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Multi-gas emission envelopes to meet greenhouse gas concentration targets: Costs versus certainty of limiting temperature increase

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Abstract

This paper presents a set of technically feasible multi-gas emission pathways (envelopes) for stabilising greenhouse gas concentration at 450, 550 and 650 ppm CO_2-equivalent and their trade-offs between direct abatement costs and probabilities to meet temperature targets. There are different pathways within the envelope. Delayed response pathways initially follow the upper boundary of the emission envelope and reduce more by the end of the century. In contrast, early action pathways first follow the lower boundary and then the upper boundary. The latter require an early peak in the global emissions but keeps the option open for shifting to lower concentration targets in the future. Costs evaluations depend on the discount rate. Early action profiles have high costs early on, but learning-by-doing and smoother reduction rates over time lead to in most cases to lower costs across the century (net present value (NPV)). To achieve the 450 ppm CO_2-equivalent, the global emissions need to peak before 2020. The NPV of costs increase from 0.2% of cumulative gross domestic product to 1.0% as the shift is made from 650 to 450 ppm (discount rate 5%). However, the chances of limiting global mean warming to 2 °C above pre-industrial levels are very small for peaking and stabilisation at 650 ppm (1–23%) and 550 ppm (1–48%), but increase for a peaking at 510 ppm with subsequent stabilisation 450 ppm to 14–67%.

Keywords: Climate change; Mitigation costs; Climate target; Scenario; Emissions pathway; Climate risks

1. Introduction

The aim of this study is to develop multi-gas emission envelopes (consistent sets of emission pathways) for the six greenhouse gases (GHGs) covered under the Kyoto Protocol (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) that are compatible with stabilising GHG concentrations. The ultimate aim is to avoid dangerous climate change. To determine allowable levels of GHG emissions, we will have to back-calculate from acceptable levels of climate change to emissions. This is not simple. Apart from the question of what an acceptable level of climate change constitutes—a political issue—there are major scientific uncertainties in the cause–effect chain. Many of these uncertainties also influence the shape of the emission envelope that results in a certain GHG concentration target, such as the baseline emissions and the potential to mitigate the different GHGs.

Several authors have earlier published emission pathways or envelopes leading to different concentration targets, i.e. (a) Eickhout et al. (2003); (b) Enting et al. (1994); (c) O'Neill and Oppenheimer (2004); (d) Wigley (2003b); (e) Wigley et al. (1996) and (f) van Vuuren et al. (2005). Unfortunately, these studies suffer from one or more of the following four limitations. First of all, most studies focus mainly on CO_2 only (b, c, d and e). As non-CO_2 emissions contribute to the human-induced climate changes, the reduction of these non-CO_2 emissions will of course have advantages in terms of either avoiding climate impacts for a given CO_2 emission path (Hansen et al., 2000; Meinshausen et al., 2006) or reducing mitigation costs for avoiding certain levels of climate change (e.g., Manne and Richels, 2001; van Vuuren et al., 2003, 2006b). Secondly, some of these studies have developed only pathways leading to GHG concentration targets of 550 ppm

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CO_2-eq and higher (a, c and f).[1] Studies that use recently published probability density functions (PDFs) for climate sensitivity show that for achieving low temperature increase targets, such as the 2 °C target which has been adopted as the long-term target of EU policy, these concentration levels have only a low degree of certainty (Hare and Meinshausen, 2006; Meinshausen, 2006). Thirdly, most of these studies present emission pathways rather than emission envelopes, thus they do not account for important uncertainties such as baseline emissions and timing of climate policies (a, b). And finally, this study attempts to take into account the actual mitigation potential, and the possible rates of emission reductions—rather than setting a constraint to following a smooth concentration profile (a, b, c, d and e). Alternative approaches have attempted to define possible pathways on the basis of a larger set of criteria, such as long-term temperature targets and maximum reduction rates, mapping out corridors of emissions consistent with these criteria, like in the tolerable windows approach (Bruckner et al., 2003; Toth et al., 1997) or the safe landing approach (Swart et al., 1998). These methodologies suffer less from the limitations discussed above but were still only focusing on CO_2, and had problems dealing with high levels of uncertainty.

