assume simultaneous full global participation in the climate coalition, allowing for the most cost-effective mitigation on a global level. Those studies are presented in section 3.1.1. Studies that explicitly model delayed participation of developing countries in a global climate agreement or even differentiate emission reduction targets between developed and developing countries are presented separately in section 3.1.2.

Results of carbon market players from the private sectors are presented last, as they focus on one specific segment of the global carbon market, the EU-ETS. Their forecasts of the price the EU Allowance (EUA) are presented in section 3.3.

### 2.2.1 Model typology and relevant factors affecting model results

Several types of scientific models are employed around the world to assess the effects of climate policy on economic systems and emission levels. Understanding their differences is crucial for a correct interpretation and comparison of their outcomes. The most basic distinction is between top-down (economic) and bottom-up (engineering) models. In the modelling literature, different and more elaborate model classifications can be found. Most models would fall into one of the categories discussed next, though many models also have characteristics of both.

*a) Top-down models*

Top-down models are rooted in the macro-economic tradition and hence focus on market interactions within the whole economy. They have little technological detail in the energy sector (van Vuuren et al., 2009). Edenhofer et al (2006) and Springer (2003) provide a concise overview of the different model types. Among top-down models, the most common types are:

- Optimal growth models (or Iintegrated assessment models): In these models economic growth is a major driver of GHG emissions. These models are aimed at understanding growth dynamics over long term horizons. Their key property is their social welfare maximizing behaviour. They help answer the questions of whether, when and how to address the problem of climate change. Their economic component belongs to one of the other model groups described here, most commonly the CGE.
- Computable general equilibrium models (CGE): They can be static or dynamic. Their major advantage is their ability to model the influence of energy policy on other industry sectors and often also on international trade. A major shortcoming is their assumption of perfect markets, which are supposed to be in equilibrium at the starting point of the analysis. Furthermore, CGE models typically do not include any mitigation measures at negative cost, since they assume no-regret options to be developed in the baseline.
- Simulation and econometric models (or macroeconomic models): they are based on a disequilibrium macroeconomic structure and allow for imperfect competition.

---

[2] It must be noted that these carbon prices were usually presented on graphs as a function of time for the period until 2100 which means most of the figures in the table have read from such graphs and may not be always accurate to the last cipher.

[3] This exchange rate was employed by Russ et al (2007) to convert the outcomes of their GEM-E3 model from US$ to EUR, hence we employed the same exchange rate to convert their results back to US$.

*b) Bottom-up models*
Bottom-up models look at technology from an engineering point of view. A stylized bottom-up approach focuses on the substitutability of individual energy technologies and their relative costs. The typical bottom-up approach focuses on the energy system itself (and not on the relationship with the economy as a whole). In many bottom-up approaches, the current energy system is not necessarily assumed to be optimal. Therefore, analysts tend to find that currently several cost-efficient technologies are not used due to implementation barriers – and low-costs improvements can be made by using these technologies (van Vuuren et al., 2009).

The most typical bottom-up model type is:

- Energy system models: Their main advantage is that they represent the energy sector in much more detail than top-down models, while their main disadvantages are that energy demand is externally determined and independent of price and they represent only the energy sector.

*c) Hybrid models*
Recently, an increasing number of hybrid models have emerged, which aim at combining the advantages of both perspectives by linking macro-economic and technology model components.

There is considerable debate in the literature on whether there is a systematic difference in the estimates provided by top-down or bottom-up models. Previous model comparison exercises have either shown that:

- Bottom-up models were providing systematically higher reduction potentials and lower costs compared to the top-down studies (Springer, 2003).
- There are differences even within the group of top-down models, as CGE models (top-down) tend to calculate higher mitigation costs than both energy system models (bottom-up) as well as economic growth models (top-down) (Loschel 2002), a finding confirmed by Edenhofer et al. (2006).
- Bottom-up models provide slightly less potential at low prices – and comparable estimates at high prices for total greenhouse gases (van Vuuren et al., 2009), which is contrary to any previous assessments.
- Finally Kuik et al (2008) performed a meta-analysis of recent studies into the costs of GHG mitigation policies that aim at the long-term stabilization of these gases in the atmosphere. They analyzed a data set comprising of differences and results of twenty-six different models to determine which of the different model elements have a statistically significant influence on the results. They find that the model type (so a model being top-down or bottom-up) does not have a statistically significant influence on the resulting carbon price at all.

Regardless on whether there is a systematic bias caused by the model type, (Edenhofer et al. (2006) argue the underlying reason for any differences is most likely in the assumptions commonly made by 'CGE modelers', 'energy system modelers', and 'economic growth modelers', e.g. about foresight and intertemporal behavior of the agents etc.

There are several other parameters to which the marginal carbon price estimates are sensitive, even when they analyse the cost of achieving the same stabilization level. According to Kuik et al. (2008) these are:

- GHG included ($CO_2$ only, multigas),
- emission baselines (increase in emissions within a given timeframe),
- assumed energy prices (oil price assumptions)
- induced technical change (additional technical change that occurs as a result of climate policy),
- intertemporal dynamics (whether a model solves the optimum for any given time step or for the whole period analysed),
- the inclusion of a backstop technology (e.g. CCS or a very expensive renewable option).

Most likely there are even more factors affecting the marginal carbon price, such as the discount level and assumptions on the price of renewables. These parameters should be kept in mind when comparing any model results because even results belonging to models of the same type can be significantly diverging due to different assumptions on those parameters. The overview in this study thus presents the carbon prices calculated by the different models together with the model elements found to have a significant effect on the result.

## 2.3 Approach to assessing the predictive power of model-based carbon price projections

The scientific-model based studies included in the literature overview in section 3 all attempt assessing the economic costs of long-term climate targets and present the carbon price as a function. By contrast, most studies assessing the impact of the first Kyoto commitment period provide a point estimate of the carbon price for the mid-period year 2010. These model-based price estimates for 2010 will be contrasted to actual forward market prices for carbon credits with delivery in 2010 to give an insight into the predictive power of the model-based estimates.

As argued by Pan (2005), conceptually, JI and CDM are partial emission trading among Annex I countries and global trading, respectively. This means we can interpret the price projections for trading among Annex B countries as an approximation of the Emission Reduction Units (or ERUs, the carbon credits earned under the JI), while the carbon credit under the assumption of worldwide trading could be seen as a proxy of the Certified Emission Reduction (CER) traded under the CDM. Only one study explicitly attempted at estimating the price of the EUA traded under the EU-ETS (Klepper & Peterson, 2006), to which we compare the market EUA price.

To assess the gap between model-based projections and the actual market price of carbon credits we plot both on the same graph. We only present results from studies based on assumptions that were closest to the actual developments of the carbon market in the Kyoto period, these are: 1) the absence of the US in the Kyoto Protocol and 2) limited sales of 'hot air' by the Economies in Transition (EITs).

The average market prices have been calculated from daily closing prices for each type of credit since the beginning of trading. The average forward CER price for delivery in 2010 consists of price quotations from mid 2007 to the end of November 2008, while the average EUA forward price for delivery in 2012 consists of quotations from beginning of 2006 to end of November 2008. The ERU prices are the average 2008 prices, which call for additional caution when comparing model-based price projections for 2010 with market data for 2008 (there is no reported forward prices for this type of carbon credit).

# 3 Overview of model results and analysis

## 3.1 Models assuming perfect carbon markets and full participation of developing countries

Table 3.1 presents the carbon price as estimated by the different models together with their individual parameters, such as the GHG included in abatement efforts, assumptions on emission baselines, the presence of induced technological change, intertemporal dynamic optimization and the existence of a back-stop technology[4]. Twenty-one studies are based on top-down modelling, which include a similar number of CGE models and integrated assessment models. There is only one macro-economic study in the dataset (the E3MG model). There are five studies using bottom-up models and a further five based on hybrid models, often integrating a top-down model of the economic system and a bottom-up model of mitigation options.

*Table 3.1 Overview of studies' main characteristics and model results for carbon prices in 2020 under a global cooperation climate regime*

| **Study no.** | **Author(s)** | **Model name** | **Model type** | **stabil. level (in $CO_2$ eq)** | **GHG included** | **Emissions baseline (ratio 2100/ 2000)[5]** | **ITC[a]** | **IDO[b]** | **BST[c]** | **Carbon prices in 2020 in $(2008)/ $tCO_2$** |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | *Kainuma et al. (1998)* | AIMS | top-down | n.s. | multigas | 3.1 | n.s. | no | n.s. | 53.1 |
| 2 | *Bosetti et al. (2007)* | WITCH | hybrid | 550 | $CO_2$ only (?) | 3.0 | yes | yes | yes | 88.7 |
| | | | | 650 | | | | | | 40.8 |
| 3 | *Tavoni et al. (2007)* | WITCH+forestry model | hybrid | 650 | $CO_2$ only (?) | 3.0 | yes | yes | yes | 29.0 |
| | | | | | | | | | | 9.7 |
| 4 | *Paltsev et al. (2005)* | EPPA | top-down | 650 | multigas | 3.9 | yes | no | yes | 25.2 |
| 5 | *Vaillancourt et al, 2004* | MARKAL | bottom-up | 650 | multigas | A1B scenario | na | na | na | 13.1 |
| 6 | *Sarofim et al, 2005* | MIT-IGSM | top-down | 550 | multigas | n.s. | no | no | yes | 2.6 |
| | | | | 650 | | | | | | 0.6 |
| 7 | *Kemfert & Truong, 2007* | WIAGEM | top-down | 490 | multigas | 3.1 | yes | yes | yes | 31.4 |
| | | | | 550 | | | | | | 21.8 |
| 8 | *Jensen (2006)* | EDGE | top-down | 650 | multigas | 1.4 (til 2030) | no | no | no | 0.7 |
| 9 | *Fujino et al. (2006)* | AIM | top-down | 650 | $CO_2$ only | 2.3 | no | no | no | 29.4 |
| | | | | | multigas | | | | | 21.0 |
| 10 | *Hanson and Laitner (2006)* | AMIGA | top-down | 650 | $CO_2$ only | 2.8 | yes | no | no | 23.5 |
| | | | | | multigas | | | | | 16.1 |
| 11 | *Böhringer et al. (2006)* | PACE | top-down | 650 | $CO_2$ only | 1.9 | no | yes | no | 18.7 |
| | | | | | multigas | | | | | 9.3 |
| 12 | *Jiang et* | IPAC | top- | 650 | $CO_2$ only | 2.3 | no | no | n.s. | 26.2 |

---

[4] A backstop technology is a carbon-free technology whose usage is not restricted by scarcity of non-reproducible production factors.

[5] We report the long time horizon for emission baselines (until 2100) because this is the time-span relevant for achieving a certain stabilization level of atmospheric concentration of GHG.

| Study no. | Author(s) | Model name | Model type | stabil. level (in $CO_2$ eq) | GHG included | Emissions baseline (ratio 2100/ 2000)[5] | ITC[a] | IDO[b] | BST[c] | Carbon prices in 2020 in $(2008)/ $tCO_2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | *al. (2006)* | | down | | multigas | | | | | 14.9 |
| 13 | *Fawcett and Sands (2006)* | SGM | top-down | 650 | $CO_2$ only | n.s. | no | no | no | 63.5 |
| | | | | | multigas | | | | | 18.7 |
| 14 | *Kemfert et al. (2006)* | WIAGEM | top-down | 650 | $CO_2$ only | 2.5 | yes | yes | no | 24.2 |
| | | | | | multigas | | | | | 12.1 |
| 15 | *Aaheim et al. (2006)* | COMBAT | top-down | 650 | $CO_2$ only | 4.1 | no | yes | no | 26.2 |
| | | | | | multigas | | | | | 22.4 |
| 16 | *Manne and Richels (2006)* | MERGE | hybrid | 550 | $CO_2$ only | 2.9 | yes | yes | yes | 67.3 |
| | | | | | multigas | | | | | 14.9 |
| | | | | 650 | $CO_2$ only | 2.9 | yes | yes | yes | 7.5 |
| | | | | | multigas | | | | | 2.6 |
| 17 | *van Vuren et al. (2007)* | IMAGE +FAIR-SiMCaP | top-down | 450 | multigas | 2.3 | yes | no | yes | 63.5 |
| | | | | 550 | | | | | | 15.9 |
| | | | | 650 | | | | | | 7.9 |
| 18 | *(Rao and Riahi, 2006)* | MESSAGE | bottom-up | 650 | $CO_2$ only | 2.2 | no | yes | yes | 3.9 |
| | | | | | multigas | | | | | 1.2 |
| 19 | *USCCSP (2006)* | IGSM | top-down | 550 | multigas | 3.4 | no | no | yes | 107.7 |
| | | | | 650 | | | | | | 31.2 |
| | | MERGE | hybrid | 550 | multigas | 3.4 | yes | yes | yes | 45.7 |
| | | | | 650 | | | | | | 3.3 |
| | | MiniCAM* | top-down | 550 | multigas | 3.2 | no | no | yes | 34.4 |
| | | | | 650 | | | | | | 5.5 |
| 20 | *Masui et al. (2006)* | AIM/Dynamic-Global | top-down | 550 | $CO_2$ only | 2.0 | yes | yes | yes | 4.8 |
| | | | | | | | no | | | 4.8 |
| 21 | *Bosetti et al. (2006)* | FEEM/ RICE** | top-down | 550 | $CO_2$ only | n.s. | yes | yes | no | 23.9 |
| | | | | | | | no | | | 43.1 |
| 22 | *Popp (2006)* | ENTICE-BR | top-down | 490 | $CO_2$ only | n.s. | yes | yes | yes | 34.5 |
| | | | | 550 | | | yes | | | 12.3 |
| | | | | 550 | | | no | | | 28.7 |
| 23 | *Edenhofer et al. (2006b)* | MIND | top-down | 550 | $CO_2$ only | n.s. | yes | yes | yes | 26.3 |
| | | | | | | | no | | | 234.6 |
| 24 | *Gerlagh (2006)* | DEMETER-1CCS | top-down | 550 | $CO_2$ only | 2.0 | yes | yes | yes | 4.8 |
| | | | | | | | no | | | 9.6 |
| 25 | *Sano et al. (2006)* | DNE21+ | bottom-up | 550 | $CO_2$ only | 3.4 | yes | no | yes | 52.7 |
| | | | | | | | no | | | 57.4 |
| 26 | *Hedenus et al. (2006)* | GET-LFL | bottom-up | 550 | $CO_2$ only | 3.2 | yes | no | yes | 67.0 |
| | | | | | | | no | | | 67.0 |
| 27 | *Rao et al.* | MESSAGE- | hybrid | 600 | multigas | 2.0 | yes | no | yes | 14.4 |

| Study no. | Author(s) | Model name | Model type | stabil. level (in $CO_2$ eq) | GHG included | Emissions baseline (ratio 2100/ 2000)[5] | ITC[a] | IDO[b] | BST[c] | Carbon prices in 2020 in \$(2008)/ $tCO_2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | *(2006)* | MACRO-MAGICC | | | | 2.6 | no | | | 14.4 |
| 28 | *Barker et al. (2006)* | E3MG | Macro-economic | 550 | $CO_2$ only | 2.0 | yes | no | yes | 51.7 |
| | | | | | | | no | | | 88.1 |
| 29 | *Crassous et al. (2006)* | IMACLIM-R | top-down | 550 | n.s. | n.s. | yes | no | no | 28.7 |
| | | | | | | | no | | | 95.7 |
| 30 | *IIASA (2007)* | MESSAGE | bottom-up | 470 | multigas | 0.9 (B1) | no | yes | no | 76.6 |
| | | | | 480 | | 1.7 (B2) | | | | 54.6 |

a- Induced technological change, b-Intertemporal dynamic optimization, c-Back-stop technology
* Same results using the MiniCAM have been presented also in Edmonds et al (2006)
** Results reported here are for the FEEM/RICE fast version (assumes faster technological development)

