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RIVM report 490200 001

Mitigation scenarios in a world oriented at sustainable development: the role of technology, efficiency and timing

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September 2000

This study has been performed in the context of the project Climate OptiOns for the Long-term (COOL) (project number 490200), financed by the Dutch National research Programme on Global Air Pollution and Climate Change and the Ministry of Housing, Spatial Planning and the Environment.

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Abstract

Two different mitigation scenarios for stabilising carbon dioxide concentration at 450 ppmv by 2100 have been developed, founded on the recently developed IPCC-SRES B1 baseline scenario. In both, a global uniform carbon tax was used to induce a variety of mitigation measures – assuming the presence of an international mechanism for cost-efficient implementation of measures (for instance emission trading or the Clean Development Mechanism). The two scenarios differ in the timing of mitigation action (early action versus delayed response). Analysis of the scenarios has led to the following findings. First, stabilisation at a carbon dioxide concentration of 450 ppmv is technically feasible (requiring a 40% reduction of cumulative emissions between 2000 and 2100 compared to the baseline). Second, in the first quarter/second quarter of this century most of the reduction will come from energy efficiency and fuel-switching options, while the introduction of carbon-free supply options will later account for the bulk of the required reductions. Third, postponing measures foregoes the benefits of learning-by-doing, and, as a result, early-action seems to be a more attractive strategy for stabilisation at 450 ppmv than delayed response (about 30% lower cumulative investments between 2000 and 2100). Fourth, the most difficult period for the mitigation scenarios is the 2010-2040 period (exact timing depends on early action or delayed response), when 'bending the curve' towards a lower carbon emission system will have to be initiated. Finally, the real obstacles for implementing mitigation policies are related to (the large differences in) costs and benefits for individual countries and sectors. Hence, we believe that much political ingenuity will be required to find a method for fair burden sharing.

Samenvatting

Dit rapport beschrijft twee beleidsscenario's gericht op het stabiliseren van de koolstof dioxide concentratie op 450 ppmv in 2100. Beide scenario's zijn ontwikkeld met behulp van het TIMER model en zijn afgeleid van het recent door het *Intergovernmental Panel on Climate Change* (IPCC) ontwikkelde B1 emissie scenario. In beide scenario's wordt in het model een mondiale, uniforme belasting gebruikt om hiermee een scala aan verschillende reductie maatregelen te induceren – waarbij ervan uit wordt gegaan dat een internationaal mechanisme bestaat voor kosten effectieve implementatie van maatregelen (met name emissie handel of het *Clean Development Mechanism*). De twee scenario's verschillen wat betreft het moment dat actie wordt ondernomen (*'Early Action'* of *'Delayed Response'*). Analyse van de scenario's leidt tot de volgende conclusies. Ten eerste, tonen de scenario's aan dat stabilisatie van de koolstof dioxide concentratie op een niveau van 450 ppmv technisch mogelijk is (wereldwijd vereist dit een reductie van 40% van de emissies tussen 2000 en 2100 ten opzichte van de B1 baseline). Ten tweede, zal in het eerste en tweede kwart van de 21ste eeuw het grootste deel van deze reducties komen van verbeterde energie-efficiency en substitutie tussen fossiele brandstoffen; daarentegen zal versnelde introductie van hernieuwbare energie het grootste deel van de emissie reducties na 2050 voor zijn rekening nemen. Ten derde, leidt uitstel van maatregelen tot een vertraagde ontwikkeling van schone technologie (door het missen van *'learning-by-doing'*), waardoor het *'Early-Action'* scenario een aantrekkelijkere strategie lijkt dan het *'Delayed-Response'* scenario (de eerste vereist 30% minder cumulatieve investeringen tussen 2000 en 2100). Ten vierde, lijkt in beide scenario's de moeilijkste periode te liggen tussen 2010 en 2040, wanneer de emissie trend daadwerkelijk moet worden afgebogen (het exacte tijdstip hangt natuurlijk af van het tijdstip van actie). Tenslotte blijkt uit de resultaten dat de echte obstakels voor het implementeren van beleidsmaatregelen de (grote verschillen in) kosten en voordelen voor individuele landen en sectoren zijn. Wij geloven daarom dat er behoefte is aan verdere uitwerking van methodes voor lasten-verdeling.

Preface

The analysis described in this paper has been done using the IMAGE – TIMER model and has been presented at the third Global COOL workshop July 2000 in Zeist, The Netherlands. The analysis has been performed in the context of the Global Dialogue of the COOL project (Climate OptiOns for the Long term). The COOL project is a participatory integrated assessment project financed by the Dutch National Research Programme on Global Air Pollution and Climate Change. The Global Dialogue of the COOL project is primarily directed at stakeholders involved in international climate policy-making within the context of the UN-FCCC, including representatives of environmental and industrial NGOs. The global dialogue aims at exploring critical policy issues relevant for developing effective long-term control of the problem of climate change, through international strategies. More information on the COOL project can be found at the internet site www.nop.nl\cool.

Contents

1. Introduction

The 1992 United Nations Convention on Climate Change (UNFCCC) aims to stabilise greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system. At the moment, as a result of the involved uncertainties, scientists are still not able to indicate the highest concentration levels below which this condition can be considered as met. In fact, such levels can only be agreed upon after political deliberation. However, most available studies seem to agree that baseline emission scenarios, depicting a world without additional climate change policies, will result in significant to severe climate change. Mitigation scenarios are developed to explore the required efforts and possible impacts of climate policies.

Recently, a new set of baseline scenarios has been developed in an international and interdisciplinary modelling effort involving six modelling groups (Nakicenovic et al., 2000). These baseline scenarios are divided into four scenario families, based on differences in governance and the orientation towards social and environmental concerns. One of the scenario families, the so-called 'B1 family', describes a prosperous and fair world, that as a result of a general orientation towards 'sustainable development' leads to relatively low emissions of greenhouse gases. Carbon dioxide emissions, for instance, peak at around twice the current emission level in 2050 and, spurred by a decreasing population, decline thereafter. Nevertheless, the expected increase in atmospheric carbon dioxide concentration to about 550 ppmv in 2100 will almost certainly cause climate change with adverse impacts in many parts of the world (de Vries et al., 2000a). In the B1 scenario family 'baseline' trends already lead to a relatively slow growth of greenhouse gas emissions in comparison to other scenarios; hence, it is an important question whether there is any scope left for further reduction.

Here, we explore the results of two different scenarios for mitigation down to the level of 450 ppmv reduction by 2100, using the IMAGE/TIMER energy model and the B1 scenario as a baseline (this level of ambition is based on the COOL project discussed later in this paper; COOL, 2000). Earlier, it has been shown that reduction costs and option, among others, depend on 1) the baseline scenario, 2) the ultimate concentration rate, 3) the timing of measures, 4) responses in the form of technological change, 5) potential for emission trading and joint implementation and 6) possibility of recycling policy revenues (see e.g. Azar and Dowlatabadi 1999; Bollen, Manders and Timmer 2000). We will discuss some of these points in the sections on methodology and results. We pay explicitly attention to the timing of measures, which has been subject of debate after publication of the article of Wigley et al. (1996), who pointed out that postponing abatement actions was not only physically possible, but also more cost effective. Other authors argued in response that this conclusion depends on the assumptions about technological change (Azar, 1998; Janssen and de Vries, 2000), inertia and uncertainty (Ha-Duong et al., 1997) and the level of the stabilisation target (Azar, 1998). In the analysis described in this paper technological change is an endogenous part of the IMAGE/TIMER model. We have therefore decided to develop two different scenarios both leading to 450 ppmv stabilisation, that differ in the moment that action is started ('early action' starting in 2005 versus 'delayed response' in which action is postponed to 2020).

The IMAGE 2.2 model is an framework of several models, developed to study the long-term dynamics of global change and the linkages that exist between changes in atmosphere, land use and land cover, water availability and human activities. The energy model of IMAGE 2.2, TIMER is a multi-region energy model, which can be used both as stand-alone model or within the IMAGE 2.2 framework[1]. Its main objective is to analyse the long-term dynamics of energy conservation and the transition to non-fossil fuels within an integrated modelling framework. Within the model, several possibilities to simulate policies exist. Instead of designing differentiated policies for each region or sector, here we introduce a uniform ’carbon tax’ in all regions to simulate the presence of international climate policies in order to explore the responses in the modelled energy system to reach 450 ppmv stabilisation. It should be noted that the ‘carbon tax’ is used as a proxy for different kind of mitigation pressures on the system – we do not intend to be explicit on the type of instruments used. Clearly, introducing such a generalised 'carbon tax' implies the presence of effective mechanisms of international cooperation (e.g. emission trading and/or the Clean Development Mechanism). The main focus of this paper will be on the global scale.