The emission envelopes developed in this paper are designed to overcome these four categories of limitations, while still using a relatively simple, well-defined methodology. This methodology uses the FAIR–SiMCaP model that is able to relate long-term concentration targets to different multi-gas emission pathways (Section 2). This model is fed with information from several specialised models on baseline emissions, mitigation potential and costs (time- and baseline-dependent marginal abatement costs (MAC) curves). This allows us to develop pathways that can be technically achievable. The method used to include reduction potentials and costs and its limitations are described in Section 2.3. The simple method covers direct abatement costs but does not capture indirect impacts on economic growth. It should be noted that developing multi-gas emission pathways is less straightforward than developing emission pathways for CO_2 only, as the reduction needs to be somehow distributed among the different gases, which all have specific radiative properties, lifetimes and mitigation costs and potential.[2] In the literature, two major approaches for determining 'economically optimal' shares are used: (a) 100-year global warming potentials (GWPs) as exchange rates between the gases to find 'optimal' split-ups of aggregated (CO_2-eq) GHG emission paths and (b) substitution instead of GWPs determined on the basis of cost-effectiveness in realising a long-term target within the model (e.g., Manne and Richels, 2001). Given the fact that this GWP approach (a) reflects the current political framework (e.g., the Kyoto Protocol) and that policies develop incrementally rather than based on perfect foresight, we used the GWP approach for the development of the multi-gas pathways.

An important issue related to the different emission pathways forming the emission envelopes is the timing of abatement effort. This issue of the *timing* was initiated, in particular, by Hammit et al. (1992) and Wigley et al. (1996). Wigley et al. argued that postponing abatement actions could be more cost-effective than early action strategies because of the benefits of technology development, more CO_2 absorption by the biosphere and ocean, and by discounting future costs. Other authors, however, responded that this conclusion would depend on the many (controversial) assumptions about the impact of declining costs for new technologies, discount factors applied to future climate change mitigation (and adaptation) costs (Azar and Dowlatabadi, 1999) and the role of inertia in the economic and energy system (limited capital turn-over) and uncertainty (Ha-Duong et al., 1997). Assuming induced technology change due to policy implementation and learning-by-doing (instead of changes being simply a function of time), explicit capital turnover rates could lead to a preference for early action, or at least a distribution of the reduction effort over the century as a whole. The debate about optimal timing is still ongoing. Yohe et al. (2004) recently showed that applying hedging strategies (i.e., cost-optimal reduction pathways incorporating the risk of more, or less, stringent action later in the century if new knowledge appears) to deal with uncertainties may lead to relatively early reduction pathways leaving as many options open as possible. Here, we address the issue of timing by developing a different set of emission pathways[3] (from early action to delayed response).

As such, the analysis presented here focuses on three questions for climate policy making:

- What are multi-gas emission envelopes that are technically feasible, and compatible with stabilising GHG concentrations at 450, 550 and 650 ppm CO_2-eq, and their resulting emission reductions?
- What are the effects of timing of abatement action on the emission pathways, and the resulting abatement costs?

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[1] 'CO_2 equivalents' express the increased radiative forcing of other GHGs in terms of the equivalent CO_2 concentration that would result in the same level of forcing. In this paper, the definition of CO_2-eq concentrations includes the Kyoto gases, tropospheric ozone and sulphur aerosols.

[2] Meinshausen et al. (2006) provides an overview of different methods that can be used for this purpose.

[3] It is possible to draw a formal distinction between *scenarios* and emission *pathways*. While the emission pathway focus solely on emissions, a *scenario* represents a more complete description of possible future states of the world, including their socio-economic characteristics and energy and transport infrastructures. The emission envelopes described in this paper focus on the emission trajectory, and are therefore called pathways; however, as they are constructed on the basis of reduction potential of expert models, the difference between scenarios and pathways is less obvious than for emission pathways constructed in other studies.

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- And finally, what is the likelihood that these emission envelopes will meet a range of temperature-change targets, including the EU 2 °C target?

The analysis builds on earlier work of Den Elzen and Meinshausen (2005, 2006), which presented multi-gas emission pathways meeting the GHG concentration stabilisation targets of 400, 450, 500 and 550 ppm CO_2-eq. The analysis updates the earlier one with: (i) updated baseline scenarios; (ii) improved reduction potentials and abatement costs of GHG sources; (iii) more detailed analyses of emission envelopes (multiple sets of emission pathways) and (iv) feasible pathways for the 450 ppm concentration target.[4] van Vuuren et al. (2006a) (at the global level) and den Elzen et al. (2005) (at the regional level) elaborated the pathways developed here in terms of the technical and economic implications.

