ELSEVIER

Energy Policy 33 (2005) 2138–2151

ENERGY POLICY

www.elsevier.com/locate/enpol

Abatement costs of post-Kyoto climate regimes

Michel den Elzen*, Paul Lucas, Detlef van Vuuren

National Institute for Public Health and the Environment (RIVM), Global Sustainability and Climate, P.O. Box 1, 3720 BA Bilthoven, The Netherlands

Abstract

This article analyses the abatement costs of three post-Kyoto regimes for differentiating commitments compatible with stabilising atmospheric greenhouse gases concentrations at 550 ppmv CO_2 equivalent in 2100. The three regimes explored are: (1) the Multi-Stage approach assumes a gradual increase in the number of Parties involved who are adopting either emission intensity or reductions targets; (2) the Brazilian Proposal approach, i.e. the allocation or reductions based on countries' contribution to temperature increase; (3) Contraction & Convergence, with full participation in convergence of per capita emission allowances. In 2050, the global costs increase up to about 1% of the world GDP, ranging from 0.5% to 1.5%, depending on baseline scenario and marginal abatement costs. Four groups of regions can be identified on the basis of similar costs (expressed as the percentage of GDP). These are: (1) OECD regions with average costs; (2) FSU, the Middle East and Latin America with high costs; (3) South-East Asia and East Asia (incl. China) with low costs; and (4) South Asia (incl. India) and Africa with net gains from emissions trading for most regimes. The Brazilian Proposal approach gives the highest costs for groups 1 and 2. The distribution of costs for the Contraction & Convergence approach highly depends on the convergence year. The Multi-Stage approach and Contraction & Convergence (convergence year 2050) seem to result in relatively the most even distribution of costs amongst all Parties.

Keywords: Future commitments; Abatement costs; Emissions trading

1. Introduction

The ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC) (Article 2) is to 'stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system' (UNFCCC, 1992). However, current uncertainties do not allow unambiguous determination concentration levels below which this condition can be considered fulfilled. In fact, determination of these 'safe' concentration levels is not only a scientific issue but also related to perceptions, values and political negotiations. IPCC's Third Assessment Report (IPCC, 2001a) nevertheless indicates that such stabilisation will require substantial reductions in global GHG emissions of more than 60% of the 1990 level. This implies that future global emission reductions will require substantial efforts in future emission control by all countries, going far beyond the type of reduction currently applied to developed countries in the Kyoto Protocol. This raises important questions about what levels of commitments from developed and developing countries will be needed in the future, what level of differentiation of commitments among countries will be fair and what the cost implications of these commitments will be. According to the Kyoto Protocol (UNFCCC, 1997a), a review of future commitments for Annex I Parties will have been initiated by 2005.

Both prior to and following the negotiations on the Kyoto Protocol, there have been many proposals for differentiating mitigation commitments among countries, both from academic circles as well as from Parties to the UNFCCC (see, for example, Banuri et al., 1996; Reiner and Jacoby, 1997; Rose et al., 1998; Ringius et al., 1998; Torvanger and Godal, 1999; Depledge, 2000; Baumert et al., 2002; OECD/IEA, 2002). The number of comparative studies systematically evaluating the implications of various post-Kyoto regime options for a wider range of implications on a global scale is, however, still limited. Amongst the most comprehensive quantitative analysis of post-Kyoto regimes at a global

---

*Corresponding author. Tel.: +31-30-2743584; fax: +31-30-27424435.

E-mail address: michel.den.elzen@rivm.nl (M. den Elzen).

0301-4215/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2004.04.012

scale are studies by Jacoby et al. (1997, 1999), Blanchard et al. (2002), Höhne et al. (2003), den Elzen (2002) and the German Advisory Council on Global Change (WBGU, 2003). Most studies have limitations concerning either the options reviewed, the level of elaboration (rather stylised/academic approaches), the level of analysis (Annex I only), the link to (long-term) climate objectives, the time horizon, the GHGs involved (CO_2-only instead of all (Kyoto) GHGs) or the quantification of economic cost implications (often absent).

This article aims to systematically evaluate the regional reduction efforts and abatement costs for three international regimes for differentiating future (post-Kyoto) commitments compatible with the long-term UNFCCC objective. These regimes are outlined below.

(1) The *Multi-Stage approach* is an incremental but rule-based approach, which assumes a gradual increase in the number of Annex I Parties involved who are adopting binding quantified emission intensity targets or absolute reduction objectives, whether absolute or dynamic. More specifically, it consists of a system that divides countries into different groups, with different types of commitment (stages). The number of countries involved and their level of commitment gradually increase over time according to pre-defined participation rules (Berk and den Elzen, 2001).

(2) The *Brazilian Proposal approach* is based on a proposal from Brazil (during the negotiations on the Kyoto Protocol) to differentiate *Annex I* emission reductions on the basis of their contributions to global temperature increase (UNFCCC, 1997b). Here, it is applied in combination with an income threshold for the participation of the non-Annex I regions (den Elzen et al., 2003).

(3) The *Contraction & Convergence* approach assumes universal participation and defines emission allowances on the basis of convergence of per capita emission allowances under a contracting global emission profile (Meyer, 2000).

So far, the Brazilian Proposal approach is the only climate regime that has been formally discussed and documented within the UNFCCC, and for this reason it is analysed here. The Contraction & Convergence approach, the most widely known, has much appeal in the developing world. The Multi-Stage approach is selected here, as this approach best satisfies the various types of criteria (environmental, political, economic, technical, institutional) in the multi-criteria evaluation of various approaches of Höhne et al. (2003) and den Elzen et al. (2003).

The three approaches differ structurally in a number of ways. First, the Brazilian Proposal and Multi-Stage approaches are based on a gradual extension of the number of countries participating in global greenhouse gas emission abatement, while in the Contraction & Convergence approach all countries participate from the start. Secondly, where the Brazilian Proposal and Multi-Stage approaches concern the allocation of emission abatement efforts (burden sharing), the Contraction & Convergence approach is based on the allocation of rights to use the (constrained) capacity of the atmosphere to absorb emissions (resource sharing). Thirdly, Multi-Stage defines different types of commitments, while in the Brazilian Proposal and Contraction & Convergence approaches, all countries have similar commitments (absolute targets). Finally, the different approaches are based on different equity principles.

Den Elzen et al. (2003) developed a typology of four key equity principles that seem most relevant for characterising various proposals for the differentiation of commitments. These principles are: (1) *Egalitarian*, i.e. all human beings have equal rights in the ‘use’ of the atmosphere; (2) *Sovereignty*, i.e. all countries have the right to use the atmosphere, and current emissions constitute a ‘status-quo right’; (3) *Responsibility*, i.e. the greater the contribution to the problem, the greater the share of the user in the mitigation/economic burden; and (4) *Capability*: The greater the capacity to act or ability to pay, the greater the share in the mitigation/economic burden. The Contraction & Convergence approach is based on a combination of both the egalitarian and sovereignty principle. The Brazilian Proposal approach is clearly oriented to the responsibility principle. The Multi-Stage approach is based on a combination of responsibility and capability principles, but may also include elements related to the egalitarian principle, for example, using per capita-related burden-sharing keys such as per capita emissions.

For our analysis of the consequences of these regimes, we not only need to define the method for differentiating commitments, but also the overall global emission objective. The global emissions should, in principle, be based on the UNFCCC objective to prevent ‘dangerous interference with the climate system’. As indicated earlier, neither scientific nor political uncertainties allow us to unambiguously derive one particular GHG stabilisation level that would fulfil this objective. Some studies indicate that a maximum temperature increase of 2°C over pre-industrial levels might limit risks of large-scale disruption of the climate system (O’Neill and Oppenheimer, 2002; WBGU, 2003). The European Council (1996), for instance, also adopted the 2°C target for its long-term climate objective. As indicated by Eickhout et al. (2003), a 2°C target would, for medium estimates of uncertainties involved, translate into a stabilisation of GHG concentrations at 550 ppmv CO_2 equivalent[1] in 2100. For analytical purposes, we

---

[1] The CO_2-equivalent concentration is a measure of radiative forcing of the set of the six greenhouse gases covered under the Kyoto Protocol (i.e. carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and

have selected a global emission profile in this study that would lead to stabilisation at this level; however, as part of the uncertainty analysis we have also tested the alternative target of 650 ppmv CO_2 equivalent for 2150.