The results of the studies presented vary significantly due to the differences identified earlier, particularly the different assumptions on future emissions under a business-as-usual scenario. These occur because studies use different assumptions on economic growth, industry structure and technological developments, resulting in widely differing baseline emissions paths over time. The studies included in our overview differ significantly in their assumptions on emission baselines up until 2100, which vary from 1.9 to 4.1 times the emission levels in 2000.

Many of them explore cost differences for the two cases where only $CO_2$ mitigation is considered or all GHGs are included in abatement efforts. Induced technological change and inter-temporal dynamic optimization are included in more or less half of the models and backstop technology in two-thirds. An extensive debate about the influence of those determinants on the model results are beyond the scope of this paper but can be found in Kuik et al. (2008).

The carbon credit prices presented here are global carbon prices set on a single global carbon market and equal the marginal abatement cost of the last abatement option in the least-cost abatement mix required to achieve a pre-determined GHG stabilization target. It is worth noting again, that the carbon price can equal the marginal abatement cost only in a perfect carbon market, where no restrictions are posed on emissions trading and perfect information is available to all market players. In reality, carbon markets are far from being perfect and globally integrated (as will be discussed in chapter 4), so these estimates must be considered with care.

For a more systematic first analysis, we present the minimum, maximum, average and standard deviation for all estimates, for studies that consider only $CO_2$ abatement, for studies that consider all GHGs and for different stabilization levels (irrespective of the gasses included). A summary of this analysis is presented in table 3.2.

*Table 3.2 Summary statistics of model-based projections of 2020 carbon prices (\$2008/$tCO_2$)*

| | All estimates | $CO_2$ only | Multigas | $CO_2$eq stabilization at 450 ppm | $CO_2$eq stabilization at 550 ppm | $CO_2$eq stabilization at 650 |
|---|---|---|---|---|---|---|
| Min | 0.6 | 3.9 | 0.6 | 31.4 | 2.6 | 0.6 |
| Max | 234.6 | 234.6 | 107.7 | 76.6 | 234.6 | 63.5 |
| Average | 33.6 | 41.0 | 24.4 | 52.1 | 48.2 | 17.3 |
| St. dev | 36.4 | 43.5 | 24.7 | 19.2 | 48.2 | 13.5 |
| No of observ. | 64 | 31 | 31 | 5 | 25 | 33 |

As virtually all studies have found, multigas mitigation represents a cheaper abatement option compared to $CO_2$ abatement only; the average carbon price in the first case being 24 $/t$CO_2$ and in the second 41 $/t$CO_2$. As expected, stabilization at lower GHG concentration levels entails higher mitigation costs with the average carbon price in 2020 estimated at 52 $/t$CO_2$ for the 450 ppm stabilization target, 48 $/t$CO_2$ for the 550 ppm target and only 17 $/t$CO_2$ for the 650 ppm target. High figures for standard deviation, which measures the dispersion of the estimates from their mean (average), again point to the large differences between the results of the different models.

Interestingly, the difference between the average carbon credit price for the 450 and 550 ppm targets does not appear to be very large, although it is difficult to draw any solid conclusions on this due to the small number of observations available for the lowest stabilization level. Clearly, more research into the costs of low stabilization levels are required across the scientific forums to allow for significant comparison of different model results.

### 3.1.1 Models assuming delayed participation of developing countries

The models and their outcomes presented in the previous section assume full global participation in achieving a certain GHG stabilization level that allows the possibility of reducing emissions in the most cost-effective way anywhere in the world, which is often referred to as the 'when' and 'where' flexibility. This efficient mitigation strategy implies that an emissions trading scheme is present and emissions reductions are always made where and when they are cost optimal. Under an optimal mitigation scheme the developing countries are prominent contributors to mitigation efforts from the start of the global regime (Keppo & Rao, 2007). The macroeconomic modelling results reported in the IPCC’s Fourth Assessment Report (IPCC, 2007) also largely rely on the assumptions of full ‘when-and-where’ flexibility. That is, there would be flexibility across both space and time as to where and when reductions would be made (Richels et al., 2007). Such a first-best regime is characterized by the fact that it minimizes the economic costs of stabilization. To the extent the real world deviates from the first-best world, the global cost of stabilization will be higher (Edmonds et al., 2008).

There are few studies available that explore the effect of delayed developing countries participation on the carbon market. They are summarized in table 3.3. The results presented here are based on the assumption of full participation by all Annex I (AI) countries (including the US) and imperfect trade, whereby international trading gradually develops in time including more countries and sectors. Although all the studies in table 3.3 assume that non-Annex I (NAI) countries join the global climate coalition at some point in the future, they differ substantially on the timing of NAI involvement, the reduction levels they achieve and their availability as a source of carbon credits prior to their assuming emission reduction targets. Hence, there is again considerable variation in carbon price projections even for achieving the same stabilization levels.

*Table 3.3 Overview of studies and model results for carbon prices in 2020 in case of delayed participation of developing countries*

| Author(s) | Model name | stabilization level ( in $CO_2$ eq) | Year of NAI joining climate coalition | NAI countries with targets | trade with NAI before NAI join coalition | Carbon prices in $(2008)/tCO2 in 2020 |
|---|---|---|---|---|---|---|
| Bossetti et al (2008) | WITCH | 550 | 2035 | all | no | 478,7 |
| | | | | | yes | 119,7 |
| Edmonds et al. (2008) | MiniCAM | 550 | 2020-2035 | most advanced | no | 55,5 |
| | | 550 | 2035-2050 | | | 277,4 |
| | | 650 | 2020-2035 | | | 7,4 |
| | | 650 | 2035-2050 | | | 11,1 |
| Richels et al (2007) | MERGE | 550 | 2060 | all | no | 181,3 |
| | | 650 | | | | 92,5 |
| Russ et al (2007)[6] | POLES | 450 | After 2020 | high income | yes | 48<br>(in developed countries)<br>22<br>(in developing countries) |
| Russ et al (2009)[7] | POLES | 450 | 2012 | Brazil, China, India | yes | 66<br>(in developed countries)<br>30<br>(in developing countries) |
| Den Elzen et al (2008) | FAIR | 450 | 2012 | All except LDCs | Yes | 103 |

The first three studies assume that after NAI countries join the global climate agreement their participation is full and complete and emission abatement can now proceed in the most cost-efficient manner anywhere in the world, much as in the studies in table 3.1. In Bossetti et al (2008), allowing trading between AI and NAI even if NAI does not take on any emission targets leads to a carbon price which is almost the same as in the case of NAI entering the climate coalition immediately. Of course, for the period prior to NAI joining the climate coalition or if no trading is assumed, AI countries assume higher emission reductions, leading to higher mitigation costs for them.

The main difference of the last three studies in table 3.4 is that they do not simply follow the global MAC curve but they assign a certain level of emission reduction to both AI and NAI countries, and impose a certain level of abatement in AI even if cheaper options in NAI are still available. In all three cases the AI reduction target is 30% below 1990 levels and NAI reductions are 9, 16 and 8 per cent below baseline for Brazil, China and India in Russ et al (2009) and average of 16% below baseline for all NAI in den Elzen et al (2008).

Furthermore, Russ et al (2007) and Russ et al (2009) no longer assume ideal pathways with perfect trading in all sectors across all time periods and world regions. Instead, they aim at being more realistic while at the same time maintaining the idea of economic efficiency by a gradually developing global carbon market across sectors and countries, resulting in different abatement and thus different carbon costs (Russ et al., 2009). A carbon market exists for the sectors included in the EU ETS but it is not perfect and thus it does not equalise marginal abatement costs for the involved sectors on a global scale. Instead of this, the effective carbon prices are assumed to vary between the various regions in the world because of differences in transaction costs (see figure below), and they converge over time. Energy intensive sectors in developing countries are exposed to a low carbon price in 2012, simulating the limited

---

[6] This study includes the scenario analysis conducted as a contribution to the European Commission’s Communication of January 2007 on 'Limiting Global Climate Change to 2 Degrees Celsius – The Way Ahead for 2020 and Beyond (COM(2007)2).

[7] This study summarizes the modelling activities for the European Comission’s Communication 'Towards a comprehensive climate change agreement in Copenhagen', published on 28/1/2009.

penetration or visibility of a carbon price for all individual firms through policy instruments such as the CDM (Russ et al., 2009).

The only conclusions that can be drawn from the studies in table 3.3 is the intuitive finding that trading with NAI countries even before they enter the global climate coalition and pursue domestic mitigation action lowers the carbon price and thus the overall mitigation costs for AI countries.

Apart from this, no other observable trend can be detected: for example, in Edmonds et al (2008), the 550 ppm $CO_2$eq limit becomes unfeasible if NAI countries delay their participation after 2035, while in Richels et al (2007), the same stabilization level is still achievable if NAI only join the climate coalition only by 2060 and even at a cost lower then in both Bossetti et al's (2008) and Edmonds et al's (2008) scenario of NAI participation from 2035.

Bossetti et al (2008) estimate a carbon price almost twice as high as Edmonds et al (2008) for the 550 ppm target, despite both employing hybrid models with similar characteristics and similar assumptions on baseline emissions. Furthermore, den Elzen et al (2008) also calculate a price much higher then Russ et al (2009) for the same target of 450 ppm.

The difference in carbon price from the two JRC studies (Russ et al., 2007 and Russ eta al., 2009) is party explained by the fact that in the previous study by Russ et al. (2007), developing countries were assumed to be allowed to sell all their emission reductions compared to the baseline as carbon credits. In the 2009 study however, it has been assumed that they also have to carry out domestic reductions which they can not sell.

Despite their differencies, all studies are in accordance that delaying non-Annex I countries accession to a global climate coalition, significantly increases the cost of stabilizing the atmospheric GHG concentration at low levels. Keppo and Rao (2007) furthermore find that even short-term postponement of participation from some regions can often lead to a delay of mitigation measures on the global level. Mitigation costs are found to substantially increase as a result of delayed participation of NAI-the extent of the increase depends on the relative importance of the region that postpones its participation, the stringency of the climate target and the ability to reorganize mitigation measures. Their analysis also shows that a region's decision to delay its participation in an international climate regime can lead to accumulated inertia in its energy system and thus to a delayed 'technological transition' toward a low-carbon future (Keppo & Rao, 2007). All studies thus point to the urgency of domestic mitigation efforts in non-Annex I countries to achieve low stabilization levels without extremely high carbon prices.

A comparison with the studies included in the previous section shows that the average projected carbon price in studies assuming full global cooperation is indeed lower than the average estimate of studies assuming imperfect cooperation. However, most estimates assuming delayed NAI country participation (except for Bossetti et al, 2008) fall within the range of estimates of studies assuming full cooperation and because of the small number of former, such comparisons are of limited value.

## 3.2 Traded volumes, costs and benefits of climate policies

As most studies do not assume region-specific emission reduction targets, but rather assume full flexibility in achieving a certain level of stabilization, they cannot provide estimates of financial flows from one region to the other through carbon trade. In those studies costs are always represented on a global level.

There are, however, few exceptions. Some of the studies included in the overview do attempt some kind of differentiated constraints on a regional (or even country) level by making assumptions on the initial allocation of emission permits (Bossetti et al., 2007; Bossetti et al., 2008, Vaillancourt et al., 2004) or assume outright targets for developed and developing countries (den Elzen et al., 2008; Russ et al., 2009). This way, it is possible to estimate how much trade would develop under different stabilization scenarios and what kind of costs would be faced by different regions (countries).

Again, different studies have different focuses (from industrial $CO_2$ only to all GHGs), use different delineations of country groups (Annex I & non-Annex I, OECD & non-OECD, major countries only etc), different cost indicators (net present value percent GDP losses until 2100, gross & net mitigation costs in billion USD, fraction of total social cost of stabilization etc) and different time horizons and discount rates. Because of these differences it is extremely difficult to harmonize the different estimates of climate policy costs borne by the different regions, so an overview of those estimates is presented in Appendix A, in the same fashion as they are presented in the original studies. Furthermore, it must be noted that these values are computed under different assumption on the timing and level of participation of countries in the global climate coalition, which crucially affects the results, so they should not be directly compared.