Thus, the questions that are addressed in our analysis are: 1) Is it possible to mitigate the greenhouse gas emissions of the B1 scenario in order to reach a level of 450 ppmv ? 2) What would be the contribution of various mitigation options ? 3) What are the costs of mitigation ? 4) Does postponing action lead to cost reductions(or cost increases) ? and 5) What are the consequences for various sectors or regions ?

The organisation of the paper is as follows: First, we address some of the methodological issues, including some features of the TIMER model and in particular the way technological change is included. We briefly present a narrative of the world in our baseline B1 scenario and how this is implemented in TIMER and pay some attention to meaningful indicators policy impacts. Next, we discuss the results of our mitigation scenarios. The last section discusses our results and presents the main conclusions.

[1] TIMER is an acronym for Targets Image Energy Regional model. IMAGE is an acronym for Integrated Model to Assess the Global Environment (e.g. Alcamo, Kreileman and Leemans, 1998).

2. Methodology

The TIMER model has been originally developed as a one world model which has been described in detail in De Vries and Van den Wijngaart (1995) and Janssen and de Vries (2000). More recently, the model has been implemented for 17 world regions (regional breakdown is described by Kreileman et al., 1998; see Appendix A). The regional TIMER energy model contains all dynamics of the one-world model, but in addition includes two forms of regional interaction, i.e. fuel trade and technology-transfer. In the model, a combination of bottom-up engineering information and specific rules and mechanisms about investment behaviour and technology is used to simulate long-term structural dynamics of the energy system. The output is a rather detailed picture of how energy demand, fuel costs and competing supply technologies develop over time in the different regions.

The demand submodel of TIMER determines demand for fuels and electricity in 5 sectors (industry, transport, residential sector, services and other) based on structural [economic] change, autonomous and price-induced change in energy-intensity ('energy conservation') and price-based fuel substitution. Next, the demand for electricity is fulfilled by fossil-fuel based thermal power, hydropower and a non-thermal alternative (solar, wind, nuclear). The latter penetrates the market based on relative costs and learning. The exploration and exploitation of fossil fuels (either for electricity or direct fuel use) is described in terms of depletion and technological development. Instead of fossil fuels biofuels can be used which are assumed to be subject to technological development as well as depletion dynamics.

An important aspect of the TIMER model is the endogenous formulation of technological development. Azar and Dowlatabadi (1999) indicate that climate policy is often discussed as a lever with which to bring about climate-friendly technical innovation and diffusion. Nevertheless, most models routinely treat technology as a factor that is independent of policy. In the TIMER model, instead, technology development is described in terms of log-linear learning curves, according to which the efficiency of process improves with accumulated output ('learning-by-doing'). Such learning curves are used for price-induced energy efficiency improvement, fossil fuel production, non-fossil based electricity[2] and biofuels. The log-linear relationships between cost/efficiency and accumulated output has been observed historically for many processes – and has been suggested by several authors as a meaningful presentation of technological change in global energy models (Grübler, Nakicenovic and Victor, 1998; Azar and Dowlatabadi, 1999). Using learning curves implies that the potential for technological adoption becomes path-dependent. For instance, cheap solar energy will only be available around 2050 if sufficient experience has been built up in the preceding period. We believe that this is a crucial aspect of technological development in the real world.

In the TIMER model, the population and economic activity trajectories are exogenous and taken from the SRES Marker scenarios (as implemented by the macro-economic model WorldScan and the population model Phoenix – Nakicenovic et al., 2000;Hilderink, 2000; de Vries et al., 2000a; de Vries and Van Vuuren, 2000). We do not account for any feedback from energy system to these drivers – neither in the baseline and in the mitigation scenarios.

[2] For non-fossil based electricity two learning curves are used, one representing nuclear power and one representing solar, wind and other renewables (not hydropower). As already more cumulative output is generated by nuclear power, learning in 'standard' scenarios will be slower for nuclear power than for the second group.

We realise that this is an important limitation. On the other hand, the uncertainties involved in these feed-backs are very large. We consider the approach of macro-economic models that do provide consistent links with the rest of economy and the approach of the TIMER model, with more energy system insights, as complementary (see also Janssen and De Vries, 2000). The TIMER model and its model calibration for the 1971 – 1995 period are described in de Vries et al. (2000b).

3. Characteristics of the B1 world and options for mitigation

3.1 B1-Baseline scenario

One of the contribution of the new set of IPCC scenarios is that the quantitative scenarios have been based on qualitative descriptions of a possible world (storylines) (Nakicenovic et al., 2000). The B1 storyline, that is used as baseline in this paper, describes a convergent world with rapid changes in economic structures towards a service and information economy. The emphasis is on global solutions to economic, social and environmental sustainability but without additional climate initiatives. An important trend in the scenario is that rapid economic growth in current low-income countries leads to a fast drop in fertility, resulting finally in a population that peaks at 8,000 million persons in 2050 and then drops to 7,000 million by 2100.

The implementation of B1 in the IMAGE 2.2 framework has been described in detail by de Vries et al. (2000a) and de Vries and Van Vuuren (2000). The total global primary energy supply of the B1 scenario implementation in TIMER is shown on the left hand of Figure 3. Basic assumptions in the energy model are relatively fast dematerialization and technology improvement trends and a mild preference for more environmentally friendly fuel types. Although the choice for energy efficiency and environmentally friendly fuel types is motivated by environmental problems other than climate change, the solution of this problem does benefit from the measures taken (co-benefits). The model indicates that total energy supply is expected to peak around 2050 - and than decreases (Figure 3). The market share of coal remains relatively limited – it is used primarily in electric power generation and industry. In the second half of the century, non-thermal electricity and biofuels slowly start to gain market share, as they become increasingly competitive. As a consequence the greenhouse gas emissions in the B1 scenario remain relatively low. Carbon dioxide emissions peak at around 12 GtC in 2050 and decline thereafter. In the B1 scenario, the energy system is by far the largest source of emissions and is therefore the focus of this paper. The low emissions resulting from the B1 baseline scenario are certainly not achieved without (policy) effort; however, as these are no deliberate climate policies and as most of the changes result from changes in economic structure and behavioural changes no costs can be attached to it.

3.2 Options for mitigation

The conditions of such a world clearly also set the scene for climate mitigation policies. Our considerations here are partly based on the COOL (Climate OptiOns for the Long-term) workshops organised as a dialogue between scientists and policy-makers from different countries around the world (COOL, 2000). The main objectives of these workshops is to identify strategies that could lead to stabilisation of greenhouse gases. In one the workshops, participants have tried to identify which climate impacts should be considered as unacceptable in the context of the climate convention - and to what stabilisation level this would lead. This has led to several conclusions. First, not only stabilisation levels were found to be important but also the rate of temperature change, and thus the emission profile. Secondly, as the precautionary principle was assumed to be a leading principle in a B1 type of world, stabilisation of carbon dioxide concentration should be at relatively low levels – such as 450 ppmv. In a B1 world, aiming for 450 ppmv stabilisation, governments are assumed to take the lead in formulating preventive and adaptive action. Moreover, those in the industrialised countries take the lead and support the less developed regions in a variety of ways, among them transfer of energy-efficiency and renewable-energy related technologies. We believe that internalisation of associated costs – by means of energy taxes or other financial instruments – would also be one of the policy instruments that will be considered in such a world. In contrast, one may expect a dislike for physical carbon sequestration in view of associated environmental risks; hence, we left that option out of our analysis. Finally, in a B1 world there will be awareness of winners and losers under different scenarios, those affected by climate change or those hit disproportionately hard by climate change policies being compensated one way or another. We will pay attention to this further on in this paper.

3.3 Response dynamics

As mentioned in the introduction, the main instrument used to construct our scenarios is the introduction of a world-wide uniform carbon tax, as a proxy of the total mitigation pressure on the energy system. As indicated before, the global uniformity of the tax implies marginal costs in different regions are more-or-less equalised. Such a scenario is only feasible as result of some form of international cooperation, for instance in the form of emission trading. In the model, the tax is levied at the consumer end of the chain[3]. This will result in several responses:

1. price-induced investments in energy-efficiency, accelerated by learning-by-doing;
2. price-induced fossil fuel substitution;
3. changes in the trade patterns of (fossil) fuels;
4. price-induced acceleration of investments in non-fossil options wind / solar energy, nuclear energy and biofuels, accelerated by the learning-by-doing dynamics.
5. Slower depletion of fossil fuels leading to lower prices but also a lower rate of innovation.