The basic methodology of the analysis consists of three steps: (1) starting with a baseline emissions scenario and a global emission profile, defining the global emission reduction objective; (2) calculating regional emission reduction targets for the three regimes within the context of this global reduction objective; (3) using these targets for the calculation of emissions trading and total abatement costs for each region. For the model analysis, we used the Framework to Assess International Regimes for the differentiation of commitments (FAIR) 2.0 model. FAIR is designed to quantitatively explore a range of alternative climate regimes for the differentiation of future commitments compatible with long-term stabilisation of atmospheric greenhouse gas concentrations (den Elzen and Lucas, 2003).

Section 2 presents the baseline scenario and the emission profile. Section 3 describes the regimes explored in more detail, while Section 4 presents the analysis of the emission reduction allowances (or assigned amounts) for the regimes. This is followed by an analysis of abatement costs and emissions trading in Section 5. Section 6 puts our evaluation into perspective and contains a sensitivity analysis of the key determining factors for the outcomes. Section 7 presents the conclusions.

2. The global emission reduction objective

In our analysis we used the Common POLES IMAGE baseline scenario (Criqui et al., 2003; van Vuuren et al., 2003) as the baseline scenario (Fig. 1). This scenario assumes a continued process of globalisation, medium technology development and a strong dependence on fossil fuels. GHG emissions in this scenario increase from 35 $GtCO_2$ equivalent today, to more than 90 $GtCO_2$ equivalent in 2050 for the set of six GHGs considered in the Kyoto Protocol; this corresponds to a medium-level emissions scenario when compared to the IPCC SRES emissions scenarios.[2] As a result, the baseline reaches a GHG concentration of 930 ppmv CO_2 equivalent by 2100.

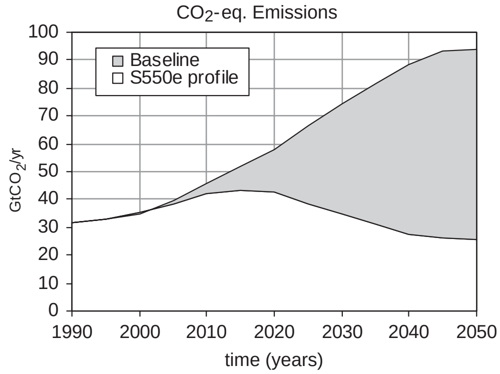

Fig. 1. The global emission reduction objective: the difference between the baseline emissions and the S550e emission profile.

The baseline emissions are compared to a constrained GHG emission profile, corresponding to a stabilisation of total GHG concentration at a level of about 550 ppmv CO_2 equivalent, hereafter referred to as S550e (Fig. 1). This profile was developed with the integrated climate assessment model IMAGE 2.2 (IMAGE-team, 2001), as described in Eickhout et al. (2003). For the short term (up to 2012), the profile incorporates the implementation of the Annex I Kyoto Protocol targets (including banking of excess emission allowances) and adoption of the proposed greenhouse gas intensity target for the USA (−18% between 2002 and 2012) (White-House, 2002). Non-Annex I countries are assumed to follow their baseline emissions in the 1995–2012 period. After 2012, the profile was calculated using an adapted version of the methodology developed by Enting et al. (1994). It should be noted, however, that the flexibility in achieving the 550 ppmv stabilisation is very limited, since even under stringent reductions by 2020 the concentration has already reached the 500 ppmv level, and absolute reductions of global emissions are needed to avoid overshooting the target (Eickhout et al., 2003). The emissions therefore already need to return to 1990 levels by 2030 as shown in Fig. 1. The difference between the baseline scenario and the stabilisation scenario is the global emission reduction objective.

3. The three climate regimes explored

The three different regimes and the specific assumptions under which these regimes will be explored here (as

---

(*footnote continued*)
sulphur hexafluoride (SF_6)) expressed in terms of the CO_2 concentration that would result in the same level of (additional) radiative forcing.

[2] The baseline and emission profiles are all expressed in CO_2-equivalent emissions, calculated using the emissions of the six GHGs combined with the 100 year global warming potentials (GWPs) (IPCC, 2001b). Since the introduction of the GWP concept (1990), it has been subject of continuous scientific debate on the question of whether it provides an adequate measure for combining the different effects on the climate system of the different greenhouse gases. The GWP concept is very sensitive to the time horizon selected, and can only partly take into account the impacts of the different lifetimes of the various gases. Economists currently criticise GWP for not taking economic efficiency into account. However, despite its limitations, the GWP concept is convenient and has been widely used in policy documents such as the Kyoto Protocol. To date, no alternative measure has attained a comparable status in policy documents.

Table 1
The assumptions of the policy parameters of the cases of the three regimes explored

Climate regime	Parameters	S550e profile
Multi-Stage	First participation threshold	Capability–Responsibility[a] index = 5
	Second participation threshold	Capability–Responsibility[a] index = 12
	Intensity targets	Income-dependent function with a maximum of 3.0%/year at 50% of 1995 Annex I per capita PPP income
Brazilian proposal approach	Participation threshold	40% of 1995 Annex I per capita PPP income
Contraction & Convergence	Convergence year	2050 (Contraction & Convergence 2050) 2100 (Contraction & Convergence 2100)

[a] The Capacity–Responsibility index is defined as the sum of per capita income (in €1000) and per capita CO_2-equivalent emissions (in ton CO_2), using one-to-one weighting combined with a normalisation make the index 'unitless' (Criqui et al., 2003).

cases) are described in the next three sections. For the Contraction & Convergence approach we, in fact, assume two cases with different convergence years, 2050 and 2100 (Table 1).

3.1. Multi-Stage approach

The Multi-Stage approach consists of a system to divide countries into groups with different levels of efforts and types of commitments (stages). The aim of such a system is to ensure that countries with similar circumstances—in economic, developmental and environmental terms—have comparable responsibilities, i.e. commitments under the climate regime. Moreover, the system defines when a country's level of commitment changes according to pre-determined rules related to a change in its circumstances.

The Multi-Stage approach thus results in an incremental evolution of the climate change regime, i.e. a gradual expansion over time of the group of countries with commitments (Annex I), with countries adopting different levels and types of commitments according to participation and differentiation rules. The approach was first developed by Gupta (1998). Later, in Berk and den Elzen (2001) and den Elzen (2002), the approach was elaborated into a quantitative scheme for defining mitigation commitments under global emission profiles compatible with the UNFCCC objective of stabilising GHG concentrations. den Elzen et al. (2004) developed a simpler case with several new types of participation thresholds. We have selected one of the most promising cases from this work. Here, the Multi-Stage approach is based on three consecutive stages for the commitments of non-Annex I regions beyond 2012: i.e. Stage 1—no commitment (baseline emissions), Stage 2—emission limitation targets (intensity targets) and Stage 3—absolute reduction targets. Participation thresholds are used for the transition from Stages 1 to 2 and from Stages 2 to 3.

Participation thresholds are based on a Capability–Responsibility index. The index originates in the principles used by Criqui and Kouvaritakis (2000), and is defined as the sum of per capita GDP income (in PPP€1000 per capita[3]), which relates to the capability to act, and of per capita CO_2-equivalent emissions (in ton CO_2 per capita), reflecting the responsibility in climate change. Because it combines variables with different characteristics, this composite index should in principle be normalised and/or weighted. It happens, however, that one-to-one weighting combined with normalisation (to make it 'unitless') produces satisfactory results. On any date, the index can simply be computed as the sum of GDP and of total GHG emissions, and divided by the population of the region or country considered (Criqui et al., 2003). Current (2000) index values vary widely between countries, ranging from below 2 for Eastern and Western Africa, 4 for India and 8 for China, to as high as 29 for Europe and 25 for the USA.

For Stage 2, the intensity improvement targets are defined as a linear function of per capita income level, and thereby relax the emission limitations for the low-income, non-Annex I regions. A maximum rate is adopted to avoid de-carbonisation rates that would outpace those of economic growth. In Stage 3, the total reduction effort[4] to achieve the global emission profile is shared among all participating regions on the basis of a burden-sharing key (here, per capita emissions).[5] This key tends to result in a convergence of per capita emission levels, as mentioned in the preamble of the

---

[3] GDP levels of different countries are normally compared on the basis of conversion to a common currency using market exchange rates (MER). However, this is known to underestimate the real income levels of low-income countries. Therefore, an alternative conversion has been developed on the basis of purchasing power parity (PPP). Here, we have usually used PPP-based GDP estimates; however, MER-based estimates for comparison are used where required.