Nevertheless, some general insights can be drawn:

- *The costs for developing countries as a group participating in a global climate agreement and limiting their emissions in line with a global target of 450 to 550 ppm $CO_2$eq are estimated to be from a fraction of a percent of their GDP* (Russ et al., 2009, den Elzen et al., 2008, Vaillancourt et al., 2004) *to a maximum of 7% of GDP* (Bossetti et al., 2007), the latter figure belonging to the unrealistic sovereignty principle for initial allocation of emission permits that assigns most reductions to developing countries.
- *Delaying participation in a climate agreement does not seem to significantly reduce costs for developing countries.* Bossetti et al (2007) and Bossetti et al (2008) estimate costs (under different emission allocation schemes) in the order of a few percent of GDP regardless of whether emission constraints are adopted immediately or only in 2035. Vaillancourt et al (2004) estimate the costs to be a fraction of a percent assuming immediate emission constraints for developing countries and den Elzen et al (2008) and Russ et al (2009) arrive at a similar estimate assuming emission reduction targets for developing countries only for the year 2020. Edmonds et al (2008) estimate the fraction of total social cost of stabilization borne by non-Annex I countries for different dates of entry and show that they are only marginally reduced for every subsequent period of entry into the climate coalition (2012, 2020 or even 2035). Even if developing countries do not assume any targets by 2020, they are still likely to experience a slight reduction in GDP, partly due to the reduced economic activity in the developed countries, which affects them through reduced international trade (Russ et., 2007).
- *There are large differences between developing countries.* According to Bossetti et al (2007), most developing countries, and in particular Sub-Saharan Africa and South Asia would realize considerable sales of carbon credits until 2100, more under a less stringent stabilization target of 550 ppm $CO_2$ (650 $CO_2$-eq) as opposed to a target of 450 ppm $CO_2$ ( 550 $CO_2$-eq). This has a clear implication for the geographical distribution of the costs of stabilising GHG concentrations in the atmosphere. In the 550 ppm $CO_2$ (650 $CO_2$ eq) scenario, all regions but Sub-Saharan Africa and South Asia bear some costs, albeit small. Sub-Saharan Africa and South Asia gain from selling permits. In the 450 ppm $CO_2$ (550 $CO_2$eq) scenario, costs are much larger and but Sub-Saharan Africa and South Asia still get some benefits, while China faces positive costs (Bossetti et al., 2007). The regional policy costs are presented in figure A.2 in Appendix A.
- *The size of the carbon market is projected to be very large.* Bossetti et al (2007) estimate that under a 650 ppm $CO_2$eq stabilisation scenario and 'equal per capita' allocation of initial permits, the volumes traded in the carbon market could reach almost 60 GtC (220 Gt $CO_2$eq) (an average of 0.6 GtC/yr (2.2 Gt $CO_2$eq/yr) or 10% of current emissions) over the next century, a figure that goes down to 35 GtC (128 Gt $CO_2$eq) in a 550ppm $CO_2$eq scenario, where the more stringent target requires more domestic action to abate GHG emissions. Den Elzen et al estimate carbon trade to reach almost 1 Gt $CO_2$eq by 2020, from which non-Annex I countries stand to gain revenues of almost 70 billion US$. Russ et al. (2009) estimate this figure at 40 billion US$ for the same year. Vaillancourt et al. (2004) estimate the value of emissions trading between 2010 and 2050 at over one trillion US$.

## 3.3 Commercial projections

Several market players, such as consultants specializing in support services to the carbon market or banks with carbon trading desks that buy and sell carbon permits for their clients (e.g. utility companies etc) also provide estimates of future carbon prices. Those are also often based on their own in-house developed models complemented with expert judgment. In contrast with global models presented above, which estimate a global carbon price, market players tend to focus on a particular type of carbon credits, mostly the European Emission Allowance (EUAs), which is of most relevance to their clients. Table 3.4 summarizes recent projections of EUA prices for the third EU-ETS trading period ending in 2020.

*Table 3.4 Overview of EUA price projections for the period 2013-2020*

| Company | Projected average shortfall ($MtCO_2eq/y$) | Internal abatement ($MtCO_2eq/y$) | CDM/JI ($MtCO_2eq/y$) | EUA price projection (eur/t) |
|---|---|---|---|---|
| Deutsche Bank (2008) | 207 | 100 | 107 | 42 |
| Fortis* | 480 | 376 | 104 | up to 48 |
| Societe Generale* | 500 | 475 | 25 | up to 35 |
| UBS* | 440 | 332 | 108 | - |
| JP Morgan (2008) | 600 | 355 | - | 33 |
| Carbon Trust (2007) and Grubb (2008)** | - | - | - | 20-40 |

* As reported by World Bank (2008)

** Grubb (2008) updated the original 15-50 eur/t estimate published in Carbon Trust (2007)

A separate category of carbon prices estimates is performed by Point Carbon. They also calculate a *global carbon price* in 2020, assuming that a cap-and-trade scheme along the lines of the original Lieberman-Warner bill will have been introduced in the US by 2020 and that in the EU ETS there will have been a 25% reduction target, including emissions from aviation[8]. Based on all this, they assume *a carbon price of 50 eur/t (USD 78 $/t) in 2020*. The value of the whole market under these assumptions is about 2 trillion EUR (3.1 trillion US$) (Point Carbon, 2008).

---

[8] Furthermore, they assume that by 2020 trading schemes are operational in Australia, New Zealand, Canada, Japan, Korea, Mexico and Turkey.

# 4 Uncertainties and limitations of model-based carbon price projections

Edenhofer et al (2006) distinguish two basic types of uncertainties, the *parameter* uncertainty, which applies to use of any model and the *model* uncertainty, which applies to comparison of results from different models. The latter means a structural uncertainty, defined as the uncertainty arising from having more than one plausible model structure (Morgan and Henrion 1990). This means that even models based on the same assumptions regarding their basic parameters can lead to different results. These issues need to be kept in mind when comparing results of different models.

Parameter uncertainty concerns all models irrespective of their type and must be taken into account when interpreting the results of any model. This type of uncertainty is discussed in more detail. It refers to a lack of empirical knowledge to calibrate the parameters of a model to their 'true' values. Parameter uncertainty implies an uncertainty of the predictions of any one model and discrepancies may result even in case of otherwise very similar models. In other words, no modeler has full information on 'real world developments' and while he can offer his best estimate of a certain development (e.g. on GDP growth rates and the related emission rates), they cannot predict with full certainty what the actual development of those parameters will be (the current credit crises that depressed economic growth rates worldwide, is a good example of the type of uncertainties faced by models trying to mimic global developments).

Out of the specific assumptions that influence the results of the model-studies, one of the most important ones underlying the stabilization scenarios includes the flexibility in policy design, seeking out least-cost options for emissions control regardless of where they occur, what substances are controlled, or when they occur (the *where, what,* and *when* flexibility). Allowing for these flexibilities will, under specified conditions, lead to least cost abatement. The economic characteristics of the scenarios fed into models normally assume a policy designed with the intent of achieving the required reductions in GHG emissions in a least-cost way. The assumptions used in these scenarios are convenient for analytical purposes, but it must always be kept in mind that they are idealized descriptions of possible outcomes and can be very different from the actual situation for many reasons. Springer & Varilek (2004) group them in factors that could increase and decrease the price. The two most important factors in the first group are:

- *Transaction costs*: In practice, emissions market participants will face transaction costs such as emissions monitoring and verification expenditures and fees for lawyers and brokers to assist with transactions. Onerous or complicated trading rules and failure to harmonize national trading systems will increase such costs.[9]
- *Emission trading scheme coverage*: Because emissions trading is not well suited to some sectors of the economy with numerous small sources, such as housing and transport, emissions reduction opportunities will have to be captured by other, potentially less-efficient policies. To the extent that some of these opportunities are not covered by an emissions trading regime or not captured by non-trading policy measures, those sectors that are covered by emissions trading will have to shoulder a greater share of countries' national emissions reduction targets, which will raise overall abatement costs and permit prices.

The opposite effect will come from factors that may decrease prices, which might be the following:

- *Banking*: Calculations of likely permit prices in any one time period overlook the possibility of capturing cost savings by banking unused permits from one time period to another. Most emissions trading programs allow for some form of banking. In this sense, intra-period

---

[9] More recently, the transaction costs associated with the use of the Kyoto flexible mechanisms are assumed to consist of a constant US$0.55 per tonne $CO_2$eq emissions plus 2% of the total costs (Michaelowa and Jotzo, 2005). The problem with this approach is of course that transaction costs are not constant and can differ significantly among mitigation measures and countries.

banking could exert downward price pressure. (On the other hand, if credits are banked for a subsequent trading period, it can also raise the prices in the current period, since the current reductions are not immediately supplied to the market. The net effect is not clear. This situation would apply for example to the case of EUAs. The situation is different for Assigned Amount Units (AAUs). The banking of AAUs of the transition economies clearly raises the prices of other types of carbon credits.

- *Penalty charges* act as a ceiling on permit prices. If the market permit price were to rise above the level of the per-unit penalty, sources would choose to pay the penalty rather than acquire permits. Generally, less stringent sanctions for non-compliance imply lower permit prices[10].
- *Permit allocation method*: In the presence of transaction costs, permit prices are not independent of the allocation method.
- *'Supplementarity'*: The use of Kyoto flexible mechanisms is likely to continue in one form or another after 2012, but the level to which mitigation efforts in non-Annex B countries will be pursuit by parties with reduction commitments is yet to be determined. If emission reductions in non-Annex B countries continue to be credited and traded as compliance credits in Annex B countries, it can lower the carbon price.

It is extremely difficult to estimate the net effect of all the factors that cause models to over or under-estimate the costs of curbing global GHG emissions. Grubb (2008) finds that forecasts of environmental control costs (that is costs induced by environmental legislation), and of energy demand / emissions, have persistently turned out to be too high. He cites the examples of CFC phase-out – for which realized costs proved to be around a third of the initial estimates – and the case of sulphur dioxide, where costs in the US trading scheme have been half to a third of initial estimates. For the case of energy forecasting, he reveals that records of forecasting aggregate energy demand concealed a systematic error of about 5% inflation in 5-year forecasts of industrial energy demand – the area most relevant to the EU ETS - that has not improved over the years. A consistent upward bias of far less than 5% in as many years, if sustained post 2012, would imply massive overestimation of the costs and difficulty of achieving the EU cap (Grubb, 2008). The same conclusion can be generalized to caps of all other Annex I parties and also for any possible agreements in industry sectors in emerging economies. The main reason for this is due to the fact that forecasts are based on economic or sector modelling, which 'use the past' to project the future. However, such projections go astray to the extent either that input assumptions on driving forces prove wrong, or future responses may not be a continuation of past patterns. In addition, economic growth and sector output projections are liable to systematic error, as there are strong political incentives for overoptimistic growth estimates (Grubb, 2008).

Furthermore, there is also the issue of market imperfections, such as asymmetric information, imperfect foresight and irrational behaviour, all of which affect market actors. The transaction costs mentioned above can be expanded from mere financial costs to include political and institutional barriers that often do not allow for mitigation efforts where costs are lowest. In fact, several authors have concluded that tradable permit programmes may be less appropriate for developing countries due to their lack of appropriate market or enforcement institutions (Blackman and Harrington, 2000; Bell and Russell, 2002).

Next, there are strategic considerations on behalf of governments mandating or buying carbon credits. According to Grubb (2003) the EU may be a buyer, but due to political considerations it cannot aim to be a least-cost buyer. Similarly, Japan has been known to exercise buyer sovereignty over whom it wishes to trade with and on what terms. The bottom line is that there are barriers to achieving the least-cost abatement path both on the sellers of carbon credits side as well as on the buyers' side.

---

[10] However, this is not the effect that penalties have in the EU-ETS where even if a company pays a penalty for not reaching its targets, it still has to compensate for their increased emissions the next year (meaning they have to increase their reductions next year), so then the penalty does not act as a ceiling.

Carbon market fragmentation is another issue to consider. At present, no such thing as a common global carbon price exists in the first place. There are several carbon markets, encompassing both allowances and project-based assets that coexist with different degrees of interconnection, leading to a fragmented global carbon market. Carbon markets so far have mostly been operating in isolation from each other, except where there is a linking through the CDM and JI markets. Provisions for linking exist for a number of cap and trade schemes but their diversity in design creates a significant challenge (WB, 2008). Possible developments in the direction of CDM discounting and sectoral crediting could cause even further market fragmentation. On the other hand, a global carbon market as advocated by the European Commission’s latest communication on how to reach a comprehensive climate change agreement in Copenhagen (EC, 2009), where it proposes to link comparable domestic emissions trading systems to ensure an OECD-wide market by 2015 and an even broader market by 2020, would bring the real situation closer to the one assumed in the models. This suggestion seems to be regarded possible by market actors as revealed by a survey conducted by Point Carbon among participants on the carbon market. Most (73% of the sample) think that there will be a global reference carbon price in 2020 (Point Carbon, 2008).

And finally, there is general uncertainty about the future, which extends to issues outside the carbon markets but have a direct impact on them. For instance, a change in energy prices has a tremendous effect on the cost-effectiveness of particularly the more expensive mitigation options (such as biofuels) (Bakker et al., 2009).

To conclude on a more general discourse level, some authors argue that future prices are always hard to predict and that the market for GHG permits is no exceptional case. Estimates of permit prices in the US $SO_2$ market have turned out wrong, even though that market was much smaller and less complex (Ellerman et al., 2000). If attempts to predict prices regularly fail in the stock markets, why should they be more accurate in a completely new market like the one for tradable GHG emission permits?

# 5 Performance of past model-based projections

To assess the practical value of model-based projections of carbon prices, a very simple 'reality-check' exercise is performed in the next section. We contrast carbon price projections for 2010 from older model-studies and the actual 2010 forward market price of two types of carbon credits which can be seen as proxies to the carbon prices estimated in model studies. The aim of this exercise is to assess how close the model-based estimates were to actual carbon prices.