Thus, TIMER simulates a variety of technological changes in the energy system in response to mitigation measures. An important question is how to determine the (energy system) costs of the different scenarios. We define costs as the difference between the total financial costs in the energy sector for the baseline and mitigation scenario. In macro-economic models often the value of the carbon tax itself is used as an indication of the costs per unit of carbon saved. In a model with endogenous technological changes, however, costs do not necessarily equal the carbon tax because of the indicated technology developments– and in time tend to decrease in reference to the tax (see also Appendix B).

[3] Alternatively taxes could be introduced by energy producers – but van der Linden et al. (2000) found that would be very hard to implement for institutional reasons.

4. Results

4.1 Emission profiles

Two mitigation scenario profiles for annual carbon dioxide emissions have been derived, leading to about 450 ppmv carbon dioxide concentration by 2100 using the FAIR model with B1 as baseline (den Elzen et al., 2000) (Figure 1)[4]. The first implies that action is taken starting 2005, meeting the Kyoto targets in 2010 ('Early Action'), in the second action is postponed to 2020 ('Delayed Response'). The two profiles are comparable to the so-called WRE and WGI profiles (IPCC, 1995). Although both profiles lead to 450 ppmv stabilisation, the environmental impacts can differ considerably. The FAIR model indicates that, based on its standard setting, the Early Action profile could lead to fast climate change (> 0.1 degree Celsius per decade) between 2000 and 2030, followed by slower climate change after 2030. For the Delayed Response profile the model projects fast climate change (>0.1 degree Celsius) between 2000 and 2055. However, also here 450 ppmv stabilisation is reached due to a sharp bend around 2040-2050. Interestingly, in both cases the largest gap between stabilisation scenarios and baseline occurs the around 2050.

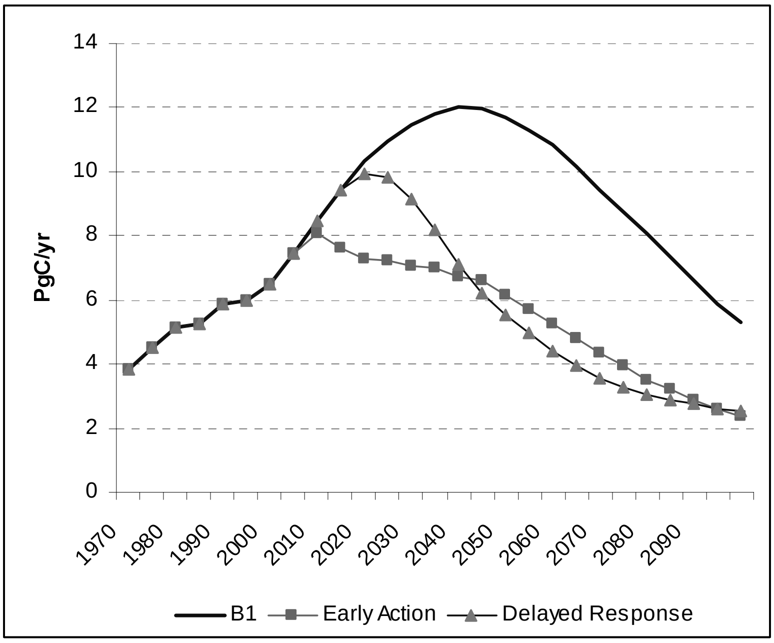

Figure 1: Energy and industry related carbon emissions of the baseline and mitigation scenarios

Next, we introduce carbon tax profiles that result in the TIMER model in the carbon dioxide emission pathways of the profiles indicated in Figure 1 (Figure 2). The 'early action' scenario requires a rapidly increasing tax from 2005 onwards, reaching a level of about 100 1995US$ per tonne carbon around 2020[5]. After 2020, the increase of the tax is much slower and finally

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[4] Land use emissions have been accounted for by subtracting the emissions first from the original profile.

[5] The impact of carbon tax on end-use prices very much depends on the carbon content of a fuel, its price and existing other taxes. For prices of coal in industry, a 100 US$/tC tax can imply an increase from 2 to 6 US$/GJ (200% increase); for prices of transport fuels in Western Europe, however, a similar tax will increase prices from 22 to 25 US$/GJ – which is less than 15%.

even stabilises. The ‘delayed response’ tax could stay at a fairly low level till 2020 (less than 25 US$of 1995 per tonne carbon). However, after 2020 it has to increase rapidly in the period 2020-2045 to follow the sharp curve of the emission profile. In fact, the tax level required to do so reached higher levels from 2030 onwards than in the 'early action' scenario.

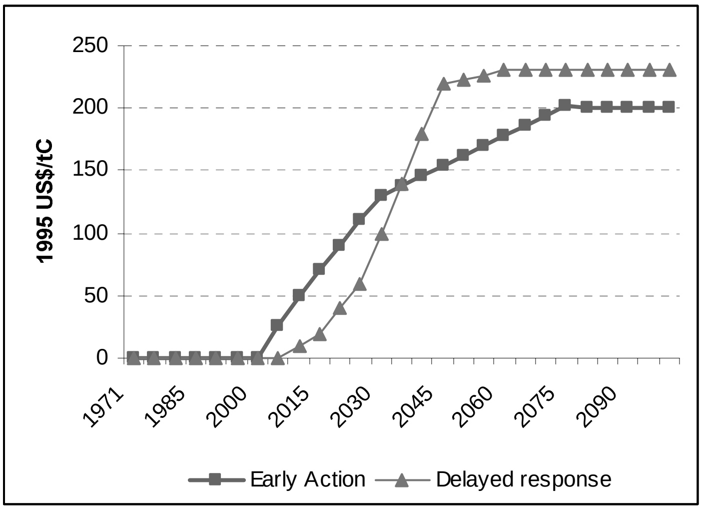


Figure 2: Carbon taxes

4.2 Energy and emission indicators

Several changes occur within the energy system that result in the reduced emissions. Figure 3 shows the resulting global energy consumption under 'early action' vis-à-vis the baseline scenario (the differences with 'delayed response' are discussed in terms of other indicators). It is clearly shown that the carbon tax enforced resulted in both less energy use (about 20%) and a lower market share for high-carbon fuels. In fact, as our policies have the form of a non-specific global carbon tax, a relatively attractive option in the model was to strongly reduce coal consumption (we will come back to this later in this paper).

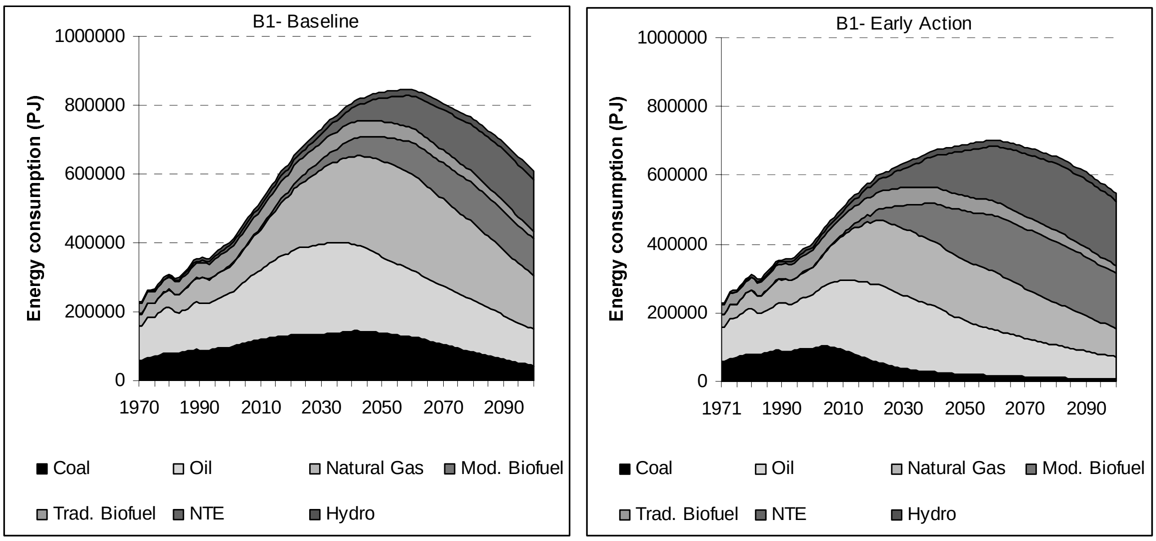


Figure 3: Total Global Primary Energy Supply under the B1 baseline scenario and the 'Early Action' 450 scenario

Note: NTE = Non-thermal electricity (nuclear, solar, wind);

In order to show the contribution of various reduction options, we have attributed all avoided carbon dioxide emissions to four different categories of options: the effects of efficiency improvement, the effects of additional biofuels, the effects of additional use of non-thermal electricity (in particular solar and wind) and the effects of fuel switching (among fossil fuels)[6].