[4] The difference in the remaining emissions, i.e. global emissions of profile minus the total emissions of all regions in Stages 1 and 2, at times t and $t-1$.

[5] The share of a region r in the total emission reduction is calculated as $X_r = (E_r * pcE_r)$ divided by the sum of X over all regions, with E_r representing the total emissions and pcE_r the per capita emissions. In this way, two regions with equal per capita emissions but different total emissions make the same relative reduction effort compared to their emissions.

Marrakesh Accords. All Annex I regions (including the USA)[6] are assumed to be in Stage 3 after 2012.

3.2. Brazilian proposal approach

During the negotiations of the Kyoto Protocol, the delegation of Brazil presented an approach for distributing the burden of emission reductions *among Annex I Parties* based on the effect of their cumulative historical emissions from 1840 on the global average surface temperature (UNFCCC, 1997b). The Brazilian Proposal was not adopted but did receive support, especially from developing countries, and has become a subject of continued debate and analysis (e.g. UNFCCC, 2002). Although the proposal was initially only developed for further discussion on differentiation of commitments among Annex I countries, it is obviously interesting to consider how the approach can be adopted for application on the global scale. Berk and den Elzen (2001) argued that in such case, a threshold for participation of the non-Annex I regions should be added that would avoid immediate binding targets for developing countries. Such a threshold would allow low-income countries (with considerably lower per capita emissions than high-income countries) to focus on economic development. Such an extended Brazilian Proposal case (from now on referred to as the Brazilian Proposal *approach* to indicate the difference from the original proposal[7]) has been elaborated on by den Elzen et al. (2003). We have selected an income threshold for participation of non-Annex I regions from their work, i.e. 40% of 1995 Annex I per capita income, measured in PPP terms. This income level is about PPPS$7000, which is close to the present (2000) level of per capita PPP income in Russia, Bulgaria and Latvia. It corresponds roughly with the lowest Annex I per capita PPP income (except that of Romania and the Ukraine). For the regions that have passed the threshold, the remaining reduction burden[8] to achieve the global emission profile is shared among all participating regions on the basis of temperature contribution calculations. For the latter, we used the UNFCCC (2002) attribution methodology, an updated and improved version of the original methodology of the Brazilian Proposal, which is analysed in detail in den Elzen et al. (2002). The temperature contributions are based on calculated contributions at a point in time 5 years earlier than the point in time of calculations of the reductions (for example, the contribution of a region in 2050 is based on its contribution to the global temperature increase in 2045).

3.3. Contraction & Convergence

An alternative approach, which would represent a major shift from the present Kyoto Protocol approach, is the so-called ‘Contraction & Convergence’ approach (Meyer, 2000). Instead of focusing on the question of how to share the emission reduction burden as in the present Kyoto Protocol, this approach starts from the assumption that the atmosphere is a global common to which all are equally entitled, and focuses on sharing the use of the atmosphere (resource sharing). More specifically, the approach defines emission rights on the basis of a convergence of per capita emissions under a contracting global emission profile. In the approach, all Parties participate immediately after 2012, with per capita emission permits (rights) converging towards equal levels over time. More specifically, over time, all shares converge from actual proportions in emissions to shares based on the distribution of population in the convergence year.

In this analysis, we explore two cases with different convergence years, 2050 and 2100, since the results of the approach are so strongly dependent on the convergence year chosen. These are the Contraction & Convergence 2050 case and Contraction & Convergence 2100 case. A linear convergence is assumed for both cases.

4. Regional emission allowances

This section evaluates the regional emission allowances for the reference cases of the Brazilian Proposal, the Multi-Stage approach and Contraction & Convergence. The first step in the evaluation is a more general comparison of emission reduction levels for Annex I and non-Annex I regions. Fig. 2 depicts the change in the regional emission allowances compared to the baseline levels for 10 aggregated regions[9], providing information on the magnitude of effort required from the different Parties.

---

[6] Obviously, there is no certainty that this will happen, but this also holds for the assumption made in this analysis that the Kyoto Protocol will enter into force. However, it is hard to conceive of any global climate regime that is compatible with stabilising GHG concentrations at 550 ppmv equivalent, if the USA decide to stay out even after 2012.

[7] Den Elzen and Schaeffer (2002) have extensively analysed the deficiencies in the original proposal.

[8] The difference in the remaining emissions, i.e. global emissions of profile minus the total emissions of all non-participating non-Annex I regions at times t and $t-1$.

[9] Calculations were done at the level of 17 regions, i.e. Canada, USA, OECD-Europe, Eastern Europe, FSU, Oceania and Japan (Annex I regions); Central America, South America and Middle East and Turkey (middle- and high-income non-Annex I regions); Northern Africa, Southern Africa, East Asia (incl. China) and South-East Asia (low-middle income non-Annex I regions); Western Africa, Eastern Africa and South Asia (incl. India) (low-income non-Annex I regions) (IMAGE-team, 2001). Here, we aggregated these 17 regions to 10 regions for reporting reasons as shown in Fig. 2.

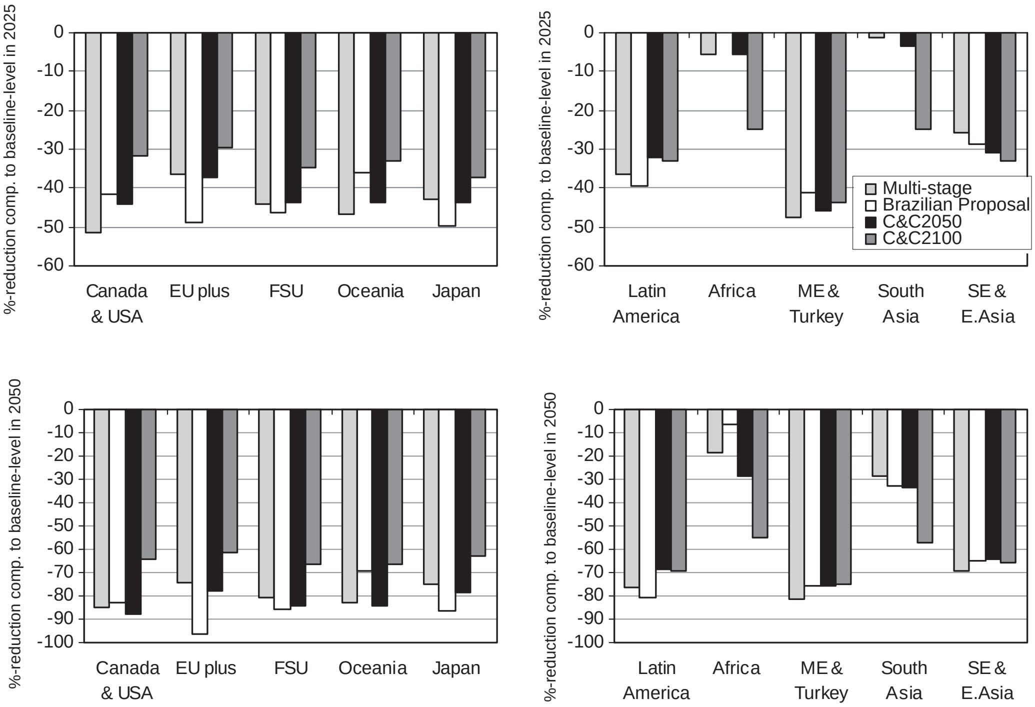

Fig. 2. Percentage change in emission allowances relative to the baseline emissions.

Annex I regions: Fig. 2 shows that the Annex I commitments need to be deepened in all cases after 2012. In almost all cases, reductions of 40–50% in 2025 and 75–95% in 2050 are required for Annex I regions. Contraction & Convergence 2100 forms an exception with somewhat lower reductions. Compared to their 1990 emission levels, the emission reductions are obviously lower, from 15% to 45% in 2025 and 70% to 90% in 2050.