Since the coming into force of the Kyoto protocol, an extensive body of literature has attempted to analyse the international market for Kyoto units. Most of the analysis use global models, as the ones discussed in the previous section. Springer (2003) and Haites (2004) provide a useful survey of the models used and key results for the Kyoto period from 2008-2012. Here, *we only include studies explicitly assuming the non-participation of the US.*

The second problematic assumption relates to the surplus AAUs in the first commitment period (the so-called 'hot air') in EITs. Almost all models show that EITs would have substantial AAUs surpluses, but the range of it varies sharply (Chen 2003). Even more than the existence of 'hot air', what matters for estimates of the carbon price in 2010 is the amount of it that the EITs are assumed to supply to the carbon market. Some of the studies assume a 'perfectly competitive' international market for Kyoto units where Russia and other transition economies are willing to sell their surplus Kyoto units even if the market price is very low and buyers always purchase the lowest cost units. Under such assumptions the demand for CERs in most of these analyses is zero. Those studies were not included into our overview as the current reality is completely different. Other analyses assume strategic behaviour by Russia, and possibly other transition economies. Since Russia's projected surplus is large relative to the anticipated demand for Kyoto units, it can increase the total revenue it receives by limiting the quantity it sells and thus raising the market price while simultaneously increasing the market for CERs (Haites, 2004).

Similarly to the analyses in the previous section, we must point to the important differences in the models presented here. The models used for these analyses differ in several ways, including their structure, the emissions covered ($CO_2$ only versus all greenhouse gases), the coverage of sinks (none to maximum allowable sinks), the potential scale of CDM activity (none to all reductions from business as usual emissions in developing countries), transaction costs for project-based mechanisms (none to 30%) and of course the amount of surplus AAUs sold by EITs. All of the models assume efficient domestic policies and no restrictions on domestic or international trade of Kyoto units except those explicitly modelled.

*Table 5.1 Overview of carbon price projections for 2010*[11] *(excl US participation)*

| Study | Model name | GHG included | Amount of AAU sold | Trading | Carbon prices in 2010 in $(2008)/tCO$_2$ |
|---|---|---|---|---|---|
| Den Elzen & De Moor (2002) | FAIR | multigas | 30%* (moderate growth scenario) | worldwide | **4,8** |
| Michaelowa & Jotzo (2002) | PET (calibrated version) | CO$_2$ only | 33% | worldwide | **6,7** |
| Blanchard et al (2002) | POLES | CO$_2$ only | 10%* | worldwide | **8,2** |
| Grütter (2001) | CERT | multigas | 50% | worldwide | **1,5** |
| Manne & Richels (2004) | MERGE | CO$_2$ only | n.s. (very restricted)** | worldwide | **48,4** |
| McKibbin & Wilcoxen (2004) | G-CUBE | n.s. | n.s. (very restricted)** | worldwide | **10,2** |
| Babiker et al (2002) | MIT-EPPA | multigas | 50% | within Annex B | **13,3** |
| Böhringer (2001) | G-TAP based CGE model | CO$_2$ only | 40%* | within Annex B | **27,6** |
| Böhringer & Löschel (2001) | POLES | CO$_2$ only | 23% | within Annex B | **7,7** |
| Eyckmans et al (2001) | MacGEM | CO$_2$ only | 15%* | within Annex B | **28,4** |
| Löschel & Zhang (2002) | Mathematical model+POLES | CO$_2$ only | 47%* | Within Annex B | **22** |
| Klepper & Peterson (2006) | DART | CO$_2$ only | 0% | Annex B (no CDM) | **15,9*** ** |
|  |  |  |  | worldwide (including CDM) | **11,5*** ** |

* revenue optimizing sales of AAUs
** assumed 0% for graphical representation
*** prices for 2012

As expected, for the most part, studies assuming worldwide trading (which allows mitigating GHG in the regions with the lowest mitigation costs) present lower carbon prices then those assuming trading to take place within Annex B countries only. However, this is not the case on the actual carbon market where CERs (traded globally) have consistently exhibited a higher price compared to the ERUs (traded among AI countries only).

---

[11] Similarly to before, all estimates were brought to the same unit measure (those expressed in tC were recalculated to tCO2 by multiplying it with the conversion factor 12/44. Where currency units were not specified, 1995$ were assumed and finally prices were brought to 2008 levels by using IMF world inflation figures (defined by changes in average consumer prices).

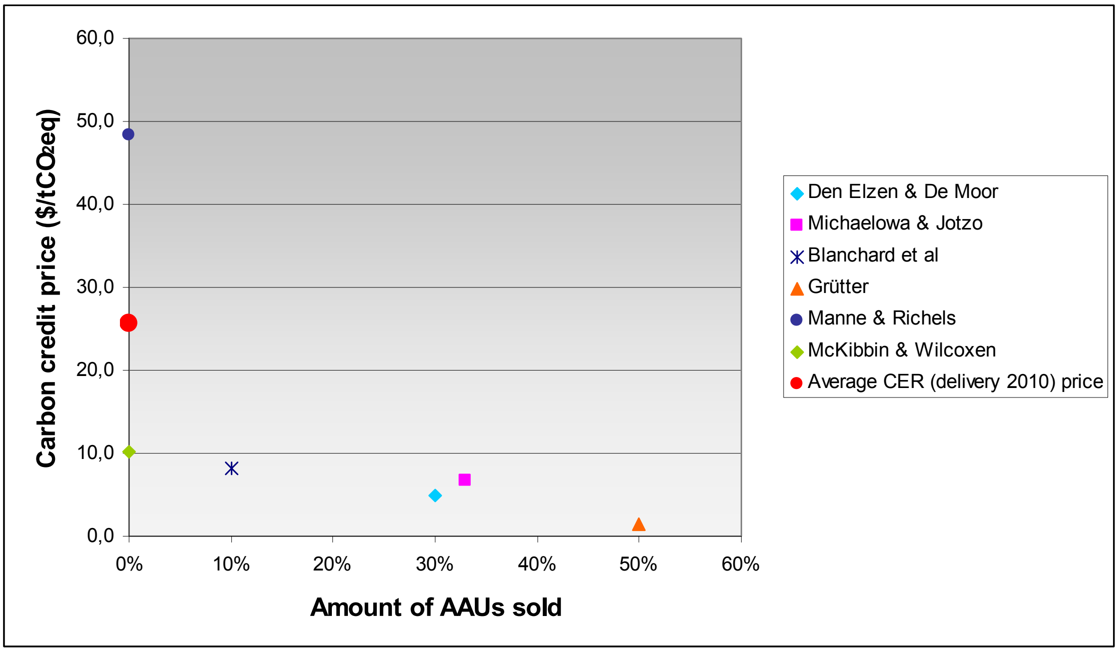


*Figure 5.1 Model-based carbon price estimates under the assumption of worldwide trading and average market CER price (forward contract with delivery in 2010). Data source: Table 5.1 and NordPool (2008)*

Figure 5.1 shows the carbon prices calculated by different models under different assumptions on AAU sales and the average forward market price of CERs (delivery 2010). With the exception of Manne & Richels (2004) who estimate the carbon price to be the double of what it actually became so far, most studies assuming worldwide trading seem to have significantly underestimated the price for CERs. The main reason is in their supposition on AAU sales, which in most instances (except in Manne & Richels, 2004 and McKibbin and Wilcoxen, 2004) assumed a higher amount of AAUs sold compared to what has actually reached the market so far. According to Point Carbon's market news in 2008, only some 40 Mt of AAUs from EIT have been sold so far,[12] which represents only a fraction of the surplus AAUs available (the World Bank (2008) estimates surplus AAUs over the Kyoto commitment period to be 7,305 $MtCO_2eq$)[13]. This means that considerably less AAUs have reached the market so far than the (AAU seller's) revenue maximizing levels assumed in the models. If more hot air was sold to the market (as can still be the case), there would be less demand for CERS and their price might drop closer to the average value of model-based estimates.

In fact, trade in government emission units (AAUs) is predicted to rocket in the first half of this year (Point Carbon, 2009). Countries that are overachieving their target to cut emissions under the Kyoto protocol expect to sell up to 100 million of their AAUs to governments struggling to meet their climate goals. Most credits are expected to come from East Europe. Still, this kind of amount continues to be considerably lower than what models predicted would reach the market, hence continuing to limit the price influence of 'hot air' on other carbon credit types. Furthermore, the current low carbon prices are inducing many seller countries continue to delay their first AAU-deals (Point Carbon, 2009) thus continuing to restrict the supply of surplus AAUs to the market.

---

[12] Although by the end of 2008 there were more deals approaching finalization.

[13] Given less then 1% of all AAUs has reached the markets o far, in the graph, the market price for CERs is represented on 0% of AAU sales (x-axis). The same applies for the representation of ERU price in figure 5.2. This des not mean that more AAUs sales might not be realized before the end of the Kyoto period.

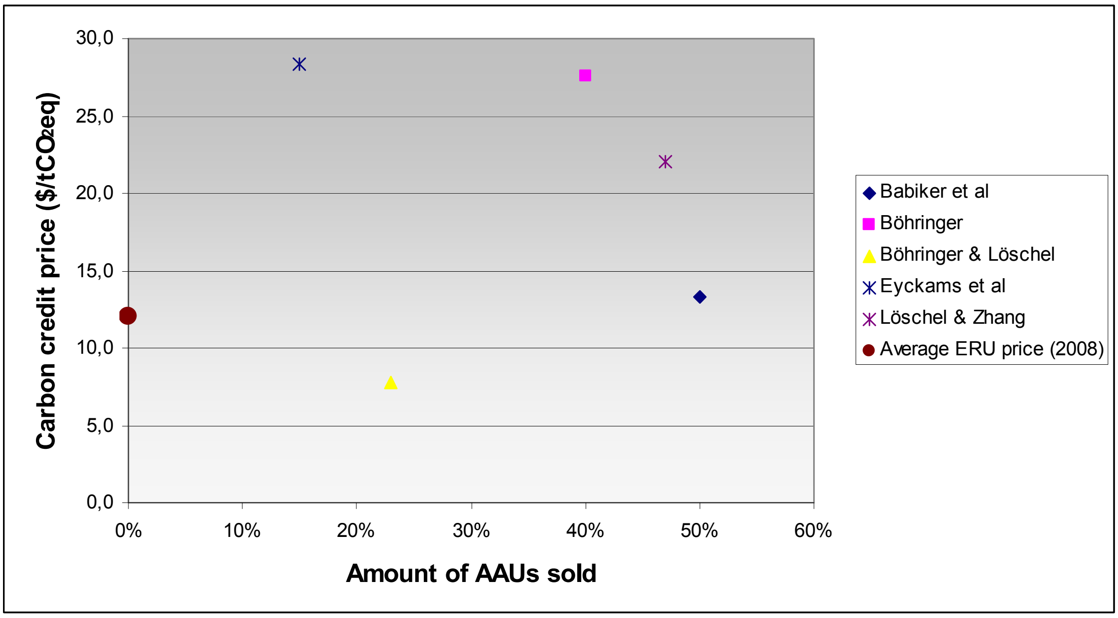


*Figure 5.2 Model-based carbon price estimates under Annex B trading only and average ERU price. Source: See table 5.1 and Point Carbon (2008b)*

Figure 5.2 shows carbon credit prices calculated by a number of models assuming trading to be restricted among Annex B countries and a certain level of AAU sales and the actual market price of the ERU. A similar relationship between the amounts of AAUs sold and the carbon credit price can be observed here: The higher the amount of AAUs sold, the lower the carbon credit price (with the exception of Böhringer & Löschel, 2002). In contrast to the previous case however, the model-based studies seem to significantly overestimate the price of this type of carbon credits, especially considering that if more 'hot air' had been sold to the market, the price of the ERUs would most likely have been even lower.

The prices of both CERs and EAUs have been varying significantly in the period observed, and both have exhibited a rapid decline in the second half of 2008 as a result of the credit crisis that has depressed oil prices and reduced demand for credits from the industrial sector, both major determinants of the prices for carbon credits. Because of this, one might argue that it has limited value on comparing any model-based point estimates with an average market price that masks such significant variations over a period of time. However, even this observation carries significant relevance in again pointing to the limitations of model-based price estimates for such an unstable phenomena as the carbon price.

One study only explicitly models the possible price of the carbon credits in 2012 within the EU-ETS (Klepper & Peterson, 2006) for the two cases where CDM credits are not allowed to be used by sectors covered by the EU-ETS and for the case where they are. The price for the first case is estimated at 15,9 $/tCO$_2$ (or 10,8 EUR/ tCO$_2$) and 11,5 $/tCO$_2$ (7,8 EUR/ tCO$_2$) for the second. Both are significantly lower than the average EUA forward price for 2012 which by the end of 2008[14] was at 34,36 $/tCO$_2$ (or 23,38 EUR/tCO$_2$). The discussion on the influence of excess AAUs on EUA prices is not relevant for this case, since 'hot air' credits are not allowed into the EU ETS.

The main conclusion from this short analysis is that model-based estimates of carbon prices must always be interpreted together with the main assumptions they are built upon and a verification of the likelihood of these assumptions developing in reality.

---

[14] Calculated as average of the period 2006 to end of November 2008.

# 6 Conclusions

In this report we present and analyse results from model-based studies exploring the cost of reaching a pre-determined GHG stabilization level and the carbon price that would develop under the given emission constraints in these models. The average model-based carbon price projection for 2020 for the scenario of most interest for a future climate agreement is at 52 $\$/CO_2$ for a GHG concentration stabilization target of 450 ppm $CO_2$-eq. This figure is, however, based on a very limited number of observations from studies, since as yet very little research has been done on carbon prices at low stabilization levels and more work (by the various scientific forums exploring the cost of GHG mitigation and climate policy) would be needed for a comparison of results across all existing models.

Use and interpretation of any model-based result needs to be careful both when comparing results of different models and when using them independently. The results across models vary significantly, due to the many differences that characterise the various models, and due to different model parameters and the assumptions they use for developing their outlook on future developments. Possibly the most important underlying assumption of most recent model studies for the situation in 2020 is the one of perfect, global carbon markets allowing full flexibility in GHG mitigation, which is clearly quite far from the actual developments in climate policy so far.