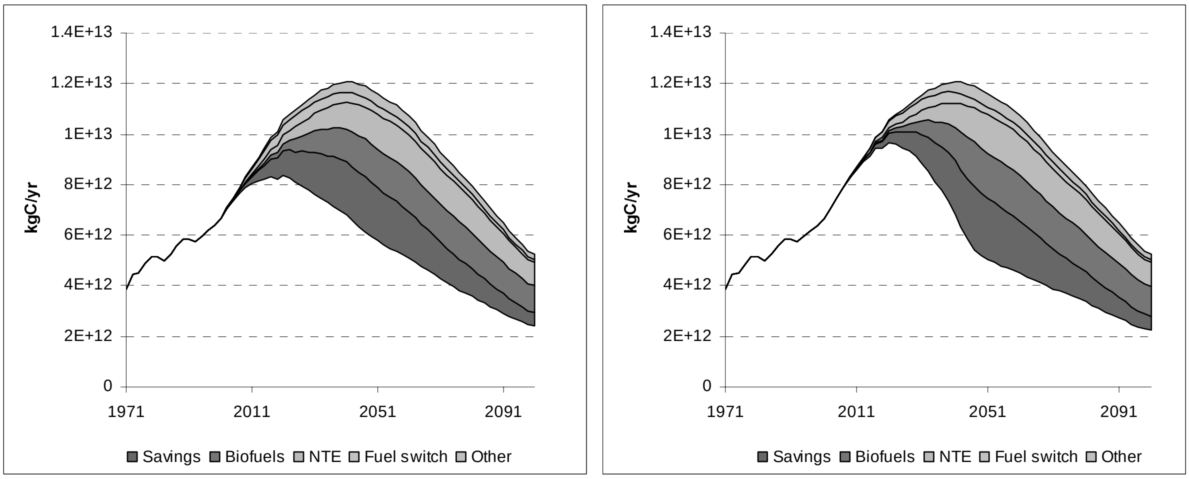


Figure 4: Carbon dioxide mitigation categories (Early Action left; Delayed Response right)
Note: NTE = Non-thermal electricity (nuclear, solar, wind);

Figure 4 shows that in the 2005-2030 period energy savings contribute most to avoided carbon dioxide emission. Its contribution starts to decline thereafter as the cheap energy-efficiency options are depleted and over-all fuel costs stabilise due to cost-reducing supply innovations. Something similar holds for fuel switching between the various types of fossil fuels. In the first twenty years after the onset of policies, the share of fuel switching in total mitigation is considerable. Between 2010 and 2020 in the early action scenario, for instance, its contribution varies between 20-40 per cent of the total carbon emission reduction. However, after this period its share declines rapidly as fossil fuels, including natural gas, are replaced by non-fossil options. After 2050, the combined effect of renewable mitigation options start to dominate. Of all carbon containing fuels, coal is reduced most – while consumption of natural gas is reduced slightly more than oil. The latter may sound counter-intuitive but is a result of the fact that natural gas is used much than oil more for electric power generation, a sector where several non-carbon alternatives exist. In contrast, in the transport sector in which oil is mainly used, options are more limited and more costly. Comparison of the Early Action and Delayed Response scenarios in Figure 4 shows that the period of rapid reduction in the latter (2040-2050) is mainly brought about by energy efficiency and additional use of biofuels.

[6] It should be noted that the attribution depends somewhat on the methodology chosen, in particular on the order of attribution. Here first energy savings have been attributed for, next biofuels and non-thermal electricity and finally fuel-switch. Because of the sequence chosen, the effects of the latter are limited only to the changes in the remaining use of fossil fuels, after energy savings and additional non-fossil options have been accounted for.

An alternative method for analysing the level of changes in the energy system is by means of two factors of the Kaya identity (eq. 1), energy intensity and the carbon factor (Kaya, 1989).

CO_2 Emissions = Pop. x (GDP/pop) x (Energy / GDP) x (CO_2/Energy) (1)

Figure 5 shows that between 1970 and 1995 global energy intensity has improved at a rate between 0 - 2.0 % per year, reaching the highest levels during and just after the two consecutive energy crises in the 1970s and 1980s. Global carbon intensity improved at a much slower rate around 0.3% per year. At the global level, the indicators are also a function of the relative shares of different regions in the global average: if the share of a carbon-intensive region in the total consumption of energy increases, this will cause the annual improvement rate of the carbon factor to decline or even reach negative values.

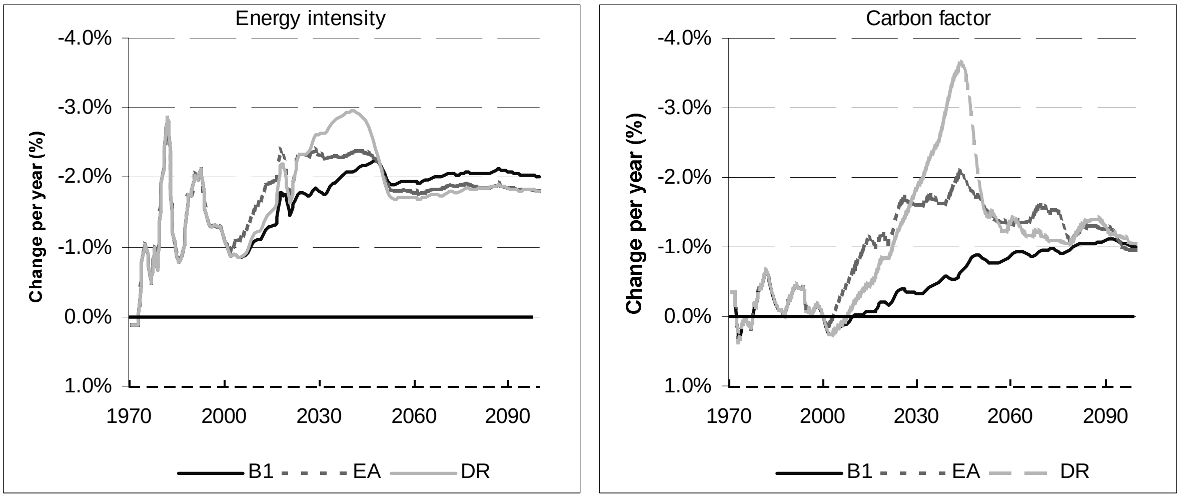


Figure 5: Kaya-indicators
Note: EA = Early Action; DR = Delayed Response; values for the y-axis shown in reverse order.

In the B1 baseline scenario, the improvement of both energy intensity and the carbon factor reach levels at the higher end of the historic range – in compliance with the story line of the scenario. For the carbon factor, this is in particular the case after 2040 when the energy-efficiency potential declines and fossil fuels tend to become more expensive as result of depletion. Between 2000 and 2030, in contrast, strong growth of energy consumption in India and China implies an upward pressure on the carbon factor, resulting in improvement levels just above zero.

In the mitigation scenarios the carbon tax stirs up the improvement of both energy intensity and the carbon factor significantly (Figure 5). First of all, the rate of energy intensity improvement reaches a level between 2 and 3 % per year in the 2000-2050 period. For the early action scenario this is about 0.5% above the baseline. The delayed response even reaches a level an improvement rate of 3% per year for a short period of time, about 1% above the baseline. After 2050, further measures to improve energy efficiency tend to become more costly – and improvement rates levels off at values around the baseline. This is also due to the fact that costs of non-fossil energy at that time have reached levels that are competitive with fossil-based sources, relaxing the end-use energy costs. The rate of decline of the carbon factor in the mitigation scenarios is for the whole scenario time horizon higher than for the B1 baseline scenario. Again, the sharp bend required in the delayed response emission profile is reflected by very high rates of change required around 2040.

Several conclusions can be drawn from this analysis:
- in both mitigation scenarios energy intensity and the carbon factor improve at an average rate of about 2% per year, at higher end of the historic range for the former and significantly above historic rates for the latter;
- comparison with the baseline scenario shows that the improvement in the carbon factor (i.e. use of alternative energy sources) is a more important contributor than the improvement in energy intensity (i.e. energy efficiency), especially in the difficult transition period 2030-2050.

Analysis using a database of mitigation scenarios by Morita et al. (2000) shows that a similar conclusion is found for many other models and scenarios. It is clear that the changes in carbon intensity and energy intensity shown here are historically unprecedented and require considerable technical change – however, they do not seem to be impossible. In fact, as Azar and Dowlatatabadi (1999) point out, we face a choice between technological change (here measured as change of energy intensity and the carbon factor) at historically unprecedented rates or a change in atmospheric composition unlike any experienced since the dawn of humanity.