Non-Annex I regions: Most non-Annex I regions will need to reduce their emissions by 2025 compared to baseline levels, but emissions can increase compared to 1990 under all regimes analysed. For non-Annex I regions, the results are generally more differentiated for the various commitment schemes and time horizons (2025 versus 2050) than for Annex I regions (see Fig. 2). For the low-income regions (Africa and South Asia), the reductions compared to the baseline levels in 2025 are limited (from less than 10%), but increase to 20–40% in 2050. Only the Contraction & Convergence 2100 case forms an exception, with much higher reductions for the low-income regions. For the middle-income regions (Latin America, Middle East and Turkey, and South-East and East Asia), these reductions increase from approximately 35–50% in 2025 to about 60–85% in 2050. Now, the Contraction & Convergence 2100 case gives somewhat higher reductions than the Contraction & Convergence 2050 case.

Comparison of the regimes: The following observations can be made from Fig. 2 on comparison of the different regimes:

- The Multi-Stage case gives results similar to the Contraction & Convergence 2050 case. In fact, the Multi-Stage case leads to some convergence in the per capita emissions by 2050 too as a result of the applied burden-sharing key based on per capita emissions (not shown here).
- The Brazilian Proposal case leads to the highest reductions for EU plus (i.e. OECD-Europe and Eastern Europe) and Japan due to their relatively large historical contributions to temperature increase. The non-Annex I regions with large historical land-use emissions, such as Latin America, also show relatively large reduction efforts. Africa, South Asia and also South-East and East Asia benefit from the non-binding commitments before participating in the reductions.
- The two Contraction & Convergence cases clearly show the difference in the convergence year to have a major influence. An ‘early’ convergence year (2050) results in much higher reductions in Annex I emissions than a later convergence year. An early convergence year can also create substantial excess emission allowances for the low-income non-Annex I regions. However, under the considered baseline and S550e profile, the Contraction & Convergence 2050 case does not lead to significant excess emissions. In fact, due to the higher per capita emissions of Southern Africa, there are no excess emissions for Africa as a whole. On the other hand, a ‘late’ convergence year (2100) results in substantial emission limitations for the low-income non-Annex I regions.

More generally, the Contraction & Convergence approach leads to the lowest reductions for EU plus and Japan because of their relative low per capita emissions and the fact that all countries contribute. The earlier contribution of the non-Annex I regions results in large reductions for South Asia and South-East and East Asia. Since the per capita emissions for East Asia (China) are close to the world average per capita emissions, they do not gain in the short term from the convergence. South Asia (India) is better off with the income thresholds under the Multi-Stage case, while in the short-term, the low-income African regions (Eastern and Western Africa) gain from the excess emissions.

5. Abatement costs

5.1. Methodology and assumptions

As the previous section showed that the four climate regime cases explored lead to a wide range of future emission allowances per region, this section explores the consequences of these climate regimes in terms of abatement costs using the mitigation costs model of FAIR 2.0, taking into account the impacts of emissions trading. This model makes use of aggregated permit demand and supply curves, derived from marginal abatement cost (MAC) curves for the different regions, gases and sources.[10] The permit demand and supply curves are used to determine the international market equilibrium permit price (henceforth known simply as 'permit price') on the basis of the same methodology as applied by Ellerman and Decaux (1998). This methodology distributes the regional emission reduction objective over the different gases and sources following a least-cost approach, taking full advantage of the flexible Kyoto Mechanisms as defined under the Kyoto Protocol, i.e. International Emissions Trading (IET), Joint Implementation (JI) and the Clean Development Mechanism (CDM). Subsequently, the permit price is used to determine the buyers and sellers on the international trading market, the accompanying financial flows of permit trading and the regional abatement costs resulting from domestic and external abatements. The banked emission allowances of the FSU during the Kyoto period are all fully used in the second commitment period (2015), while banking and/or borrowing of permits between periods after Kyoto is not assumed.

Although the methodology based on MAC curves has the great advantage of being transparent and easy to apply, it also has a number of limitations. First of all, MAC curves only represent direct cost effects with feedback to the overall economy; this means that there is no direct link with macroeconomic indicators such as GDP or utility losses. Furthermore, the MAC curves have been created outside the system and can therefore not respond to the actual interactions resulting from mitigation action such as those resulting from abatement efforts in other countries (carbon leakage, technology transfer). Finally, using the MAC curve methodology, we found that emission reductions do not lead to structural changes of the system and result in an unaffected baseline.

Different sets of MAC curves for different emission sources are used here (for more details, see van Vuuren et al., 2003). Response curves from the TIMER energy system model (van Vuuren et al., 2004) are used for the energy and industry-related CO_2 emissions. These curves include technological developments, learning effects and system inertia.[11] MAC curves of Criqui (2002) are used for the energy- and industry-related non-CO_2 GHG emissions. These curves are based on detailed abatement options per gas and per source.[12] Because these curves were constructed for 2010 only, technological improvements of 2% reduction increase per 5 years is assumed. Finally, for emission reductions through sinks, only carbon credits from forest management and Afforestation, Reforestation and Deforestation (ARD) projects are considered. For the sink credits from ARD projects, we used the MAC curves of Graveland et al. (2002), while taking conservative estimates—along with negligible costs—for sinks from forest management.[13]

Transaction costs, consisting of a constant €0.50/ton CO_2 equivalent emissions plus 2% of the total costs, were assumed for the use of the Kyoto Mechanisms. Due to the project basis of CDM, only a limited amount of the abatement potential is assumed to be operationally available on the market. This availability is set at

---

[10] A MAC curve, differing per country, reflects the additional costs of reducing the last unit of carbon as a function of the level of abatement.

[11] In order to take on the role of path dependency in the emission reductions, a large number of response curves have been calculated, assuming a linear increase in the permit price after the first commitment period and the final value in the evaluation year. The response curves are converted into MAC curves to be used in FAIR. Under the baseline, regional differences in pay-back times for energy-efficiency investments are used to introduce differences in energy-efficiency levels among regions. In the mitigation cases it is assumed that the high carbon prices and the emergence of an international permit market will lead to converging pay-back times, with full convergence at €80/ton CO_2 (van Vuuren et al., 2004).

[12] MAC curves were not available for the large agricultural emission sources of CH_4 and N_2O. As it is unlikely that these sources will remain unabated under ambitious climate targets, we assumed a linear reduction towards a maximum of 35% compared to the baseline levels within a period of 30 years, when the permit price reaches a value of approximately €25/ton CO_2 equivalent.

[13] For the Annex I regions, forest management credits are assumed to remain constant after Kyoto on the basis of FAO data and Appendix Z of the Marrakesh Accords. We apply the lowest Annex I FM credit per area unit for the non-Annex I regions and multiply this by the forest area.

10% of the theoretical maximum in 2010, increases linearly in time to 30% in 2030 and remains constant afterwards. We assumed full availability for IET and JI.

The net regional costs or gains for the different regimes result from the costs of domestic abatement combined with the costs or gains from emissions trading. Given the large differences in income between the regions, the costs (or gains) are compared to regional GDP levels (the ratio is further referred to as 'effort rate'), thereby giving an indication of costs in comparison to the 'carrying capacity' of the local economy. The GDP can be expressed either in market exchange rates (MER) or in PPP terms. According to our current understanding, comparison of abatement costs to GDP measured in PPP terms might be more relevant as an indication of potential economic impacts where all reductions result from domestic abatement, while in the case of emissions trading, MER-based GDP estimates would be more relevant for comparison. As the lion's share of the reduction efforts is taken domestically, GDP in PPP terms would seem most favourable. Section 6 will go further into the implications of the use of MER- or PPP-based measurement of the effort rate.

Finally, it should be noted that estimating costs of future policies is beset with uncertainties and highly depends on assumptions made. Our costs should be regarded as lower boundary costs, given our least-cost approach and our assumptions of fully effective emissions trading, removal of implementation barriers and no strategic behaviour of suppliers in emissions trading after Kyoto Protocol. The baseline also assumes that, even without climate policy, zero and low-carbon energy technologies will continue to reduce their costs as a result of learning-by-doing through application in niche markets on the basis of existing policies and subsidies (van Vuuren et al., 2003).

5.2. International permit price and global abatement costs

Fig. 3 shows the international permit price and the global abatement costs. Over the 2010–2050 period, the permit price shows a sharp increase (from €2 to €120–150/ton CO_2 equivalent), due to the rapid increase in the global emission reduction objective (from 1 Gt CO_2 equivalent to 45 Gt CO_2 equivalent) and the exponential form of the MAC curves, with faster increasing prices for higher emission reduction objectives.