Few models exist that explicitly model delayed participation of developing countries in a global climate agreement or even different emission reduction targets for different world regions. Most seem to indicate that delaying participation of developing countries would increase the cost of mitigation for industrialized nations, while it would not significantly reduce the costs of climate policy for developing countries, once they do enter the climate coalition. However, much more work is needed in harmonizing the assumptions used in the different models, to arrive to more robust estimates of the costs of stricter climate policy for both developed and developing nations.

That models cannot consider all uncertainties surrounding the market for carbon credits is shown by comparing model-based estimates of the carbon price with forward prices of different (conceptually similar to those calculated by the models) types of carbon credits. In the case of CDM credits, most model-based estimates seem to have underestimated the prices of CERS (mainly due to wrong assumptions on the amount of 'hot air' that would reach the market), while for the case JI credits, they seem to have significantly overestimated it. Again, when relying on model-based estimates, their limitations must always be kept in mind and it must be realized that the real value lies more in the insights offered by such analysis, rather than precise numerical figures.

# 7 References

Aaheim, A., Fuglestvedt, J.S., Godal, O. (2006): Costs Savings of a Flexible Mutlig-gas Climate Policy, The Energy Journal, Multi Greenhouse Gas Mitigation and Climate Policy Special Issue.

Babiker, Mustafa, Henry D. Jacoby, John M. Reilly and David M. Reiner (2002). 'The Evolution of a Climate Regime: Kyoto to Marrakech', Report No. 82, MIT Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge.

Bakker, S., L. Beurskens, S. Grafakos, J. Jansen, J. de Joode, B. van Ruijven, D. van Vuuren (2009, forthcoming). Oil price and climate mitigation. Sensitivity of cost of mitigation options for energy price changes. PBL/ECN report 5001202020, Draft version January 2009.

Barker, T., Pan, H., Köhler, J., Warren, R., Winne, S. (2006): Decarbonizing the Global Economy with Induced Technological Change: Scenarios to 2100 using E3 MG, The Energy Journal, Endogenous Technological Change and the Economics of Atmospheric Stabilisation Special Issue.

Bell, R. and Russell, C. (2002): Environmental policy for developing countries, Issues in Science and Technology. Spring, pp. 63-70.

Blackman, A. and Harrington, W. (2000): The use of economic incentives in developing countries: Lessons from international experience with industrial air pollution. Journal of Environment and Development, 9(1), pp. 5-44.

Blanchard, O., Criqui, P. and Kitous, A. (2002): After The Hague, Bonn and Marrakech: The future international market for emissions permits and the issue of hot air, Cahier de Recherche no. 27 bis, Institut d'Economie et de Politique de l'Energie, Grenoble, January.

Böhringer, C., Löschel, A., Rutheford T.F. (2006): Efficiency Gains from 'What'-Flexibility in Climate Policy and Integrated CGE Assessment, The Energy Journal, Multi Greenhouse Gas Mitigation and Climate Policy Special Issue.

Böhringer, C. (2001): 'Climate Politics From Kyoto to Bonn: From Little to Nothing?', The Energy Journal, v. 23, n. 2, pp. 51-71.

Böhringer, C. and Löschel, A. (2001): Market Power in International Emissions Trading: The Impact of U.S. Withdrawal from the Kyoto Protocol, Discussion Paper No. 01-58, Zentrum für Europäische Wirtschaftsforschung GmbH, (ZEW), Mannheim.

Bosetti, V., Carraro, C., Tavoni, M. (2008): Delayed Participation of Developing Countries to Climate Agreements: Should Action in the EU and US be Postponed? Fondazione Eni Enrico Mattei, Working Papers, paper 229.

Bosetti, V., Carraro, C. Massetti, E. and Tavoni, M. (2007): Optimal Energy Investment and R&D Strategies to Stabilise Greenhouse Gas Atmospheric Concentrations, Fondazione Eni Enrico Mattei, Nota di Lavoro 95.2007, October 2007.

Bosetti, V., Carraro, C. and Galetti, M. (2006): The Dynamics of Carbon and Energy Intensity in a Model of Endogenous Technical Change, The Energy Journal, Endogenous Technological Change and the Economics of Atmospheric Stabilisation Special Issue.

Carbon Trust (2007): Cutting carbon in Europe: the 2020 package, Carbon Trust, UK.

Chen, W. (2003): Carbon Quota Price and CDM Potentials after Marrakesh, Energy Policy 31 (2003) 709–719.

Crassous, R., Hourcade, J.C., Sassi, O. (2006) : Endogenous Structural Change and Climate Targets Modeling Experiments with Imaclim-R, The Energy Journal, Endogenous Technological Change and the Economics of Atmospheric Stabilisation Special Issue.

Deutche Bank (2008): Emissions in remission? Looking at - and through - an EU recession, October 2008.

EC (2009): Towards a comprehensive climate change agreement in Copenhagen, COM (2009) 39, Brussels, 28.1.2009.

Edenhofer O., Lessmann, K., Kemfert, C., Grubb, M. And Köhler, J. (2006): Indiced Technological Change: Exploring its Implications for the Ecnomics of Atmospheric Stabilization: Synthesis Report from the Innovation Modeling Comparison Project, The

Energy Journal, Endogenous Technological Change and the Economics of Atmospheric Stabilisation Special Issue.

Edenhofer, O., Lessman, K. and Bauer, N. (2006b): Mitigation Strategies and Costs of Climate Protection: The Effects of ETC in the Hybrid Model MIND, The Energy Journal, Endogenous Technological Change and the Economics of Atmospheric Stabilisation Special Issue.

Edmonds, J., Clarke, L., Lurz, J. and Wise, M. (2008): Stabilizing CO2 concentrations with incomplete international cooperation, Climate Policy 8 355-376.

Ellerman, A.D., Joskow, P.L., Schmalensee, R., Montero, J.-P., Bailey, E.M., (2000): Markets for Clean Air the US Acid Rain Program. Cambridge University Press, Cambridge.

Enkvist, PA., Nucler, T. and Rosander, J. (2007): A Cost Curve for Greenhouse Gas Reduction, The McKinsey Quarterly, November 1, 2007.

Den Elzen, M.G.J., Höhne, N., van Vliet, J., Ellermann, C. (2008): Exploring comparable post-2012 reduction efforts for Annex I countries, Netherlands Environmental Assessment Agency (PBL), The Netherlands, December 2008, PBL Report 500102019/2008.

den Elzen, M.G.J. and De Moor, A.P.G. (2002): Analyzing the Kyoto Protocol under the Marrakesh Accords: Economic Efficiency and Environmental Effectiveness, Ecological Economics 43 (2002) 141-158.

Eyckmans, J., van Regemorter, D. and van Steenberghe, V. (2001): Is Kyoto Fatally Flawed? An Analysis with MacGEM, Katholieke Universiteit Leuven, Working Paper Series no 2001-18.

Fawcett, AA. and Sands, R.D. (2006): Non-CO2 Greenhouse Gases in the Second Generation Model, The Energy Journal, Multi Greenhouse Gas Mitigation and Climate Policy Special Issue.

Fisher, B. S., N. Nakicenovic, et al. (2007): Issues related to mitigation in the long term context. Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change. B. Metz, O. R. Davidson, P. R. Bosch, R. Dave and L. A. Meyer. Cambridge, Cambridge University Press.

Fujino, J., Nair, R., Kainuma, M., Masui, T., Matsuoka, Y. (2006): Multi-gas Mitigation Analysis on Stabilisation Scenarios using AIM Global Model, The Energy Journal, Multi Greenhouse Gas Mitigation and Climate Policy Special Issue.

Gerlagh, R. (2006): ITC in a Global Growth-Climate Model with CCS: The Value of Induced Technical Change for Climate Stabilization, The Energy Journal, Endogenous Technological Change and the Economics of Atmospheric Stabilisation Special Issue.

Grubb, M. (2008): Carbon prices in Phase III of the EU ETS, Climate Strategies Briefing Note.

Grubb, M (2003): The Economics of the Kyoto Protocol, World Economics, Vol. 4, No. 3, July–September 2003.

Grütter, JM. (2001): The GHG Market after Bonn, Joint Implementation Quarterly, 2001.

Gupta, S., Tirpak, D.A., Burger, N. et al. (2007): Policies, Instruments and Co-operative Arrangements. In: B. Metz, O.R. Davidson, P.R. Bosch, R. Dave and L.A. Meyer (eds), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Haites, E., S. Seres (2004): Estimating the Market Potential for the Clean Development Mechanism: Review of Models and Lessons Learned, PCFplus Report 19.

Hanson, DA. And Leitner, JA. (2006): Technology Policy and World Greenhouse Gas Emissions in the AMIGA modelling System, The Energy Journal, Multi Greenhouse Gas Mitigation and Climate Policy Special Issue.

Hedenus, F., Azar, C., Lindgren, K. (2006): Induced Technological Change in a Limited Foresight Optimization Model, The Energy Journal, Endogenous Technological Change and the Economics of Atmospheric Stabilisation Special Issue.

International Institute for Applied System Analysis (IIASA) GGI Scenario Database, 2007, Available at: http://www.iiasa.ac.at/Research/GGI/DB/.

Jiang, K., Hu, X., Sogli, Z. (2006): Multi-gas Mitigation Analysis by IPAC, The Energy Journal, Multi Greenhouse Gas Mitigation and Climate Policy Special Issue.

Jensen, J. (2006): Flexible Multi-Gas Climate Policies, The Energy Journal, Multi Greenhouse Gas Mitigation and Climate Policy Special Issue.

JP Morgan Europe Equity Research (2008): All you ever wanted to know about carbon trading 6.0, July 2008.

Kainuma, M., Matsuoka, T. and Morita, T. (1998): Analysis of Post-Kyoto Scenarios : The AIM Model, Economic Modeling of Climate Change: OECD Workshop Report, 1998.

Kemfert, C. and Truong, P.T. (2007): Impact Assessment of Emissions Stabilization Scenarios with and without Induced Technological Change, Energy Policy 35 (2007) 5337–5345.

Kemfert, C., Truong, P.T., Bruckner, T. (2006): Economic Impact assessment of Climate Change – A Multi-gas Investigation with WIAGEM-GTAPEL-ICM, The Energy Journal, Multi Greenhouse Gas Mitigation and Climate Policy Special Issue.

Keppo, I. and Rao, S. (2007): International climate regimes: Effects of delayed participation, Technological Forecasting & Social Change 74 (2007) 962–979.

Klepper, G. and Peterson, S. (2006): Emissions Trading, C.D.M., JI. and More: The Climate Strategy of the EU, The Energy Journal 27 (2) 1 – 26.

Kuik, O., Brander, L. and Tol, R.S.J. (2008): Marginal Abatement Costs of Carbon-Dioxide Emissions: A Meta-Analysis, ESRI Working Paper No. 248, June 2008.

Löshel, A. and Zhang, Z. (2002): The Economic and Environmental Implications of the US Repudiation of the Kyoto Protocol and the Subsequent Deals in Bonn and Marrakech, Review of World Economics 138 (4) 711-746.

Manne, AS., Richels, RG. (2006): The Role of Non-CO2 Greenhouse Gases and Carbon Sinks in Meeting Climate Policy Objectives, The Energy Journal, Multi Greenhouse Gas Mitigation and Climate Policy Special Issue.

Manne, A. and Richel, R. (2004): US rejection of the Kyoto Protocol: the impact on compliance costs and CO2 emissions, Energy Policy 32 (2004) 447–454.

Masui, T., Hanaoka, T., Hikita, S., Kainuma, M. (2006): Assessment of CO2 Reductions and Economic Impacts Considering Energy-Saving Investments, The Energy Journal, Endogenous Technological Change and the Economics of Atmospheric Stabilisation Special Issue.

McKibbin, W.J. and Wilcoxen, P.J. (2004): Estimates of the costs of Kyoto: Marrakesh versus the McKibbin–Wilcoxen blueprint, Energy Policy 32 (2004) 467–479.

Michaelova, A. and Jotzo, F. (2002): Estimating the CDM market under the Marrakech Accords, Climate Policy 2 (2002) 179–196.

Morgan, M. G. and M. Henrion (1990): Uncertainty – A Guide Dealing with Uncertainty in Quantitative Risk and Policy Analysis, Cambridge University Press, UK.

NoordPool (2008): NoordPool Market Data, available online on http://www.nordpool.com/en/asa/Markets/Market-data-services/.

Paltsev, S., Reilly, JM., Jacoby, HD., Eckaus, RS., McFarland, J., Sarofim, M., Asadoorian, M. and Babiker, M. (2005): The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4, MIT Joint Program on the Science and Policy of Global Change, Report No.15, August 2005.

Pan, H. (2005): The Cost Efficiency of Kyoto Flexible Mechanisms: A To-down Study with with the GEM-E3 World Model, Environmental Modeling & Software 20: 1401-1411.

Point Carbon (2008): 'Carbon Market Transactions in 2020: Dominated by Financials?' Point Carbon's Carbon Market Analyst, May 21, 2008.

Point Carbon (2008b): Carbon 2008, Post-2012 is Now, Point Carbon, 11 March 2008.

Point Carbon (2009): AAU sales to hit 100 million, Point Carbon Market News, 30 January 2009.

Popp, D. (2006): Comparison of Climate Policies in the ENTICE-BR Model, The Energy Journal, Endogenous Technological Change and the Economics of Atmospheric Stabilisation Special Issue.

Richels, R.G., Rutherford, T.F., Blanford, G.J. and Clarke, L. (2007): Managing the transition to climate stabilization, Climate Policy 7 (5): 409-428.

Rao, S., Keppo, I. and Riahi, K. (2006): Importance of Technological Change and Spillovers in Long-Term Climate Policy, The Energy Journal, Endogenous Technological Change and the Economics of Atmospheric Stabilisation Special Issue.

Rao, S. and Riahi, K. (2006): The Role of Non-CO2 Greenhouse Gases in Climate Change Mitigation: Long-Term Scenarios for the 21st Century, The Energy Journal, Multi Greenhouse Gas Mitigation and Climate Policy Special Issue.