4.3 Costs indications at the world level

Having presented the physical changes, we now focus on the costs of the different scenarios. In Figure 6 the additional energy expenditures per ton carbon avoided are plotted against the total carbon avoided compared to the baseline for the two mitigation scenarios looked at (for costs see section 3). We consider the indicator on the y-axis as a useful indicator for costs, comparable to cost estimates of other models. Without technological change, costs per ton carbon avoided are expected to increase along with the amount of carbon avoided. In Figure 7 the square drawn up by the distance to x and y-axis is an indication of the total additional investments costs. In Figure 6, we have used a zero discount rate.

As expected, both the early action and delayed response show rising costs early in the century – along with an increasing need for reductions and shifts towards lower carbon, but higher-costs energy systems. The response to this in the model is an accelerated rate of technological development of both energy savings options and low-carbon supply options (solar, wind etc.). Already around 100 1995US$/tC technological development starts to offset the rise in costs followed by an actual decrease in the costs per ton of carbon avoided. Similar results have been found in other models that include experience driven technological learning (IEA, 2000). After 2060, the mitigation scenarios start to benefit from the decreasing gap between the required emission profile to meet 450 ppmv and the original B1 scenario. This implies that costs can drop now even more rapidly.

Comparing the two scenarios in terms of overall costs (not discounted) over the complete period shows that, to meet the 450 ppmv concentration target, the early action scenario is clearly more cost-effective than the delayed response. The reason for this is that the delayed response scenario with a relatively low stabilisation target has only a short period of time in which no action is required – and a long period in which more action is required than the early action scenario. In fact, early action profits both from a smooth transition and induced technological change early on in the scenario. In contrast, the delayed response scenario suffers from a period in which a dramatic U-turn needs to be made without as yet the experience available for carbon mitigation options at low costs.

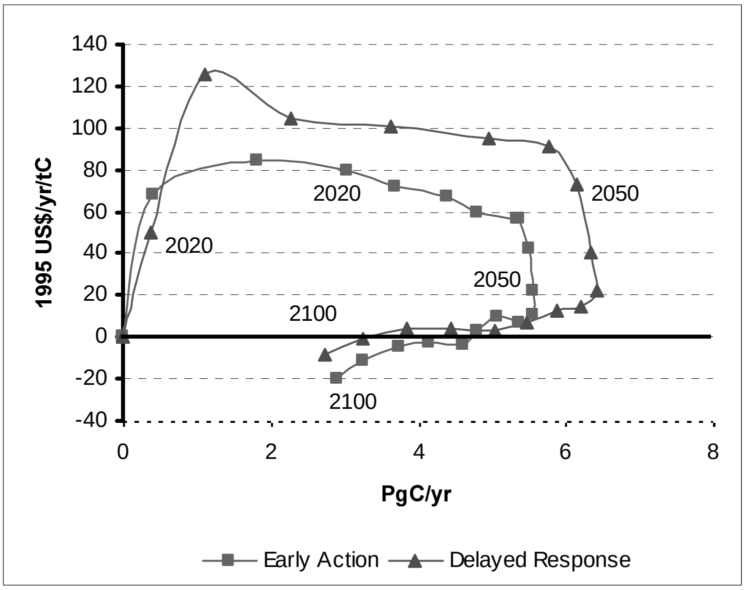


Figure 6: Additional energy system costs per ton carbon, not including the value of the carbon tax and using no discount rate

Clearly, with regard to the value of discounts rates that should be used a whole debate exists. Without going into the details of this, in Figure 7 we have plotted different values for cumulative additional expenditures over the whole century against different values for the discount rate (see also Janssen and De Vries, 2000). It shows that if discount rates are used below 3% postponement of climate-policy does not only results in terms of a longer period of considerable temperature change, but also becomes more costly from an economic point of view (as in Figure 6). At higher discount rate, delayed response is more economically attractive.

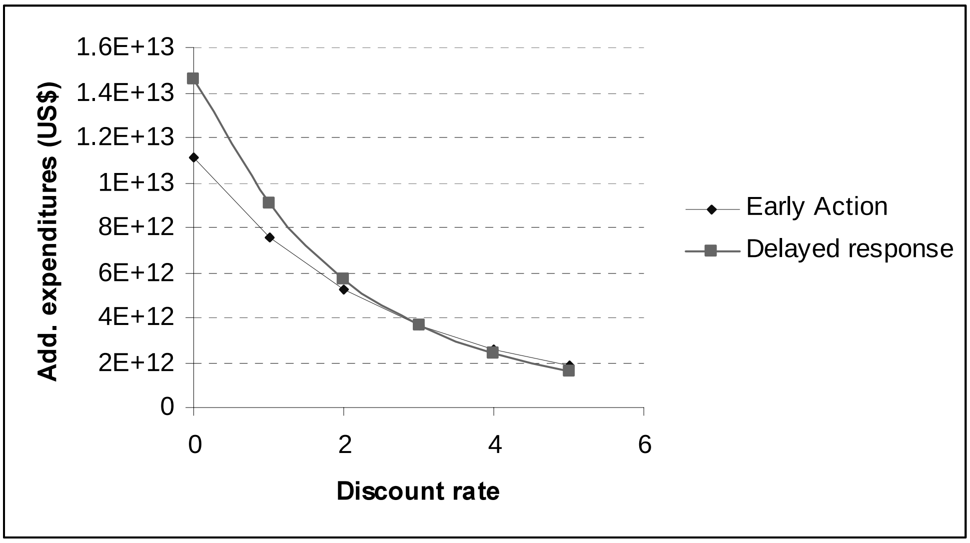


Figure 7: Cumulative additional energy system expenditures for different discount rates

4.4 Differentiation of impacts: investments, fuel trade, expenditures

Macro-economic costs are not the only or most important variable in political decision-making. The costs will be borne by different actors – and these additional costs and benefits could be just as important in terms of barriers and opportunities as macro-economic costs. In this section, we will briefly look at three issues: 1) differentiation of energy system costs, 2) impacts on fuel trade and 3) regional differentiation of expenditures.

Differentation of energy system costs

In Figure 8 we have plotted the changes in investments in the different scenarios in 1) fossil fuels, 2) biofuels, 3) non-thermal electricity, 4) thermal electricity and distribution and 5) energy efficiency. The figure shows that changes are considerable – and odd as it may sound, both increases and decreases in the investment flows shown here could present considerable obstacles that need to be overcome in order to realise these. The reduced investments in fossil fuels will imply less income for energy-exporting countries and energy companies. In particular the coal industry will be hit very hard - the scenario in fact assumes that soon after the tax reaches a level of around 100 1995US$ per ton carbon, the level of investment in coal production drops almost to zero. The experience with mine-closures in Europe suggests that such shifts are possible but not without considerable delays due to socio-political factors and often with substantial side payments in the form of social policies. At the same time, the increase in investments in energy efficiency represents another obstacle, as these investments need to be made by large and diffuse groups of end-users where lack of capital, lack of information or both present significant obstacles. These outcomes emphasise that the key to a real transition lies much more in a change in the direction of investments than in additional investments. In fact this corresponds very well with the definition of sustainable development as once formulated by the Brundtland commission: *'sustainable development is a process of change in which the use of natural resources, the direction of investments, the orientation of technological developments and institutional changes are all in harmony and to increase the present as well as future potential to meet the human needs and wishes for present as well as for future generations (*WCED, 1987*).*

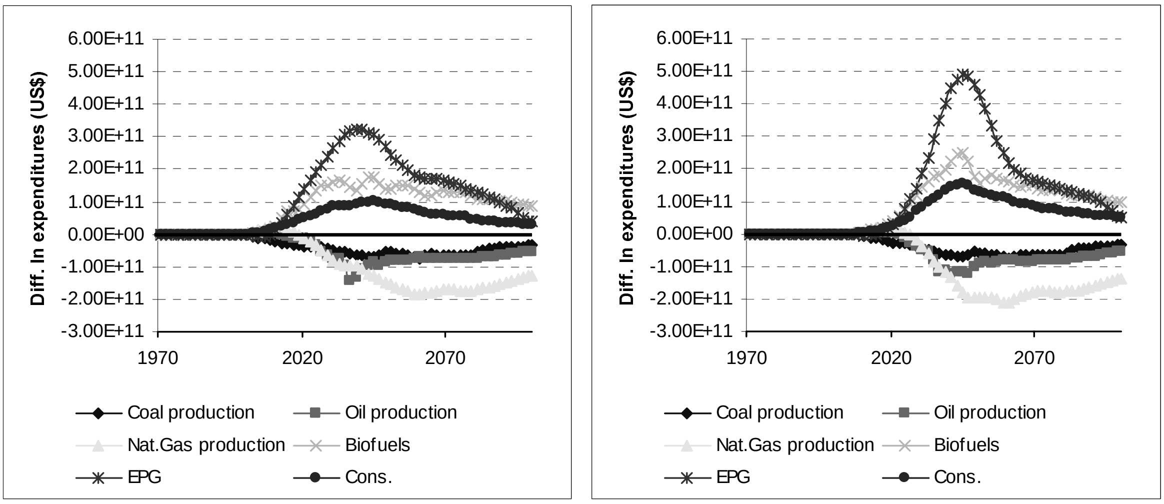


Figure 8: Differences in investment flows (Early action left; Delayed response right)