For the Contraction & Convergence cases, the permit price remains somewhat below the permit price of the Multi-Stage and Brazilian Proposal cases, but this also depends on a fully effective functioning of emissions trading. For the Contraction & Convergence cases, all non-Annex I regions are assumed to fully participate in emissions trading after 2012, whereas for the Multi-Stage and Brazilian Proposal approach, participation increases with time. The non-participating non-Annex I regions have no commitments and can, therefore, only participate through CDM. CDM allows participating regions to fulfil part of their reduction objective by buying emission reductions of non-participating regions on a project basis. The limited availability of viable CDM projects lowers the supply of emission reductions on the international market, thereby increasing the permit price. The group of participating regions is smaller for the Brazilian Proposal approach than under the Multi-Stage, resulting in a larger difference between the permit prices.

The global effort rate shows the same trend as the international permit price. It increases rapidly to a level of 0.9–1.1% up to 2040, after which total abatement costs increase more slowly than global GDP, resulting in a gradual decrease. These costs can be compared to other costs measures. The total annual energy system costs, for instance, are globally speaking around 7–8% of GDP throughout the 2000–2050 period (IMAGE-team, 2001). The estimates for costs of environmental policies in the EU countries (mostly for waste and water management) range from 1.5% to 2.75% (CBS/RIVM, 2001; Wieringa, 1995). It should be noted that these are not full macro-economic costs, but annual costs expressed as the percentage of GDP just as our costs measures for climate change policies discussed above. The macro-economic costs are mostly calculated as (cumulative) GDP losses in a specific target year. The

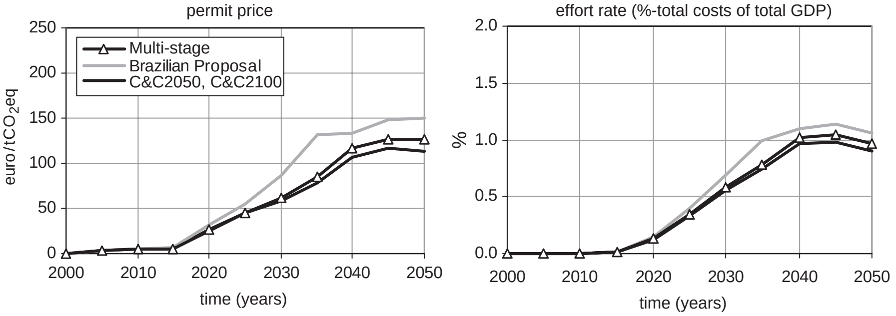

Fig. 3. The international permit price (left) and the global abatement cost development (right) from 2000 to 2050.

cumulative impact of climate policies on GDP may be lower than expected from the annual abatement costs levels due to the fact that climate policy leads mostly to substitution of investments and activities, and much less to an overall reduction of GDP.

In its Third Assessment Report (IPCC, 2001b) the IPCC presents some estimates for macro-economic costs of stabilisation of the CO_2 concentration, but these estimates also cover a considerable range. For stabilisation of the CO_2 concentration at 450 ppmv (comparable to 550 CO_2 equivalent), GDP reductions for 2050 are in the order of 2.5–3.0% (the range associated with scenario A1b and B2). WBGU (2003) also presented macro-economic costs for stabilising the CO_2 concentration of 1.5% at 450 ppmv in 2050 for their IPCC A1 T scenario.

5.3. *Regional abatement costs*

The regional abatement costs as percentage of GDP (effort rates) illustrated in Fig. 4, differ largely across the various regimes and regions. Differences between regions can partly be explained by the diversity in regional volumes traded and associated financial flows and by the differences in regional GDP. A relatively low GDP combined with high net costs can result in a higher effort rate.

Annex I regions: The effort rates of the Annex I regions—apart from the FSU—increase from 0.5–1% in 2025 to 1–2% in 2050, with an exception for the lower costs in the Contraction & Convergence 2100 case. Total abatement costs tend to be relatively high in all regimes for Canada and USA and Oceania (regions with the highest per capita emissions), and somewhat lower for the EU plus and Japan (regions with medium per capita emissions). Total costs are the highest for the FSU due to their relatively high emissions per capita and a medium income. All Annex I regions, even the FSU, act as permit-importing regions; thus, their total abatement costs also include permit expenses from permit trading. However, domestic abatement forms the major part of the total abatement, which increases in time, i.e. from about 65–90% in 2025 to 75–90% in 2050.

Non-Annex I regions: There are much larger differences between the non-Annex I regions than between the Annex I regions. The Middle East and Turkey and Latin America act as permit-importing regions, and are as such confronted with the highest abatement costs, whereas Africa, South Asia and South-East and East Asia are permit-exporting regions, and benefit from the revenues of permit trading, and have much lower abatement costs, and even gains.

More specifically, over the whole period (2010–2050), Middle East and Turkey are confronted with the highest effort rates (1–2% in 2025 and 3–4% in 2050). This is mainly due to their relatively high emission reduction objectives (as a result of relatively high per capita emissions) and low GDP (in 2050, still lower than the 1995 Annex I per capita income). In 2025, the effort rate of Latin America is of the same order as that of the Annex I regions (0.5–1%). In 2050, the more stringent reduction objective of Latin America results in higher abatement costs, which, combined with

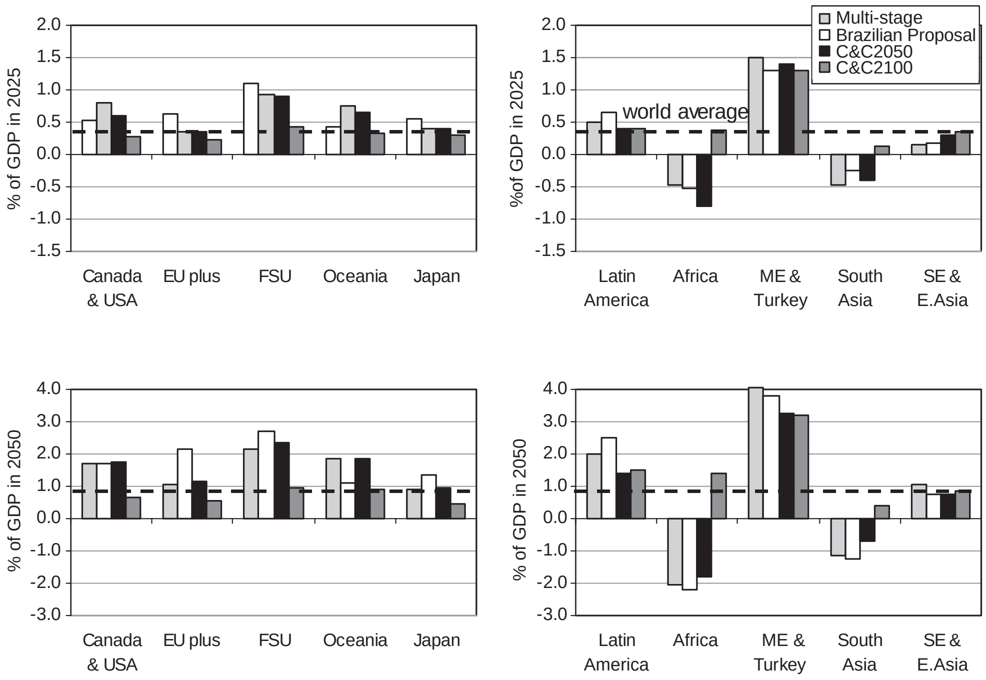

Fig. 4. Regional abatement costs as percentage of GDP in 2025 and 2050.

their medium-income results in relatively high effort rates (1.5–2%).

Except for the Contraction & Convergence 2100 case, South Asia, makes gains in all regimes, both in 2025 (0–2%) and in 2050 (0.5–1.5%). The effort rate of Africa, on the contrary, differs largely between the various regimes, and its associated large differences in emission reduction objectives. Furthermore, the effort rates show more extremes due to their relatively low GDP. More specifically, for the Contraction & Convergence 2050 case, the surplus emission allowances lead to high financial revenues, whereas the Contraction & Convergence 2100 case, with no surplus allowances and the highest reduction target, leads to the lowest financial revenues and high domestic abatement costs. For the Multi-Stage case the delayed participation in full permit trading leads to lower gains in 2025. The effort rate of South-East and East Asia is fairly low (below the world average or may even be negative) due to their relatively high gains from permit trading, which partly compensate their abatement costs of emission control.