Russ, P., Wiesenthal, T., van Regemorter, D., Ciscar, J.C. (2007): Global Climate Policy Scenarios for 2030 and Beyond: Analysis of Greenhouse Gas Emission Reduction Pathway Scenarios with the POLES and GEM-E3 Models, JRC Reference Reports, Report EUR 23032, Institute for Prospective Technological Studies, Joint Research Centre of the European Commission.

Russ, P., Ciscar, J.C., Saveyn, B., Soria, A., Szabo, L., Van Ierland, T., van Regemorter, D., Virdis, R. (2009): Economic Assessment of Post-2012 Climate Policies: Analysis of Greenhouse Gas Emission Reduction Scenarios with the POLES and GEM-E3 Models, JRC Reference Reports, Report EUR 23768, Institute for Prospective Technological Studies, Joint Research Centre of the European Commission.

Sano, F., Akimoto, K., Homma, T., Tomoda, T. (2006): Analysis of Technological Portfolios for CO2 Stabilizations and Effects of Technological Changes, The Energy Journal, Endogenous Technological Change and the Economics of Atmospheric Stabilisation Special Issue.

Sarofim, M.C., Forest, CE., Reiner, DM., Reilly, JM. (2005) : Stabilization and Global Climate Policy, Global and Planetary Change 47 (2005) 266-272.

Springer, U. (2003): The market for tradable GHG permits under the Kyoto Protocol: a survey of model studies, Energy Economics 25 (2003) 527–551.

Springer, U. and Varilek, M. (2004): Estimating the price of tradable permits for greenhouse gas emissions in 2008–12, Energy Policy 32 (2004) 611–621.

Tavoni, M., Sohngen, B., Bosetti, V. (2007): Forestry and the carbon market response to stabilize climate, Energy Policy 35 (2007) 5346–5353.

US CCSP (U.S. Climate Change Science Program) (2006): Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations, Report by the U.S. Climate Change Science Program and approved by the Climate Change Science Program Product Development Advisory Committee, Clarke, L., J. Edmonds, J. Jacoby, H. Pitcher, J. Reilly, R. Richels (Eds), 2006.

Vaillancourt, K., Loulou, R. And Kanudia, A. (2004): The role of abatement costs in GHG permit allocations: A global reduction scenario with the World-MARKAL model, GERAD G-2004-44, May 2004.

Van Vuuren, D., den Elzen, M., Lucas, P., Eickhout, B., Strengers, B., Ruijven, B., Wonink, S., van Houdt, R.(2007): Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs, Climatic Change (2007) 81:119–159.

van Vuuren, D., Hoogwijk, M., Barker, T., Riahi, K., Boeters, S., Chateau, J., Scrieciu, S., van Vliet, J., Masui, T., Blok, K., Blomen, E., Kram, T. (2009, forthcoming): Comparison of methods top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials.

World Bank (2008): State and trends of the carbon market, May 2008.

# Appendix A Estimates of costs and emissions trading induced by climate policy

## 1. Study: Bossetti et al. (2007)

Model used: WITCH

Stabilization level: 450 $CO_2$ (550ppmv $CO_2$eq) or 550 $CO_2$ (650ppmv $CO_2$eq)

Assumption on participation of developing countries: full participation in global climate coalition, no specific target but full carbon trade possible.

Permit allocation scheme/method of determining emission reductions:
1) global equal per capita (allocates emissions evenly per person).
2) sovereignty principle (non-OECD countries pay for most of the stabilisation cost).

Cost indicator: Total costs of stabilisation expressed as net present value percent GDP losses until 2100 (discount rate: 3% declining).

*Table A.1 Total costs of different stabilization levels under different permit allocation schemes (NB: a negative figure means a benefit or increase in GDP):*

| Region | World | | OECD | | Non OECD | |
|---|---|---|---|---|---|---|
| Permit allocation scheme | Equal per capita | Sovereignty principle | Equal per capita | Sovereignty principle | Equal per capita | Sovereignty principle |
| 450 $CO_2$ (550ppmv $CO_2$eq) | 3.6% | 3.7% | 4.1% | 1.0% | 2.9% | 7.2% |
| 550 $CO_2$ (650ppmv $CO_2$eq) | 0.2% | 0.3% | 0.6% | - 0.2% | - 0.3% | 0.9% |

For the case of 'equal per capita' allocation of initial permits, the study also analyses the volumes traded in the carbon market. In a 650 stabilisation scenario, almost 60 GtC (220 Gt $CO_2$eq) (an average of 0.6 GtC/yr (2.2 Gt $CO_2$eq/yr) or 10% of current emissions) are traded over the next century, a figure that goes down to 35 GtC (128 Gt $CO_2$eq) in a 550ppm scenario, where the more stringent target requires more domestic action to abate GHG emissions. Therefore, there would be more emission trading in the less ambitious abatement scenario.

The equal per capita allocation makes OECD countries – especially the US, penalised by the high rate of per-capita emissions – short and Non-OECD long of permits. This partly holds also in the 450 ppm stabilisation scenario, at least in the initial time periods. Afterwards, China and East Asia also become buyers of permits: the only big sellers remain Sub-Saharan Africa (SSA) and South Asia (SASIA).

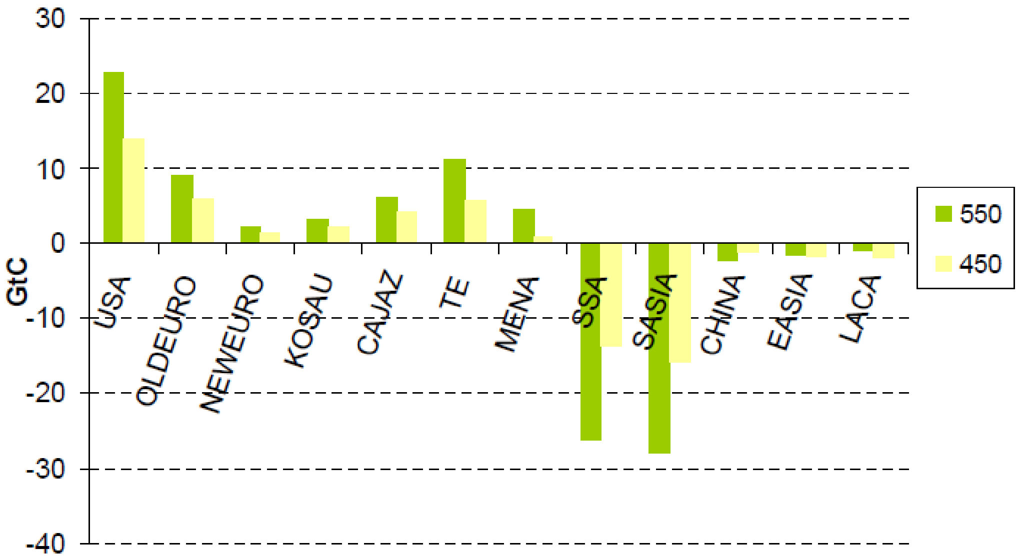


*Figure A.1 Trade of carbon permits (cumulatively to 2100) in the two stabilisation scenarios (under equal per capita allocation of initial permits)*

(Country legend: USA=Usa, OLDEURO=West Europe, NEWEURO=East Europe, KOSAU=Korea, South Africa and Australia, CAJANZ= Canada, Japan and New Zealand, TE=Transition Economies, MENA=Middle East and North Africa, SSA=Sub Saharan Africa, SASIA= South Asia, CHINA=China, EASIA= South East Asia, LACA=Latin and Central America)

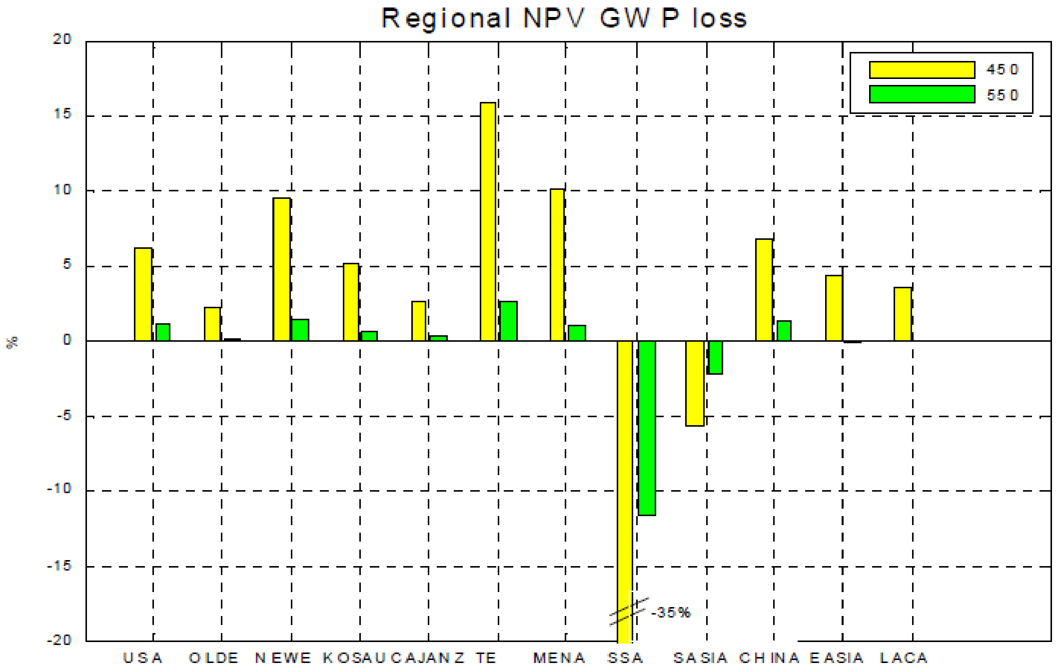


*Figure A.2 Regional policy costs (net present value. Discount rate: 3% declining)*

## 2. Study: Bossetti et al. (2008)

Model used: WITCH

Stabilization level: 450 ppm $CO_2$eq (550 ppm $CO_2$eq)

Permit allocation scheme: Contraction & converge (allowances are initially allocated on the basis of present emissions, but converge to an equal per capita emissions allocation by 2050)

Cost indicator: Total costs of stabilisation expressed as Net present value percent GDP losses until 2100 (discount rate: 5%)

Assumptions on participation of developing countries: Entry in global climate coalition in 2035 with full participation. Three different scenarios are analyzed of possible developments prior to 2035:

- No trade in carbon credits between A1 and NA1 and NA1 countries do not anticipate that they will agree on a stabilization target from 2035 onward.
- No trade between A1 and Na1 but NA1 countries set their policy strategy from 2005 to 2035 taking into account that they will participate in a climate agreement aiming at stabilizing emissions at 450 ppm from 2035 onward.
- Before 2035, NA1 can trade emission reductions from their baseline emission paths even though they do not participate to the climate policy agreement.

Permit allocation scheme/method of determining emission reductions: global contraction & converge

Table A.2 shows the economic cost of achieving the 550 ppm $CO_2$eq target in the various policy scenarios (and for the case in which NA1 would join the climate agreement immediately, for comparison).

*Table A.2 Policy costs of achieving the 550 ppm target across scenarios on NA1 participation in the global climate agreement and carbon trade*

| | World | Annex I | Non-Annex I |
|---|---|---|---|
| NAI entry now | 2.1% | 1.7% | 2.8% |
| NAI entry 2035 & no carbon trade until then | 2.8% | 3.0% | 2.5% |
| NAI Entry 2035 & no trade until then & no anticipation on NAI joining the global climate agreement | 3.7% | 3.1% | 5.1% |
| NAI entry in 2035 & carbon trade before then | 2% | 2% | 2% |

Source: Bossetti et al., 2008

## 3. Study: Vaillancourt et al., 2004

Model used: MARKAL

Stabilization level: 550 ppm $CO_2$eq (650 ppm $CO_2$eq)

Permit allocation scheme/method of determining emission reductions:

1) Equalize the net abatement costs per unit of GDP-ppp (purchase power parity) (equalizes the net costs across regions)
2) equalize net abatement cost per unit of GDP-ppp squared (allows more permits to the poorest regions, those for which the GDP is the lowest)

Cost indicator: Gross mitigation costs in billion US$ (2000) and net abatement costs per unit of GDP-ppp (purchase power parity) (discounted to 2000 US$ using a 5% discount rate) between 2010 and 2050.

Assumption on participation of developing countries: full participation in global climate coalition, no specific target but full trade possible.