Note: EPG = Electric Power Generation sector

Impacts on fuel trade patterns

An issue that seems to gain importance in the whole debate on climate policies is that of the impact on fuel production and trade patterns. This can both be important for countries that are highly dependent on fuel imports and those that are highly dependent on income generated by exports of fossil fuels such as the OPEC countries. The reflection of this can be found in art. 4.8 and 3.14 of the Kyoto protocol which indicate that adverse impacts on the latter group needs to be minimised ('*... countries whose economies are highly dependent on income generated from the production, processing and export and/or consumption of fossil fuels and associated energy-intensive productions)*.

In the TIMER model, fuel trade is modelled in a simple way by assuming that regions decide to domestically produce energy resources or to import them, the balance being based on relative prices. These prices are derived from cost-supply curves (based on Rogner, 1997) and transport costs. In addition, import and export barriers and subsidies are used to represent historic trends or to implement scenario assumptions. In the B1 world, discussed here, it is assumed that ongoing negotiations in the context of WHO and further globalisation will remove existing trade barriers. In addition, it is assumed that for environmental and convenience-related reasons the demand for coal will only grow very slowly. This implies that several developing regions that are poor in terms of oil and natural gas resources will need to start importing these fuels including India, East Africa and to some degree also China and South-East Asia. Other regions, such as Western Africa, might find themselves shifting from an oil exporting to an oil importing region, because of a growing domestic demand for oil and assumption regarding available low-costs resources. Fortunately for these regions, the same B1 scenario also assumes a strong growth of income – so that the consequences of fuel imports on balance of trade are limited to a few per cent of GDP only. For some regions, this has been indicated in the B1 lines of Table 1. It should be noted that the figures are dominated by those of oil.

Table 1: Total value of net imports and exports of coal, oil and natural gas

		Western Africa		*Eastern Africa*		*Western Europe*		*FSU*		*Middle East*		*India*		*China*	
		bln$	% GDP	bln$	% GDP	bln$	% GDP	bln$	% GDP	bln$	% GDP	bln$	% GDP	bln$	% GDP
1995	B1	10	11.1%	-1	-0.5%	-78	-0.9%	20	4.0%	72	10.0%	-9	-2.0%	-47	-2.6%
	EA	10	11.1%	-1	-0.5%	-78	-0.9%	20	4.0%	72	10.0%	-9	-2.0%	-47	-2.6%
	dif	**0**	**0.0%**	**0**	**0.0%**		**0.0%**	**0**	**0.0%**	**0**	**0.0%**	**0**	**0.0%**	**0**	**0.0%**
2020	B1	16	2.0%	-28	-5.8%	-129	-0.8%	51	3.2%	378	13.6%	-68	-2.8%	-101	-1.9%
	EA	18	2.1%	-26	-5.5%	-92	-0.6%	57	3.5%	337	12.1%	-77	-3.2%	-86	-1.6%
	dif.	**1**	**0.2%**	**1**	**0.3%**	**37**	**0.2%**	**6**	**0.3%**	**-40**	**-1.5%**	**-9**	**-0.4%**	**15**	**0.3%**
2040	B1	51	1.5%	-83	-4.2%	-118	-0.6%	184	4.9%	629	8.9%	-210	-2.6%	-153	-1.5%
	EA	14	0.4%	-58	-2.9%	-59	-0.3%	90	2.4%	530	7.5%	-153	-1.9%	-90	-0.9%
	dif.	**-37**	**-1.1%**	**25**	**1.2%**	**59**	**0.3%**	**-94**	**-2.5%**	**-99**	**-1.4%**	**57**	**0.7%**	**63**	**0.6%**

Table 1 also shows the value of net imports and exports for the same regions under the 'early-action' mitigation scenario – and the differences between these two scenarios. It can be seen that the Middle East region is expected to see its growth of oil sales reduced under mitigation. Although this reduction is considerable in absolute numbers, the 'early action' scenario still implies an enormous increase in export earnings in the Middle East region. In fact, the differences in terms of revenues of both scenarios to the 1995 situation are much larger as their mutual differences.

Also the Former Soviet Union region could see its oil exports reduced. According to the TIMER simulations, for the FSU region the issue starts to be relevant from 2040 onwards – when under the baseline the region was expected to become one of the main oil exporting regions. In the mitigation scenario, this is much less the case because 1) demand for oil starts to decline from 2040 onwards in response of the existing policies and 2) some other regions will extend their export potential period as a result of reduced demand. A similar conclusion can be drawn for all regions that were projected to become one of the oil producing regions after 2040, such as Canada, the USA and Latin America (in these regions non-conventional oil resources were exploited under the baseline scenario).

For Western Africa, mitigation interestingly enough could mean that the region is able to benefit longer from its limited oil supplies. China and in particular Eastern Africa (no resources and relatively low income) are examples of regions that could directly benefit from reduced oil demand – and the prolonged time period that cheap oil resources could be available. India shows a mixed response. In first instance, the region suffers from its forced move away from domestic cheap coal resources to imports of oil. However, in the long run reduced oil demand starts to dominate and the region benefits in terms of its balance of trade.

The conclusion of this comparison must be that the question whether mitigation has a positive or negative impact differs not only per region, but also depends strongly on the time period looked at. The Middle East is certainly not the only region with reduced revenues. As indicated earlier, the consequences could particularly be hard for coal producers.

Regional energy system expenditures
In section 4.3 we have focussed on the global additional expenditures in the energy system as a consequence of a generalised carbon tax. In the introduction we already indicated that in this paper we will not pay attention to the issue of burden sharing itself, as this only partly depends on where measures are taken but much more on who will be actually paying for these investments. This, for instance, depends on the allocation of emission reduction targets. It is clear that many of the additional measures taken in our scenarios in response to the ‘carbon tax’ could well have been financed for by other regions, via instruments as emission trading of the Clean Development Mechanism. It might, nevertheless, be worthwhile to look at the regional distribution of expenditures made (regional here means not by who but where).

Figure 9 shows for selected regions the additional energy system expenditures in the Early Action mitigation scenario as share of GDP. As the scenario was based on ‘global’ carbon tax, early on additional expenditures are made both in high- and low income regions. In fact, mitigation action takes place where costs are considered to be lowest – based on locally available technology, knowledge and labour costs. In the low income regions, these investments as share of their low GDP are low but at least of the same level as in high income countries and often even higher (in particular in India and China). Again Figure 9, clearly reflects the need of global cooperation in order to finance the additional expenditures in these low-income countries. In all regions, costs as share of GDP relax after 2040, both as result of technological development and as result of rapidly increasing levels of income.