Comparison of regimes: In general, the differences in regional costs for each region reflect the differences in reduction targets, since the reduction efforts and abatement costs are strongly related. For example, for most Annex I regions, the Brazilian Proposal case again leads not only to the highest reduction objectives but also to the highest costs. However, regimes with the lowest reduction efforts, as for example the Brazilian Proposal case for the Middle East and Turkey, can still end up with high abatement costs, and might therefore not be that attractive.

For this reason we more systematically analyse the effort rates of the three regime approaches for the various regions by comparing the effort rates with the world average. Four groups of regions with similar efforts can be identified:

(1) regions with high income and high per capita emissions generally showing average costs when compared to other regions (Annex I regions excluding the FSU);
(2) regions with medium to high per capita emissions but medium income levels and confronted with the highest costs (Middle East and Turkey, FSU, and to a lesser extend Latin America);[14]
(3) regions with low to medium income levels and per capita emissions (South-East and East Asia), and confronted with low to average costs;
(4) regions with low per capita emissions and a low income (Africa and South-Asia) that show net gains from emissions trading.

As mentioned above, the regions in the first two groups are net buyers of permits on the trading market, while the regions in the other groups are the sellers. It should be noted that the financial flows (attached to the permit trade) between these regions can become quite large, ranging from 125 to 400 billion Euro in 2025 to 600–800 billion Euro in 2050 for most regimes, except the Contraction & Convergence 2100 case, with much lower flows—35 billion Euro in 2025 and 30 billion Euro in 2050.

In this way we can evaluate whether regimes are more or less attractive in terms of abatement costs for the various regions. For group 1, the Multi-Stage and Contraction & Convergence (in particular, Contraction & Convergence 2100) could be concluded as being attractive regimes, whereas the Brazilian Proposal approach is less attractive, leading to the highest reductions and costs. For the Middle East and FSU (group 2) all regimes seem unattractive, since they all lead to high costs.[15] For Latin America, the Brazilian Proposal approach is not attractive. For group 3, Contraction & Convergence can be less attractive than regimes with an income threshold (Multi-Stage and Brazilian Proposal approach), while for group 4, all regimes are attractive, in particular, those where their allowable emission levels are larger than their baseline emissions (excess emission allowances) as under Contraction & Convergence 2050 case, leading to the highest gains.

6. Robustness of results

This section investigates to what extent the abatement costs depend on key assumptions, such as the choice of effort rates as the percentage of GDP in MER or PPP, different emissions scenarios, the set of MAC curves used and the concentration stabilisation target.[16] To assess the impacts of these key assumptions, a sensitivity analysis was performed in which the assumptions were varied one by one. As the reference case, we used the Contraction & Convergence 2050 case with the Common POLES IMAGE baseline (reference baseline), the default CO_2 MAC curves, GDP in PPP and the 550 ppmv CO_2 equivalent concentration target.

First, the effort rates were calculated as a percentage of GDP in MER (hereafter known as the GDP-MER case). Second, to assess the impacts of the baseline emissions scenario, two alternative scenarios were used,

---

[14] Based on the arguments that Latin America has costs higher than the world average; however, since their costs are less than the costs of the other group 2 regions, this region could also be placed in group 3.

[15] At the same time, these regions can also be exposed to higher costs due to lost energy trade revenues (see, van Vuuren et al., 2003).

[16] For a more extensive uncertainty analysis of other factors, like other CO_2 MAC curves from other energy-system models, other non-CO_2 MAC curves, the assumptions on sinks and non-CO_2 land-use emissions on the abatement costs, please refer to van Vuuren et al. (2003).

i.e. the IPCC SRES A1b scenario and the low-emission IPCC SRES B2 scenario (IPCC A1b and B2 cases) (IMAGE-team, 2001). A second set of TIMER CO_2 MACs was used in addition to the TIMER-based CO_2 MAC curves (MAC II case). In this second set, we assumed a more limited convergence of accepted pay-back times for mitigation measures in different parts of the world, which would result from the higher permit prices. This leads to fewer investments in energy efficiency options, and therefore high marginal abatement costs in low-income countries. Finally, to assess the impacts of the concentration target, we use the global emission profile resulting in a stabilisation of GHG concentrations at 650 ppmv CO_2 equivalent (S650e profile) of Eickhout et al. (2003).

6.1. *International permit price and global abatement costs*

Fig. 5 shows the baseline emissions scenarios and MAC curves to have a large influence on the permit price and the global abatement costs. Changing the baseline scenario affects the emission reduction objective, the MAC curves and the GDP growth (denominator of the effort rate). The low-emission B2 baseline scenario results in a lower permit price than the reference baseline, while the high-emission A1b baseline scenario results in a considerably higher price. In terms of effort rates, the differences with the reference baseline are much less—certainly for A1b with a high GDP growth rate. Fig. 5 shows that depending on the choice of the baseline, global effort rates vary between 0.25–0.75% in 2025 and 0.5–1.3% in 2050.

The second set of MAC curves results in less energy-efficiency projects available in low-income non-Annex I countries at low costs. This decreases the supply on the trading market, thereby increasing the permit price and abatement costs by a factor of $1\frac{1}{2}$, leading to a global effort rate of almost 1.5% in 2050. Finally, the influence of calculating the GDP in MER is very limited for these global indicators, since, on a global basis, the difference between the two income measures is small.

For the S650e profile, the global emissions peak later (around 2030) and at a higher level compared to the S550e profile, and would not have to be back to 1990 levels before 2070. Restricting emissions to the S650e profile will require lower abatement costs than the S550e profile (equivalent to 0.2% versus 1.0% of world GDP in 2050).

Comparing Fig. 5 with Fig. 3 shows the latter to exhibit a much smaller difference between the cases. This leads to the conclusion that both the international permit price and the global effort rate are more dependent on the baseline scenario, emission profile and MAC curves used than on the climate regimes considered.

6.2. *Regional abatement costs*

While Fig. 5 presents the global costs, with respect to the sensitivity analysis described above, Fig. 6 gives the results for the regional costs. The first bar shows the outcomes for the Contraction & Convergence 2050 case (the reference case). The first bar shows the outcomes for the Contraction & Convergence 2050 case (the reference case), while the next five bars represent the four alternative cases depicting the choice for MER instead of PPP, the two baseline scenarios, the other set of MAC curves and the S650e profile.

A conclusion similar to that found for the global effort rate above can be drawn in Fig. 6, with the baseline scenario, the MAC curve being used and the concentration stabilisation target being the most important factors. The second set of MAC curves indicates a consistent pattern of higher effort rates (gains and costs). The use of the A1b baseline results in a somewhat mixed picture, since these baselines have been mainly independently developed; therefore, regional developments across these two baseline do not necessarily need to follow the global differences. In fact, as the reference baseline generally shows higher shares of coal use compared to A1b, it depicts higher emissions for several regions (USA, Oceania, Middle East and Turkey, South-East and East Asia) with relatively high

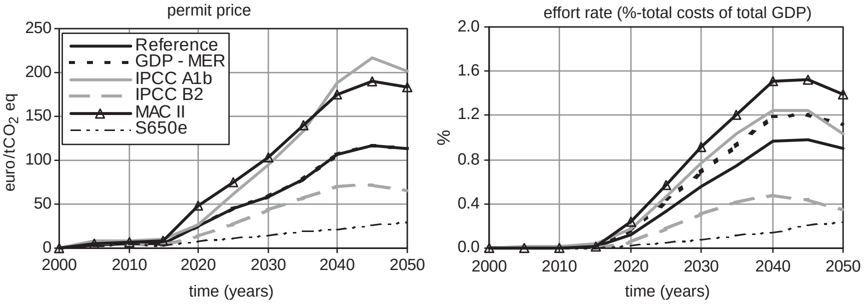

Fig. 5. The impact of key factors on the permit price (left) and the global abatement costs (right). *Note*: the GDP-MER case gives the same permit price as the reference case.