NB: the minus sign for trading indicates a surplus

*Table A.3 Permit allocations and net costs under allocation scheme equalizing net abatement costs per unit of GDP-ppp*

| Region | % Allocation | | Gross cost | Trading | Net cost | |
|---|---|---|---|---|---|---|
| | 2010 | 2050 | B$(2000) | +/- | B$(2000) | %GDP |
| Africa | 5.8 | 7.7 | 767 | -377 | 391 | 0.37 |
| Asia | 7.2 | 8.0 | 520 | 197 | 717 | 0.47 |
| Australia-NZ | 1.5 | 1.6 | 70 | -17 | 53 | 0.03 |
| Canada | 1.9 | 1.2 | 111 | -40 | 72 | 0.27 |
| China | 15.2 | 18.1 | 1518 | 270 | 1788 | 0.68 |
| Eastern Europe | 1.9 | 1.8 | 103 | 97 | 200 | 0.49 |
| FSU | 9.6 | 9.0 | 464 | 122 | 586 | 0.78 |
| India | 4.2 | 8.3 | 521 | 10 | 530 | 0.42 |
| Japan | 3.6 | 1.2 | 72 | 118 | 190 | 0.18 |
| Latin America | 5.8 | 7.9 | 919 | -135 | 784 | 0.47 |
| Mexico | 2.5 | 4.2 | 395 | -22 | 373 | 0.65 |
| Middle-East | 9.5 | 10.3 | 746 | -307 | 439 | 0.47 |
| South Korea | 1.9 | 1.4 | 68 | 99 | 167 | 0.38 |
| United States | 17.3 | 11.0 | 1316 | -222 | 1094 | 0.32 |
| Western Europe | 12.2 | 8.3 | 452 | 206 | 658 | 0.22 |
| World | 100.0 | 100.0 | 8043 | 0 | 8043 | 0.42 |

*Table A.4 Permit allocations and net costs under allocation scheme equalize net abatement cost per unit of GDP-ppp squared*

| Region | % Allocation | | Gross cost | Trading | Net cost | |
|---|---|---|---|---|---|---|
| | 2010 | 2050 | B$(2000) | +/- | B$(2000) | %GDP |
| Africa | 5.8 | 7.8 | 767 | -429 | 338 | 0.32 |
| Asia | 7.2 | 8.0 | 520 | 182 | 702 | 0.46 |
| Australia-NZ | 1.5 | 1.7 | 70 | -34 | 37 | 0.21 |
| Canada | 1.9 | 1.3 | 111 | -64 | 47 | 0.18 |
| China | 15.2 | 17.0 | 1518 | 532 | 2050 | 0.78 |
| Eastern Europe | 1.9 | 2.0 | 103 | 53 | 155 | 0.39 |
| FSU | 9.6 | 9.3 | 464 | 60 | 523 | 0.69 |
| India | 4.2 | 8.4 | 521 | -34 | 487 | 0.38 |
| Japan | 3.5 | 1.4 | 72 | 55 | 126 | 0.12 |
| Latin America | 5.8 | 7.5 | 919 | -96 | 823 | 0.50 |
| Mexico | 2.5 | 4.5 | 395 | -83 | 312 | 0.54 |
| Middle-East | 9.4 | 10.5 | 746 | -367 | 380 | 0.41 |
| South Korea | 1.8 | 1.6 | 68 | 47 | 115 | 0.26 |
| United States | 17.5 | 10.7 | 1316 | -93 | 1224 | 0.36 |
| Western Europe | 12.2 | 8.3 | 452 | 272 | 724 | 0.24 |

## 4. Study Edmonds et al. (2008)

Model used: MiniCAM

Stabilization level: 450 ppm $CO_2$eq (550 ppm $CO_2$eq) and 550 ppm $CO_2$eq (650 ppm $CO_2$eq)

Permit allocation scheme/method of determining emission reductions: none, all regions of the world are assumed to imposed a price on themselves to achieve emissions mitigation. There were no transfer payments, as would occur in a 'cap-and-trade' regime

Cost indicator: Fraction of total social cost of stabilization at alternative levels of atmospheric $CO_2$ (Global costs represent the discounted value of costs from 2005 through 2095 under a 5% discount rate).

Assumption on participation of developing countries:

- full participation from 2012: first best scenario
- Wealthiest non-Annex I regions enter the international system in 2020, 2035 or 2050 (three subcases), other non-Annex I nations enter when their percapita income reaches the level of the first participating region when it joined the regime: Graduate accession

*Table A.5 Fraction of total social cost of stabilization at alternative levels of atmospheric $CO_2$ borne by Non-Annex I Regions*

| Scenario and year of accession | 450 ppm $CO_2$eq (550 ppm $CO_2$eq) | 550 ppm $CO_2$eq (650 ppm $CO_2$eq) |
|---|---|---|
| Full participation from 2012 | 66% | 72% |
| Graduate accession from 2020 | 60% | 69% |
| Graduate accession from 2035 | 35% | 65% |
| Graduate accession from 2050 | n.a. | 59% |

Source: Edmonds et al., 2008

NB : These costs are associate with mitigation of industrial $CO_2$ only.

## 5. Study : den Elzen et al (2008)

Model used: IMAGE/TIMER + FAIR

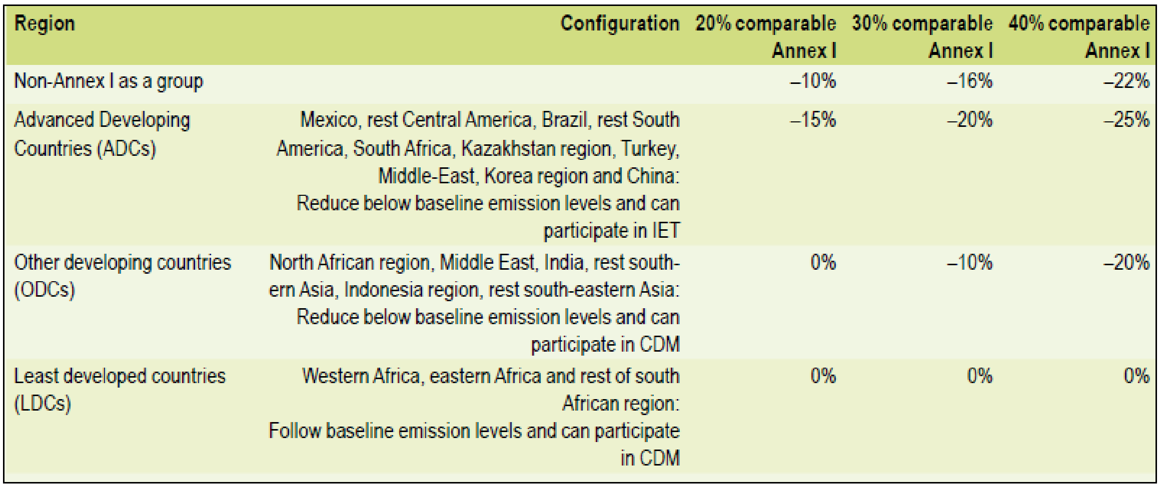
Stabilization level: 550, 450 and 400 ppm $CO_2$eq for comparable Annex I effort of 20% 30% and 40% below 1990 levels, respectively.

Permit allocation scheme/method of determining emission reductions:
Annex I: equal reduction below baseline
non-Annex I: not specified

Cost indicator: Domestic costs (from domestic mitigation), financial flows (from carbon credits trade), total costs and costs as % of GDP (all expressed in millions of 2005 US$).

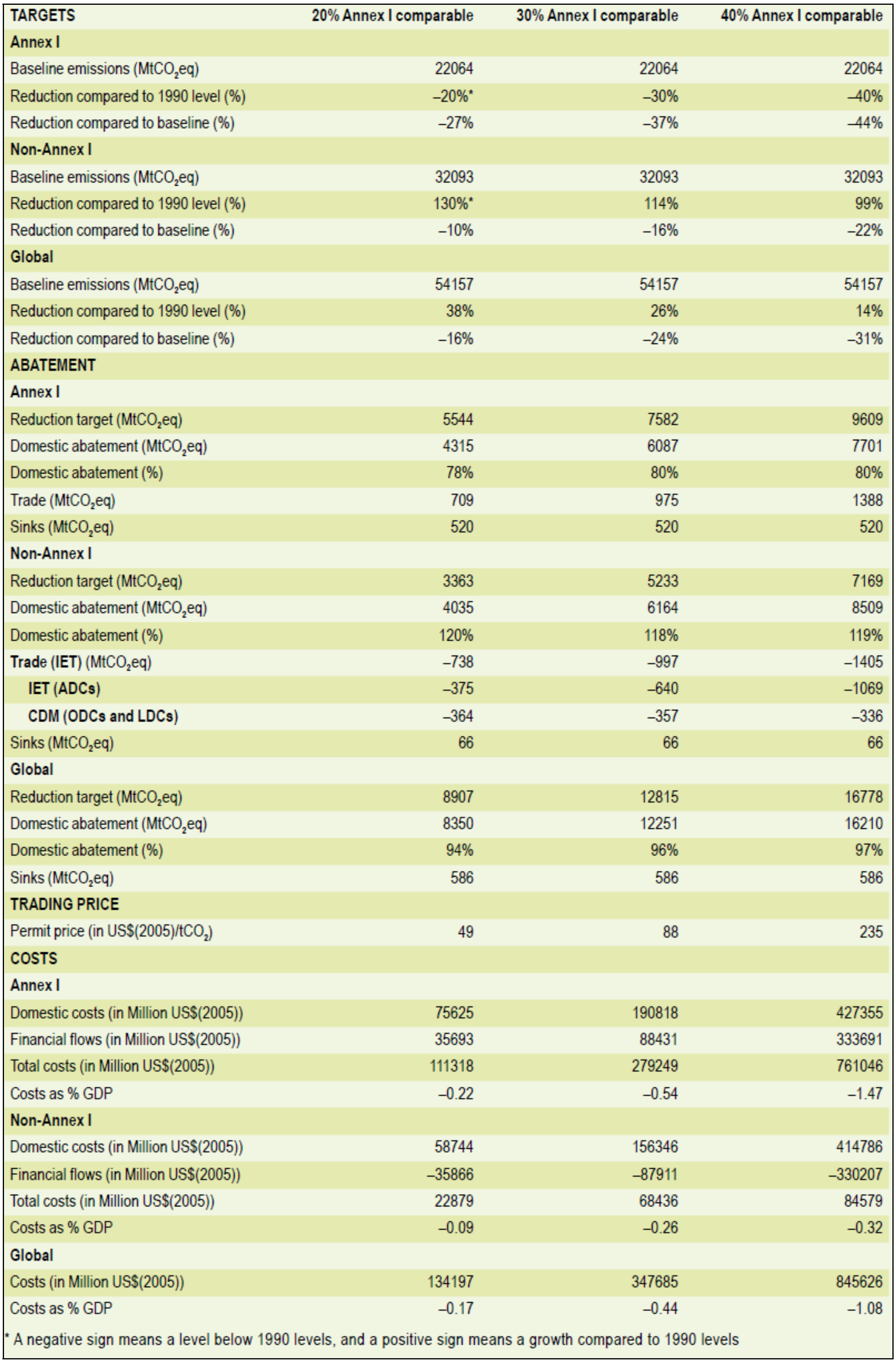
Assumption on participation of developing countries: see table A.6 below

*Table A.6 Assumed reduction levels below the baseline, by 2020, for the non-Annex I countries, grouped into Advanced Developing Countries, Other Developing Countries and Least-Developed Countries for three scenarios of Annex I reduction levels*



| Region | Configuration | 20% comparable Annex I | 30% comparable Annex I | 40% comparable Annex I |
|---|---|---|---|---|
| Non-Annex I as a group | | –10% | –16% | –22% |
| Advanced Developing Countries (ADCs) | Mexico, rest Central America, Brazil, rest South America, South Africa, Kazakhstan region, Turkey, Middle-East, Korea region and China:<br>Reduce below baseline emission levels and can participate in IET | –15% | –20% | –25% |
| Other developing countries (ODCs) | North African region, Middle East, India, rest southern Asia, Indonesia region, rest south-eastern Asia:<br>Reduce below baseline emission levels and can participate in CDM | 0% | –10% | –20% |
| Least developed countries (LDCs) | Western Africa, eastern Africa and rest of south African region:<br>Follow baseline emission levels and can participate in CDM | 0% | 0% | 0% |

*Table A.7 Main indicators for 2020 in the three scenarios*



| TARGETS | 20% Annex I comparable | 30% Annex I comparable | 40% Annex I comparable |
|---|---|---|---|
| **Annex I** | | | |
| Baseline emissions (MtCO$_2$eq) | 22064 | 22064 | 22064 |
| Reduction compared to 1990 level (%) | –20%* | –30% | –40% |
| Reduction compared to baseline (%) | –27% | –37% | –44% |
| **Non-Annex I** | | | |
| Baseline emissions (MtCO$_2$eq) | 32093 | 32093 | 32093 |
| Reduction compared to 1990 level (%) | 130%* | 114% | 99% |
| Reduction compared to baseline (%) | –10% | –16% | –22% |
| **Global** | | | |
| Baseline emissions (MtCO$_2$eq) | 54157 | 54157 | 54157 |
| Reduction compared to 1990 level (%) | 38% | 26% | 14% |
| Reduction compared to baseline (%) | –16% | –24% | –31% |
| **ABATEMENT** | | | |
| **Annex I** | | | |
| Reduction target (MtCO$_2$eq) | 5544 | 7582 | 9609 |
| Domestic abatement (MtCO$_2$eq) | 4315 | 6087 | 7701 |
| Domestic abatement (%) | 78% | 80% | 80% |
| Trade (MtCO$_2$eq) | 709 | 975 | 1388 |
| Sinks (MtCO$_2$eq) | 520 | 520 | 520 |
| **Non-Annex I** | | | |
| Reduction target (MtCO$_2$eq) | 3363 | 5233 | 7169 |
| Domestic abatement (MtCO$_2$eq) | 4035 | 6164 | 8509 |
| Domestic abatement (%) | 120% | 118% | 119% |
| **Trade (IET)** (MtCO$_2$eq) | –738 | –997 | –1405 |
| **IET (ADCs)** | –375 | –640 | –1069 |
| **CDM (ODCs and LDCs)** | –364 | –357 | –336 |
| Sinks (MtCO$_2$eq) | 66 | 66 | 66 |
| **Global** | | | |
| Reduction target (MtCO$_2$eq) | 8907 | 12815 | 16778 |
| Domestic abatement (MtCO$_2$eq) | 8350 | 12251 | 16210 |
| Domestic abatement (%) | 94% | 96% | 97% |
| Sinks (MtCO$_2$eq) | 586 | 586 | 586 |
| **TRADING PRICE** | | | |
| Permit price (in US$(2005)/tCO$_2$) | 49 | 88 | 235 |
| **COSTS** | | | |
| **Annex I** | | | |
| Domestic costs (in Million US$(2005)) | 75625 | 190818 | 427355 |
| Financial flows (in Million US$(2005)) | 35693 | 88431 | 333691 |
| Total costs (in Million US$(2005)) | 111318 | 279249 | 761046 |
| Costs as % GDP | –0.22 | –0.54 | –1.47 |
| **Non-Annex I** | | | |
| Domestic costs (in Million US$(2005)) | 58744 | 156346 | 414786 |
| Financial flows (in Million US$(2005)) | –35866 | –87911 | –330207 |
| Total costs (in Million US$(2005)) | 22879 | 68436 | 84579 |
| Costs as % GDP | –0.09 | –0.26 | –0.32 |
| **Global** | | | |
| Costs (in Million US$(2005)) | 134197 | 347685 | 845626 |
| Costs as % GDP | –0.17 | –0.44 | –1.08 |