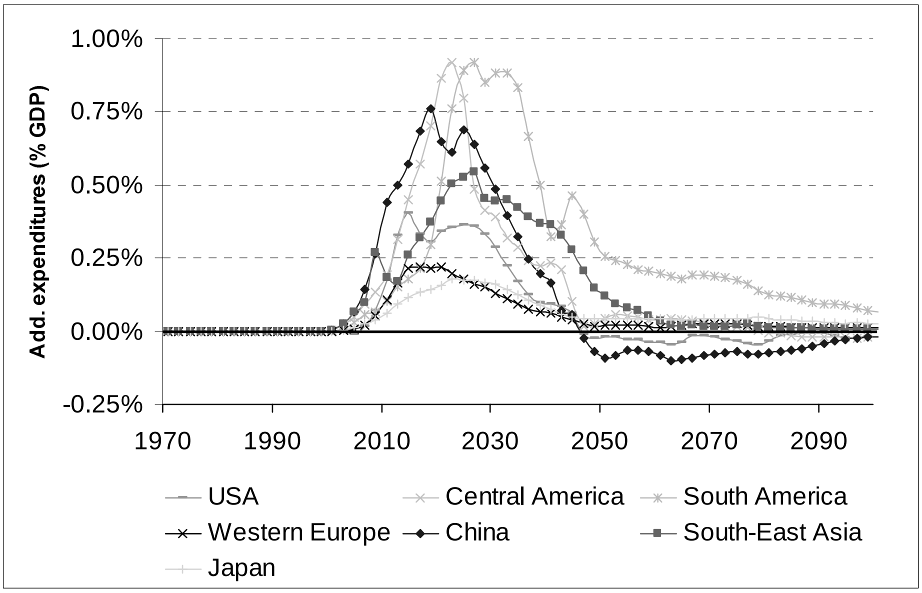


Figure 9: Geographical location of additional energy system expenditures as share of GDP, Early Action

5. Discussion and conclusions

In this paper we have studied two different mitigation scenarios based on the recently developed B1 baseline scenario. The main question was whether it was feasible to reduce global carbon dioxide emission to levels required for 450 ppmv stabilisation around 2100, given the fact that in the B1 scenario already several baseline trends have been adopted that reduce emissions. Before discussing the results of this analysis, we would like to indicate the importance of different approaches to identifying mitigation strategies. Bottom-up technology oriented studies are able to indicate potentials for mitigation based on 'real-world' engineering observations and cost-estimates. This approach is limited because it omits the dynamic interaction with social and economic factors. Macro-economic models, in contrast, analyse the larger dynamic context using a few highly aggregated production functions and are in particular able to provide consistent links between the energy system and the rest of the economy. Their analysis is however limited by the rather extreme simplification of the energy system, which has as one consequence that mitigation measures are necessarily of a quite general nature. The TIMER model more-or-less takes an intermediate position: it is able to deal with dynamic relationships among the various mitigation options but without macro-economic feedbacks.

A second important point one should realise is that mitigation options and scenarios should only be discussed in reference to a well-defined baseline. Not only is the reduction task itself a function of the baseline, but also available options for mitigation could be a function of the storyline of the baseline scenario.

Based on the analysis described in this paper, five main conclusions can be drawn.

First, stabilisation at a carbon dioxide concentration at 450 ppmv is possible through pressure on the system generating a variety of measures. Carbon taxes in both scenarios reaches levels of around 200 1995US$ per ton C at the end of the century. This result seems to be well in the range of other modelling efforts aiming for similar reductions (Fiddaman, 1997; Bollen et al., 2000; Morita et al., 2000)

Second, decomposition of the contribution of the various mitigation options shows that in the first quarter /second quarter most reduction will come from energy efficiency and fuel switching. Later in the century, the introduction of carbon-free supply options provides the bulk of the required reductions. As a result, energy intensity more-or-less remains at the higher end of the its historic range whereas decarbonisation rates reach levels far above historic rates.

Third, postponing measures foregoes the benefits of learning-by-doing. Certainly in case of an ambitious policy target (such stabilisation at 450 ppmv), 'Early Action' seems to be a more attractive strategy than 'Delayed Response', as the former implies a more gradual strategy in time, among others by creating more technology development early on. Obviously, the policy advantage of delayed response could be that no major action is required in the next 20 years. As a result, the final balance between the two scenarios in economic terms depends on the applied discount rates. Our results here are contradictory to those of Wigley et al. (1996), who pointed out that postponing abatement actions was always a more cost-effective strategy. The most important reason for this difference is that in TIMER the rate of technology development is determined by the accumulated output of a certain technology – while in the model of Wigley et al. (1996) technology development is included as an exogenous parameter, thus even happening when the technology itself is not actually applied. Azar (1998) and Azar and Dowlatibadi (1999) have discussed the role of various representation of technology development in qualitative terms – and indicated that in their view endogenous learning is a more meaningful presentation than exogenous learning. Azar and Dowlatibadi (1999) also indicate that for low stabilisation targets (such as the 450 ppmv target adopted here), early abatement is more likely to be the cost effective strategy than for high stabilisation levels.

Fourth, the most difficult period for the mitigation scenarios is the 2010-2040 period (exact timing depends on early action or delayed response) when the ‘bending of the curve’ towards a lower carbon emission system is most severe. Later on in the century, technology development induced by the policies started in the first part of the century diminish the additional cost – in some cases even resulting in negative costs. Our simulations suggest that in terms of macro-economic costs, the additional energy system expenditures are modest as result of these faster technological improvement rates.

Fifth, the real obstacles for implementing mitigation policies are related to changes in position of individual actors. Shifts in investment patterns, revenues, fuel production and trade could mean that certain actors become ‘winners’ or ‘losers’ of climate policy. An example is that the carbon tax scenarios explored cut down quickly on coal production, as in financial terms this implies a relatively cheap mitigation option everywhere. The political and socio-economic consequences, however, may be considerable. Overcoming these obstacles could be the real challenge for mitigation. Not so much additional finance is required but a re-direction of financial flows in harmony with the ambition to reduce greenhouse gasses. Hence, much political ingenuity will be required in finding a method for fair burden sharing.

Acknowledgements

The analysis has been performed in the context of the Global Dialogue of the COOL project (Climate OptiOns for the Long term). The COOL project is a participatory integrated assessment project financed by the Dutch National Research Programme on Global Air Pollution and Climate Change. The authors are grateful for the support from other members of the Global Assessment department of the National Institute of Public Health and the Environment, in particular Michel den Elzen, Marcel Berk and Rik Leemans. The authors also would like to thank Petra de Jongh for her suggestions on the attribution of the avoided carbon dioxide emissions to the various changes in the model.

References

Alcamo, J., E. Kreileman and R. Leemans (Eds.) (1998). Global change scenarios of the 21st century. Results from the IMAGE 2.1 model. Elsevier Science. London.

Azar, C. (1998). The timing of CO_2 emissions reduction – the debate revisited. *International Journal of Environmental Pollution.* **10**. 508-521

Azar, C. and Dowlatabadi H. (1999). A review of Technical Change in Assessment of Climate Policy. *Annual Review of Energy Environ.* **24**. 513-544

Bollen, J. Manders T. and Timmer H. (2000). The benefits and costs of waiting: early action versus delayed response in post-SRES stabilisation scenarios. *Environmental Economics and Policy Studies.* **3**.

COOL (2000). Assessment of Climate OptiOn for the Long Term. Description can be found at www.nop.nl/cool (September 2000).

Elzen, M. den, Berk, M. Faber, A. and Oostenrijk R. (2000). FAIR 1.0 – An interactive model to explore options for differentiation of future commitments in international climate policy making. National Institute of Public Health and the Environment, Bilthoven, The Netherlands (in prep.).

Fiddaman, T. S. (1997). *Feedback Complexity in Integrated Climate-Economy Models.* PhD-thesis. Massachusetts Institute of Technology. Cambridge. USA.

Grübler, A. Nakicenovic, N. and Victor, D.G. (1999). Dynamics of energy technologies and global change. *Energy Policy.* **27**. 247-280.

Ha-Duong M., Grubb M. J., and Hourcade J.C. (1997). Influence of socioeconomic inertia and uncertainty on optimal CO_2-emission abatement. *Nature.* **390**. 270-273.

Hilderink H. (2000). *World Population in Transition – An integrated Regional Modelling Framework.* PhD-thesis. Thela Thesis. Amsterdam.

IEA (2000). Experience curves for Energy Technology Policy. International Energy Agency, Paris.

IPCC (1995). *Climate Change 1995: The Science of Climate Change.* Intergovernmental Panel on Climate Change (IPCC).

Nakicenovic, N. et al. (2000). *Special Report on Emission Scenarios.* Cambridge University Press. London.

Janssen, M.A. and de Vries, B. (2000). Climate Change Policy Targets and the Role of Technology Change. *Climatic Change.* **46.** 1-28.

Kaya (1989). *Impacts of carbon dioxide emissions on GWP: Interpretation of proposed scenarios*. IPCC/Response Strategies Working Group. IPCC. Geneva.

Kreileman, E., van Woerden, J. and Bakkes, J.(1998). RIVM Environmental research 1998 world regions and subregions. National Institute of Public Health and the Environment, Bilthoven, The Netherlands (CIM Report no. M025/98).

Morita, T. Nakicenovic, N. and Robinson, J. (2000). Overview of Mitigation Scenarios for Global Climate Stabilisation based on New IPCC Emission Scenarios (SRES). *Environmental Economics and Policy Studies.* **3** (2).

Linden N.H. van der, Linde C. van der, Lako P., van Rooijen S.N.M. (2000). *Analysis of the impact of the Kyoto Protocol on the export revenues of OPEC member states and on the oil import requirements of non-Annex I countries.* Dutch National Research Programme on Global Air Pollution and Climate Change. Bilthoven. The Netherlands.