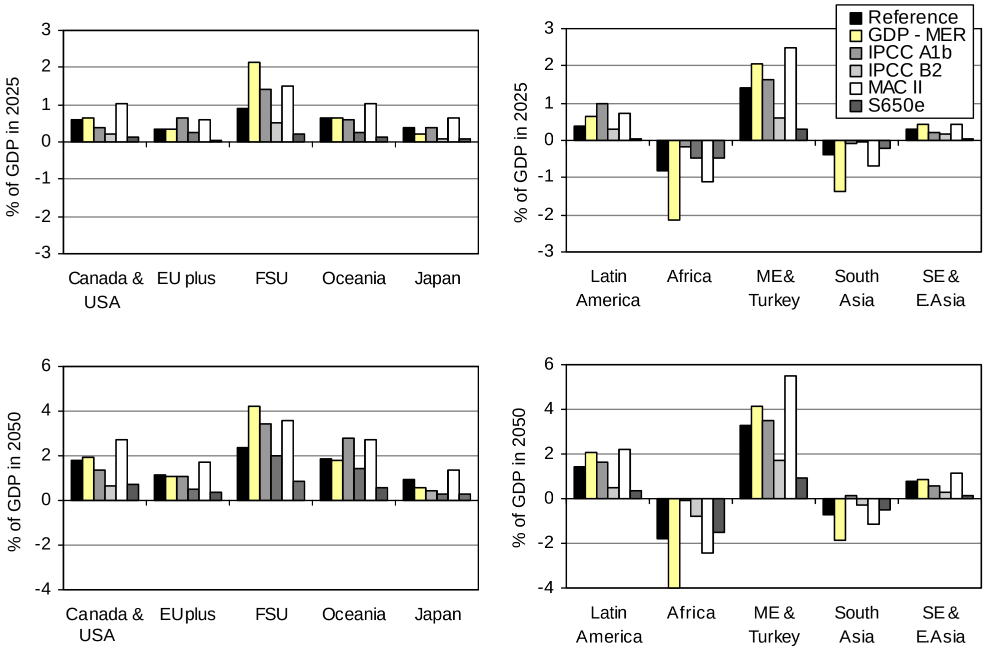

Fig. 6. The impact of key factors on the regional abatement costs as percentage of GDP in 2025 and 2050.

coal-use rates (van Vuuren et al., 2003). For the low-income non-Annex I regions, the pattern is more consistent. The A1b baseline leads to higher reduction objectives, and therefore fewer gains for Africa and even small losses for South Asia.

The choice for MER instead of PPP has a significant impact on the effort rates of the non-Annex I regions and FSU, enhancing the gains of Africa and South Asia, and the losses of the FSU, Latin America and the Middle East and Turkey. Since the MER and PPP GDP values converge in time with rising income levels in low-income countries, the difference with the reference case becomes less.

For the S650e profile, the effort rates are much smaller, but the pattern of costs and gains is similar to that seen under the S550e profile.

In contrast to their minor role in the global effort rates, the regimes explored still play an important role at regional level (compare Figs. 4 and 6), mainly due to the wider range in outcomes for the Contraction & Convergence 2100 and Brazilian Proposal cases. This last finding is valid mainly for the low-income non-Annex I regions, showing a wider range for the regimes than for the key assumptions mentioned.

7. Conclusions

Here, we have analysed the cost implications of three post-Kyoto climate regimes for differentiating future commitments under a global emission profile stabilising the greenhouse gas concentration at 550 ppmv CO_2 equivalent in 2100. The three regimes include the Multi-Stage, the Brazilian Proposal and Contraction & Convergence approaches. For the latter, we have analysed two cases with different convergence years (2050 and 2100). Most regimes show reduction objectives for Annex I regions (before emissions trading) of 35–50% in 2025, and 75–90% in 2050 in comparison to their baseline levels. The Contraction & Convergence 2100 regime forms an exception, leading to lower reduction objectives for Annex I regions and the highest reductions for non-Annex I regions. For the non-Annex I regions, reductions for the various regimes and time horizons (2025 versus 2050) can differ more sharply than for Annex I regions. In general, low-income regions (Africa, South Asia) display lower abatement efforts than middle- and high-income regions (Latin America, the Middle East and Turkey, South-East and East Asia). The reductions compared to the baseline levels in 2025 are limited for the low-income regions for most regimes (from less than 10% to even excessive emission allowances) but increase to 20–40% in 2050. For the middle- and high-income regions, these reductions increase from approximately 35–50% in 2025 to about 60–85% in 2050. Again, the Contraction & Convergence 2100 case forms an exception, with much higher reductions for the low-income regions.

In our analysis, the costs of constraining global emissions to achieve the 550 ppmv target are 0.9–1.1% of the world GDP in 2050, with a corresponding international permit price of €120–150/ton CO_2 equivalent. The global costs of the two Contraction & Convergence regimes are generally lower than the Multi-Stage and Brazilian Proposal regimes, which mainly depends on the participation level on the emissions trading market. The costs calculations are subject to considerable uncertainty. Sensitivity analysis with different assumptions on the marginal abatement costs, baseline emissions and concentration stabilisation levels show a range for the international permit price between €25 and €200/ton CO_2 equivalent, and for the global costs between 0.2% and 1.5% of the world GDP in 2050. This indicates that international permit prices and global abatement costs are more highly dependent on the baseline scenario, marginal costs estimates, and stabilisation level than on the climate regimes explored.

The regional abatement costs are more dependent on the different climate regimes, although the baseline scenario, marginal costs and stabilisation level are still of more importance. This regime dependency is valid for particularly the low-income non-Annex I regions, where the costs or revenues from emissions trading play an important role. It seems that four groups with similar abatement costs can be identified. These are: (1) regions with high per capita emissions and a high income (Annex I regions, excluding the FSU) that are confronted with average costs in comparison to other regions (1–2% of GDP in 2050); (2) regions with medium to high per capita emissions, but a medium to low income (FSU, the Middle East and Turkey, and to a lesser extent, Latin America) that are confronted with average to high costs (3–4% of GDP and lower for Latin America); (3) regions with low to medium income levels and per capita emissions (South-East and East Asia) that show low to medium cost levels (0.5–1% of GDP), and (4) regions with low per capita emissions and a low to medium income (Africa and South-Asia) that show net gains from emissions trading for most regimes (0.5–2.0% of GDP). The exception here is the Contraction & Convergence 2100 case, showing medium to high costs. In all regimes explored, the regions in the first two groups are net buyers on the international trading market, while the regions in groups 3 and 4 are the sellers.

From the perspective of the abatement costs, we can conclude that for group 1, the Multi-Stage and Contraction & Convergence approaches could be attractive regimes, whereas the Brazilian Proposal approach is rather unattractive. For the Middle East and FSU (group 2), all regimes seem unattractive since all lead to high costs, while for Latin America, the Brazilian Proposal approach is not attractive. For group 3, Contraction & Convergence can be less attractive than approaches with income thresholds (the Multi-Stage and the Brazilian Proposal). Group 4 may benefit from emissions trading under almost all regimes considered, with Contraction & Convergence 2050 leading to the highest gains. The gains of global emissions trading can provide an incentive for these non-Annex I countries to take on quantified emission limitation commitments. From the perspective of abatement costs, these findings lead to the overall conclusion that the Multi-Stage, and Contraction & Convergence 2050, seem to provide the best prospects for most Parties.

The analysis shows that the regions in group 2 could face significantly higher costs than the other regions, indicating that national circumstances need to be better accounted for in the design of future regimes so as to arrive at more acceptable costs for these regions as well.

Acknowledgements

This study drew on research performed for the Dutch Ministry of the Environment within the Climate Change Policy Support project and was also based on RIVM's contribution to the EU research project 'Greenhouse gas reduction pathways in the UNFCC post-Kyoto process up to 2025'. The authors would like to thank Patrick Criqui and Alban Kitous from CNRS-IEPE (Institute de l'Economie et de Politique de l'Energie, France) along with Marcel Berk, Bas Eickhout and Bert Metz of RIVM, as well as an anonymous reviewer for all the helpful comments and contributions.

References

Banuri, T., Göran-Mäler, K., Grubb, M., Jacobson, H.K., Yamin, F., 1996. Equity and social considerations. In: Bruce, J.P., Lee, H., Haites, E.F. (Eds.), Climate Change 1995—Economic and Social Dimensions of Climate Change, IPCC Working Group III IPCC-SAR. Cambridge University Press, Cambridge, UK.

Baumert, K., Blanchard, O., Llose, S., Perkaus, J., 2002. Building on the Kyoto Protocol: Options for Protecting the Climate. World Resource Institute, Washington DC.