* A negative sign means a level below 1990 levels, and a positive sign means a growth compared to 1990 levels

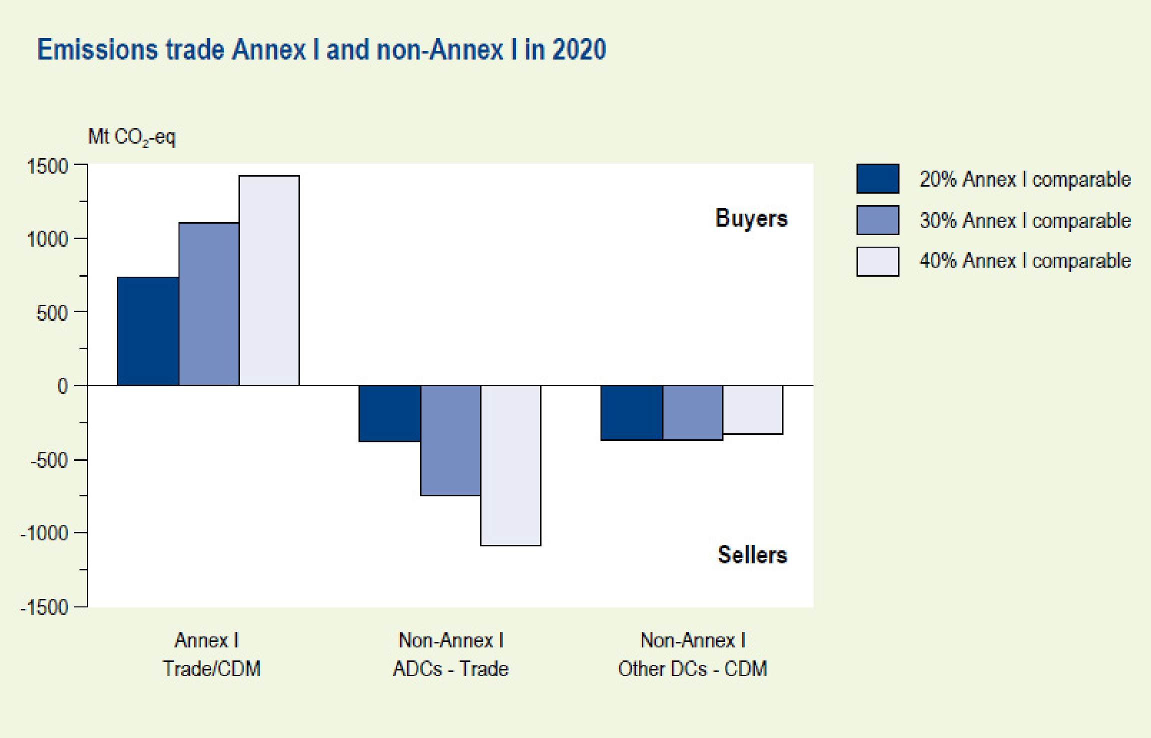


*Figure A.3 The total amount of emissions traded (MtCO2eq) between the different groups and the rest of the world, for 2020, in the three scenarios (ADCc – advanced developing countries, DCs – other developing countries)*

## 6. Study: Russ et al (2009)

Model used: POLES, GEM-E3

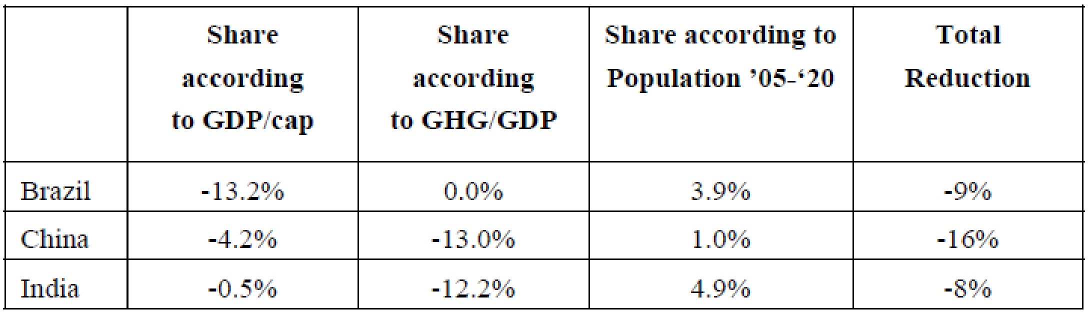
Stabilization level: 450 ppm $CO_2$eq

Permit allocation scheme/method of determining emission reductions:
For Annex I: combination of GDP/capita, GHG/GDP, GHG emission trends and population trends
For non-Annex I: same as above, except GHG emission trends

Cost indicator: total cost in billion EUR (at 2005 prices) of reducing $CO_2$ emissions from energy and non-$CO_2$ emissions from industry (in the year 2020 and cumulative over period 2013-2020)

Assumption on participation of developing countries: for assumptions in POLES, see table A.8 below. GEM-E3 assumes that developing countries undertake nationally appropriate actions themselves

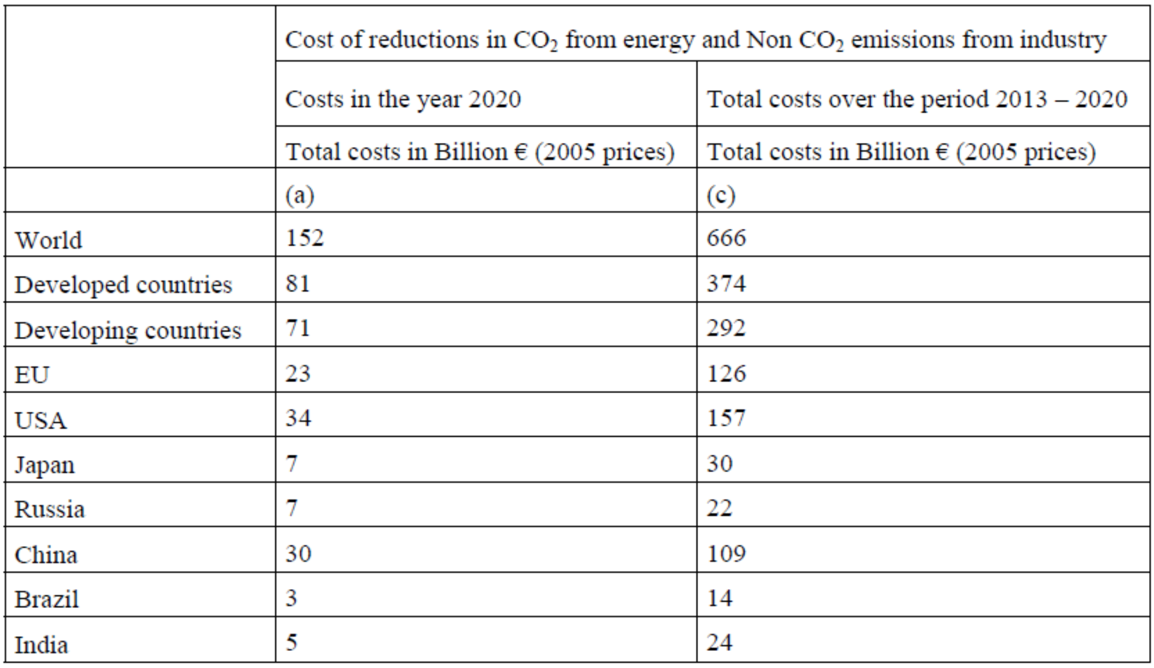
*Table A.8 Emission reductions for developing countries resulting from the three different allocation options and total reductions based on all three simultaneously (in % compared to baseline by 2020).*



| | **Share according to GDP/cap** | **Share according to GHG/GDP** | **Share according to Population '05-'20** | **Total Reduction** |
|---|---|---|---|---|
| Brazil | -13.2% | 0.0% | 3.9% | -9% |
| China | -4.2% | -13.0% | 1.0% | -16% |
| India | -0.5% | -12.2% | 4.9% | -8% |

Source: JRC/IPTS, POLES

*Table A.9 Costs in developed and developing countries of reducing $CO_2$ emissions from energy and non-$CO_2$ emissions from industry*

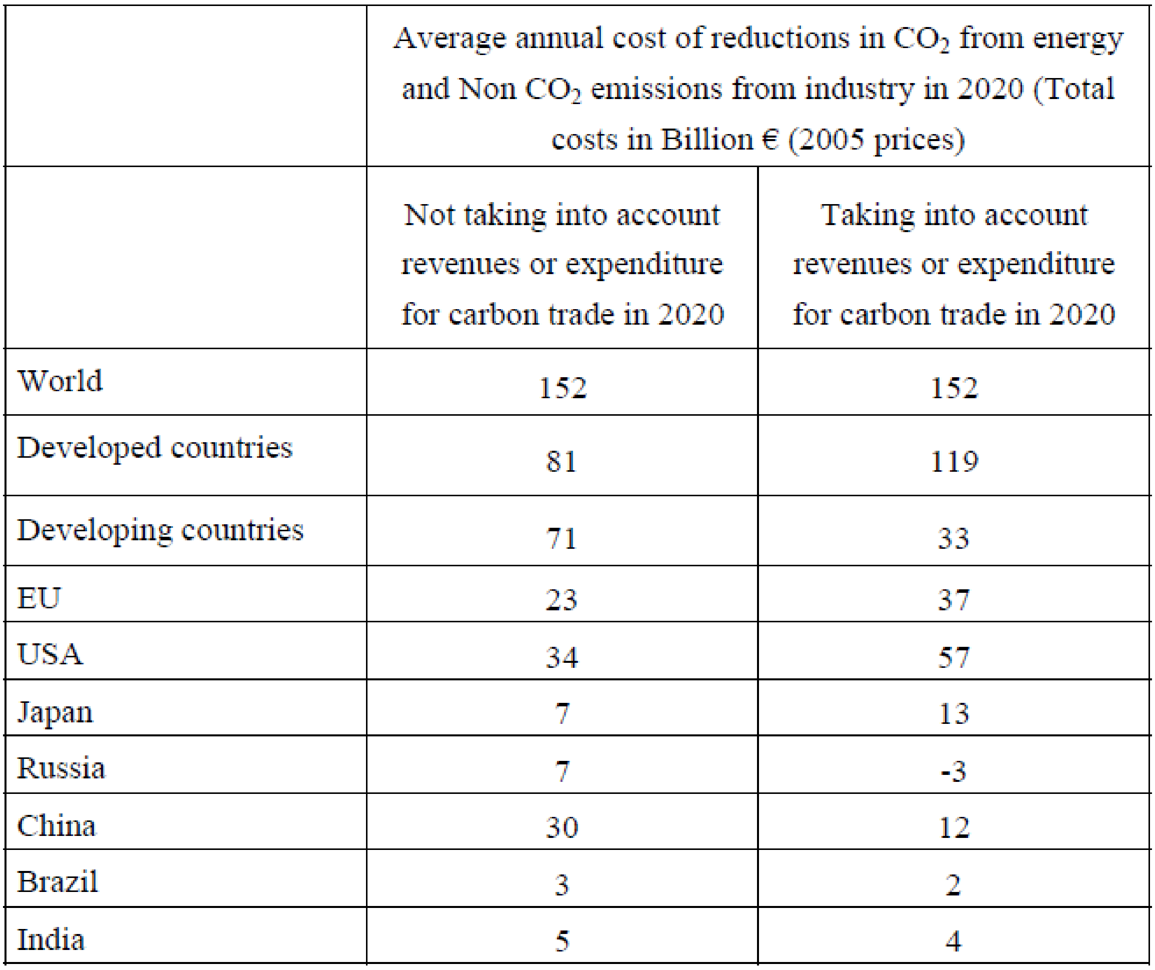


| | Cost of reductions in $CO_2$ from energy and Non $CO_2$ emissions from industry | |
|---|---|---|
| | Costs in the year 2020 | Total costs over the period 2013 – 2020 |
| | Total costs in Billion € (2005 prices) | Total costs in Billion € (2005 prices) |
| | (a) | (c) |
| World | 152 | 666 |
| Developed countries | 81 | 374 |
| Developing countries | 71 | 292 |
| EU | 23 | 126 |
| USA | 34 | 157 |
| Japan | 7 | 30 |
| Russia | 7 | 22 |
| China | 30 | 109 |
| Brazil | 3 | 14 |
| India | 5 | 24 |

Source: JRC/IPTS, POLES

The scenarios developed in this study no longer assume ideal pathways with perfect trading in all sectors across all time periods and world regions. Instead, it aims at being more realistic while at the same time maintaining the idea of economic efficiency by a gradually developing global carbon market across sectors and countries, resulting in different abatement and thus different carbon costs.

*Table A.10 Costs in developed and developing countries and trade in emissions rights in the POLES model*



| | Average annual cost of reductions in $CO_2$ from energy and Non $CO_2$ emissions from industry in 2020 (Total costs in Billion € (2005 prices) | |
|---|---|---|
| | Not taking into account revenues or expenditure for carbon trade in 2020 | Taking into account revenues or expenditure for carbon trade in 2020 |
| World | 152 | 152 |
| Developed countries | 81 | 119 |
| Developing countries | 71 | 33 |
| EU | 23 | 37 |
| USA | 34 | 57 |
| Japan | 7 | 13 |
| Russia | 7 | -3 |
| China | 30 | 12 |
| Brazil | 3 | 2 |
| India | 5 | 4 |

Source: JRC/IPTS, POLES

*Table A.11 Welfare and GDP effects under the imperfect carbon markets in the GEM-E3*

| | Welfare* compared to baseline | GDP compared to baseline |
|---|---|---|
| EU27 | -1.4% | -1.2% |
| USA | -0.7% | -0.8% |
| Japan | -0.6% | -0.6% |
| CIS | -1.4% | -3.0% |
| China | 0.3% | -0.8% |
| Brazil | -0.1% | -0.4% |
| India | -0.2% | -0.5% |
| World | -0.7% | -0.9% |

* welfare is defined as the sum of private consumption and leisure
Source: JRC/IPTS, GEM-E3