Rogner. H. H. (1997). An assessment of World Hydrocarbon Resources. *Annual Review of Energy and the Environment.* **22.** 217-262

Vries, B. de and Vuuren, D.P. van (2000). Sustainable development : The road to protecting the Earth Climate System. (in prep.).

Vries, B. de, Bollen J., Bouwman, L., Elzen M. den, Janssen M. and Kreileman, E. (2000a) Greenhouse Gas Emissions in an Equity-, Environment- and Service-Oriented World: An IMAGE-Based Scenario for the 21st Century. *Technological Forecasting and Social Change.* **63**. 137-174.

Vries, B. de, van Vuuren, D.P., and Janssen, M. (2000b). Documentation TIMER model (in prep.).

De Vries, H.J.M. and R. van den Wijngaart (1995). The Targets/IMage Energy (TIME) 1.0 Model. National Institute of Public Health and the Environment, Bilthoven, The Netherlands (RIVM report 461502016).

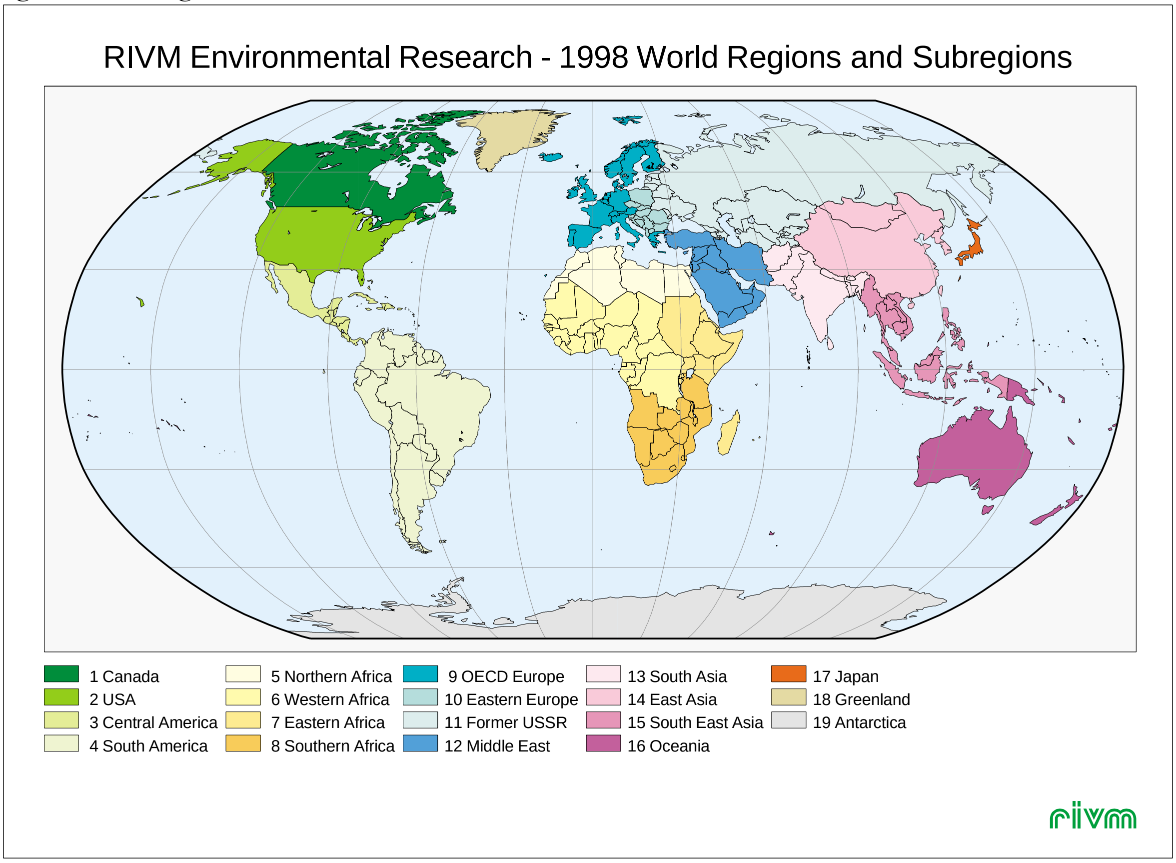
WCED (1987). *Our common future.* World Commission on Environment and Development. Oxford University Press. Oxford.

Wigley, T.M.L., Richels R. and Edmonds J.A. (1996). Economic and environmental choices in stabilisation of atmospheric CO_2 concentrations. *Nature.* **369**. 240-243.

Appendix A: Regional break-down

Figure A.1 shows the regional breakdown of the IMAGE 2.2 framework. The TIMER energy model uses the same breakdown, although region 18, Greenland and region 19, Antartica are not included.

Figure A.1: Regions used in IMAGE 2.2



Appendix B: Cost of measures in the TIMER model

Often the carbon-tax is used as indication of the costs per unit of carbon saved. In the TIMER model, however, the value of the carbon tax is not necessarily an indication of the costs. A simple example can illustrate this. Let us suppose a firm uses E GJ/yr in the form of 2 fuels: coal and natural gas. Let the coal price by p_{coal} and the natural-gas-to-coal price ratio be α which results in a market share of coal of μ. The total costs for consumers in this case equals $(\mu+ (1-\mu)*\alpha)*E*p_{coal}$ \$/yr and total carbon emissions are $(\mu+(1-\mu)*CC_{rel})*E*CC_{coal}$ kgC/yr with E being the energy consumption, CC_{coal} the carbon content of coal and CC_{rel} the natural-gas-to-coal carbon content ratio.

On introduction of a carbon tax CT, which we use as proxy for mitigation pressure on the system, the first response is to reduce total costs by investing in energy efficiency. At marginal costs of I \$/GJ_{saved}, this will reduce energy use with a factor β according to the energy efficiency supply cost curve. Two indicators can be defined for the associated mitigation costs. One is the additional energy costs for consumers, and the other is the additional energy expenditures (investments and other costs). Both can be compared to carbon emissions avoided. For energy costs for consumers, the latter would give the Marginal Mitigation Cost MMC:

$$MMC = \frac{(\mu + (1-\mu)\alpha) * \Delta[E * p_{coal}]}{(\mu + (1-\mu) * CC) * \Delta[E * CC_{coal}]} \quad \text{\$/kgC/yr} \quad [2]$$

Without fuel substitution the MMC will equal the carbon tax equivalent, forgetting for the moment the induced cost decline of energy efficiency investments due to learning-by-doing. On introducing a carbon tax, there will also be substitution of coal for gas; how much depends on the price ratio α, the price of coal and the cross-price elasticity for substitution. In the longer term, the depletion and learning dynamics in combination with changing fuel trade patterns, will further drive the MMC away from the imposed carbon tax level. We do not consider how the carbon tax is recycled in the economy.

In using the MMC as an effectiveness indicator, it is very important to understand the baseline. If the carbon tax is included, the energy costs will rise significantly. The effectiveness of energy efficiency and fuel substitution measures induced by the tax can be evaluated against the reference situation before the tax. Then, the MMC as defined in eqn. [1] will be very high indeed. If, on the other hand, the evaluation is against the reference situation after tax, the situation is quite different. At the new, higher fuel prices, energy efficiency measures are occurring at negative abatement costs because energy use is far above the minimum over-all cost level. Fuel substitution will occur at positive abatement costs if markets are sufficiently responsive or if the price ratio α is sufficiently low or both. The price ratio α can become quite low because perceived prices are used, that is, non-price effects such as comfort and transaction costs. The resulting MMC for the over-all effect of energy efficiency investments and fuel substitution can therefore be above as well as below the value of the carbon tax. In fact some simple analysis introducing a carbon tax in the system discussed above will show that the costs depend on assumptions regarding the availability of coal, the response behaviour of efficiency investments and the fact whether the carbon tax itself is factored in the costs estimates. Even if carbon reductions are quite similar the costs faced by the users differ significantly depending on definition and case.

As one of the responses in the model will be changes in technological development, the divergence between our costs indicators and the value of the carbon tax can even become much larger. In our example, a carbon tax introduced in the model will result in increased investments in energy efficiency and increased production rates of natural gas. For both, technology development will be faster than without a tax. As a result, within a few years after the introduction of the tax costs can start to relax if no further emission reduction is required. Depending on the 'learning' potential for different technologies (fossil fuels, solar, wind, nuclear power etc) this could even result in a situation where the total costs of the 'carbon tax' scenario are lower than the original situation.