Berk, M.M., den Elzen, M.G.J., 2001. Options for differentiation of future commitments in climate policy: how to realise timely participation to meet stringent climate goals? Climate Policy 1 (4), 465–480.

CBS/RIVM, 2001. Milieucompendium. Kluwer, Alphen aan den Rijn, The Netherlands.

Criqui, P., 2002. GECS Final Report Section 6: detail report. GECS—Research Project No. EVK2-CT-1999-00010. Thematic Programme: Environment and Sustainable Development, DG Research Fifth Framework Programme, CNRS-IEPE, Grenoble, France.

Criqui, P., Kitous, A., Berk, M.M., den Elzen, M.G.J., Eickhout, B., Lucas, P., van Vuuren, D.P., Kouvaritakis, N., Vanregemorter, D., 2003. Greenhouse gas reduction pathways in the UNFCCC Process up to 2025. Technical Report, CNRS-IEPE, Grenoble, France.

Criqui, P., Kouvaritakis, N., 2000. World energy projections to 2030. International Journal of Global Energy Issues 14 (1-4), 116–136.

den Elzen, M.G.J., 2002. Exploring climate regimes for differentiation of future commitments to stabilise greenhouse gas concentrations. Integrated Assessment 3 (4), 343–359.

den Elzen, M.G.J., Berk, M.M., Lucas, P., 2004. Simplified multi-stage and per capita convergence: an analysis of two climate regimes for differentiation of commitments. RIVM-Report 728001024, RIVM, Bilthoven, The Netherlands (www.rivm.nl/ieweb).

den Elzen, M.G.J., Berk, M.M., Lucas, P., Eickhout, B., van Vuuren, D.P., 2003. Exploring climate regimes for differentiation of commitments to achieve the EU climate target. RIVM-Report 728001023, RIVM, Bilthoven, The Netherlands.

den Elzen, M.G.J., Lucas, P., 2003. FAIR 2.0: a decision-support model to assess the environmental and economic consequences of future climate regimes. RIVM-Report 550015001, RIVM, Bilthoven, The Netherlands (www.rivm.nl/fair).

den Elzen, M.G.J., Schaeffer, M., 2002. Responsibility for past and future global warming: uncertainties in attributing anthropogenic climate change. Climatic change 54, 29–73.

den Elzen, M.G.J., Schaeffer, M., Eickhout, B., 2002. Responsibility for past and future global warming: time horizon and non-linearities in the climate system. RIVM-Report 728001022, Bilthoven, The Netherlands.

Depledge, J., 2000. Tracing the Origins of the Kyoto Protocol: An Article by Article Textual History. UNFCCC/TP/2000/2 UNFCCC, Bonn.

Eickhout, B., den Elzen, M.G.J.,van Vuuren, D.P., 2003. Multi-gas emission profiles for stabilising greenhouse gas concentrations. RIVM-Report 728001026, RIVM, Bilthoven, The Netherlands.

Ellerman, A.D., Decaux, A., 1998. Analysis of post-Kyoto CO_2 emissions trading using marginal abatement curves. Report No. 40, MIT, Cambridge, MA.

Enting, I.G., Wigley, T.M.L., Heimann, M., 1994. Future Emissions and Concentrations of Carbon Dioxide. Mordialloc, Australia.

European-Council, 1996. Communication on Community Strategy on Climate Change, Council Conclusions. European Commission, Brussels.

Graveland, C., Bouwman, A.F., de Vries, H.J.M., Eickhout, B., Strengers, B.J., 2002. Projections of multi-gas emissions and carbon sinks, and marginal abatement cost functions modelling for land-use related sources. RIVM-Report 461502026, Bilthoven.

Gupta, J., 1998. Encouraging Developing Country Participation in the Climate Change Regime. Institute for Environmental Studies, Vrije Universiteit, Amsterdam.

Höhne, N., Galleguillos, C., Blok, K., Harnisch, J.,Phylipsen, D., 2003. Evolution of commitments under the UNFCCC: involving newly industrialized countries and developing countries. Research-Report 20141255, UBA-FB 000412, ECOFYS Gmbh, Berlin.

IMAGE-team, 2001. The IMAGE 2.2 Implementation of The SRES Scenarios. A Comprehensive Analysis of Emissions, Climate change and Impacts in the 21st Century. CD-ROM Publication 481508018, Bilthoven, The Netherlands.

IPCC, 2001a. Climate change 2001.The science of climate change: summary for policymakers. IPCC Assessment Reports, Cambridge University Press, Cambridge, UK, pp. 1–18.

IPCC, 2001b. Climate Change 2001: Mitigation. Cambridge University Press, Cambridge, UK.

Jacoby, H.D., Eckaus, R.S., Ellerman, A.D., Prinn, R.G., Reiner, D.M., Yang, Z., 1997. QELRO Impacts: domestic markets, trade and distribution of burdens, and climate change. Energy Journal (18), 31–58.

Jacoby, H.D., Schmalensee, R., Wing, I.S., 1999. Toward a useful architecture for climate change negotiations. Report No. 49, MIT, Cambridge, MA.

Meyer, A., 2000. Contraction & Convergence. The Global Solution to Climate Change. Schumacher Briefings, Vol. 5. Green Books, Bristol, UK.

OECD/IEA, 2002. Beyond Kyoto, Energy Dynamics and Climate Stabilisation. OECD, Paris.

O'Neill, B.C., Oppenheimer, M., 2002. Climate change: dangerous climate impacts and the Kyoto Protocol. Science 296, 1971–1972.

Reiner, D.M., Jacoby, H.D., 1997. Annex-I differentiation proposals: implications for welfare, equity and policy. MIT Global Change Joint Program Report 27, MIT, Cambridge, MA.

Ringius, L., Torvanger, A., Holtsmark, B., 1998. Can multi-criteria rules fairly distribute climate burdens?—OECD results from three burden sharing rules. Energy Policy 26 (10), 777–793.

Rose, A., Stevens, B., Edmonds, J., Wise, M., 1998. International Equity and differentiation in global warming policy. Environmental & Resource Economics 12 (1), 25–51.

Torvanger, A., Godal, O., 1999. A survey of differentiation methods for national greenhouse gasa reduction targets. CICERO Report 1999, Center for International Climate and Environmental Research (CICERO), Oslo.

UNFCCC, 1992. United Nations General Assemby, United Nations Framework Convention on Climate Change, http://www.unfccc.int/resources, United Nations, New York.

UNFCCC, 1997a. Kyoto Protocol to the United Nations Framework Convention on Climate Change. FCCC/CP/L7/Add.1, United Nations Framework Convention on Climate Change, Bonn, Germany.

UNFCCC, 1997b. Paper No. 1: Brazil; Proposed Elements of a Protocol to the United Nations Framework Convention on Climate Change. UNFCCC/AGBM/1997/MISC.1/Add.3 GE.97, Bonn.

UNFCCC, 2002. Methodological issues, scientific and methodological assessment of contributions to climate change. Report of the Expert Meeting, Note by the Secretariat, FCCC/SBSTA/2002/INF.14 (http://www.unfccc.int).

van Vuuren, D., de Vries, H.J.M., Eickhout, B., Kram, T., 2004. Responses to technology and taxes in a simulated world. Energy Economics, forthcoming.

van Vuuren, D.P., den Elzen, M.G.J., Berk, M.M., Lucas, P., Eickhout, B., Eerens, H., Oostenrijk, R., 2003. Regional costs and benefits of alternative post-Kyoto climate regimes. RIVM-Report 728001025, National Institute for Public Health and the Environment, Bilthoven, The Netherlands.

WBGU, 2003. Climate Protection Strategies for the 21st Century. Kyoto and Beyond, WBGU, Berlin.

White-House, 2002. Executive Summary of Bush Climate Change Initiative, White-House, Washington, DC, http://www.whitehouse.gov/news/releases/2002/02/climatechange.html, last accessed in 05/2004.

Wieringa, K., 1995. Environment in the European Union 1995, Report for the Review of the Fifth Environmental Action Programme. European Environment Agency. Copenhagen.

Further reading

Blanchard, O., 2002. Scenarios for differentiating commitments. In: Baumert, K.A., Blanchard, O., Llose, S., Perkaus, J.F. (Eds.), Options for Protecting the Climate. WRI, Washington, DC.