In Section 2 we describe the overall modelling framework, and in Section 3 the emission envelopes and their global emission reductions and abatement cost implications. Section 4 analyses probabilistic temperature implications, using the impact of the key uncertainty in the long-term climate projections, i.e., climate sensitivity. Conclusions are drawn up in Section 5.

2. Overall methodology

2.1. The FAIR–SiMCaP model tool

In order to assess the emission implications of different stabilisation levels, this study presents new multi-gas emission pathways (emissions of all six Kyoto GHGs, sulphur aerosols (SO_2) and ozone precursors) for the scenario period of 2000–2400, based on the reduction potential as estimated by specialised models (thus attempting to ensure technical feasibility). The timing of emission reduction within these pathways is determined iteratively to match a combination of criteria based on the prescribed climate targets, technically feasible rates of reduction and cost considerations (see Section 3.1). At any moment in time, the emission reductions are distributed among the different reduction options by cost-optimisation. It should be kept in mind though that this approach does not calculate cost-effective pathways over the whole scenario period per se, but focuses on a cost-effective split among different GHG reductions for given emission limitations on global GWP-aggregated emissions.

For our method we used the FAIR–SiMCaP 1.1 model (den Elzen and Meinshausen, 2005, 2006),[5] which is a combination of the abatement costs model, FAIR 2.1 model (Framework to Assess International Regimes for the differentiation of commitments (den Elzen and Lucas, 2005; den Elzen et al., 2005)) and the SiMCaP module (‘Simple Model for Climate Policy Assessment’), pathfinder 1.0 model (Meinshausen et al., 2006). The SiMCaP pathfinder module makes use of an iterative procedure to find multi-gas emission paths that correspond to a predefined climate target. Global climate calculations make use of the simple climate model, MAGICC 4.1 (Wigley, 2003a; Wigley and Raper, 2001, 2002). In turn, the FAIR cost model distributes the difference between the global baseline and mitigation pathway following a least-cost approach using regional MAC curves[6] for the different emission sources (den Elzen et al., 2005). Furthermore, the costs model calculates the regional emission reductions (after emissions trading), international permit price and the global abatement costs. In this way, the FAIR–SiMCaP model combines the strengths of both models to: (i) calculate the cost-optimal mixes of GHG reductions for a global GWP-aggregated mitigation pathway (FAIR) and to (ii) find the global emissions pathway that is compatible with any arbitrary climate target (SiMCaP). The calculations consist of four steps (Fig. 1):

1. Using the SiMCaP model to construct a parameterised global CO_2-eq emission pathway, defined by sections of linear decreasing or increasing emission reduction rates (see for further details den Elzen and Meinshausen, 2005). The pathway includes the anthropogenic emissions of six Kyoto GHGs. One exception is formed by the LULUCF (land use, land-use change and forestry) CO_2 emissions. While we consider the use of carbon plantations as a mitigation option, we currently lack information on the potential to reduce emissions from deforestation. For that reason, LULUCF CO_2 emissions cannot be abated in the model (but are in fact already reduced in the baseline). Up to 2012, the pathway incorporates the implementation of the Annex I Kyoto Protocol targets for the Annex I regions excluding Australia and the USA. The USA follows the proposed greenhouse-gas intensity target (White-House, 2002), which is close to a number of businesses-as-usual projections.
2. The FAIR abatement cost model distributes the global emission reduction from baseline over the different regions,[7] gases and sources following a least-cost approach for 5-year intervals over 2000–2100,[8] simulating

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[4] In our earlier study we had to assume additional, exogenous developments of the marginal abatement cost curves in order to meet the lower concentration levels.

[5] FAIR-SiMCaP 1.1 is an updated version of FAIR-SiMCaP 1.0, differences being the marginal abatement costs curves and baseline emissions.

[6] MAC curves are used here that reflect the costs of abating the last tonne of CO_2-eq emissions and, in this way, describe the potential and costs of the different abatement options considered.

[7] Calculations were done for 17 regions, i.e. Canada, the USA, Central America, South America, northern Africa, western Africa, eastern Africa, southern Africa, OECD Europe, Eastern Europe, the former Soviet Union, Middle East and Turkey, South Asia (incl. India), East Asia (incl. China) and Southeast Asia, Oceania (incl. Australia) and Japan (IMAGE-team, 2001).

[8] After 2100, there are no MAC curves, and here the CO_2-eq emission reductions rates are assumed to apply to each individual gas, except where non-reducible fractions 0.9 and 0.3 have been defined for N_2O and CH_4, respectively.

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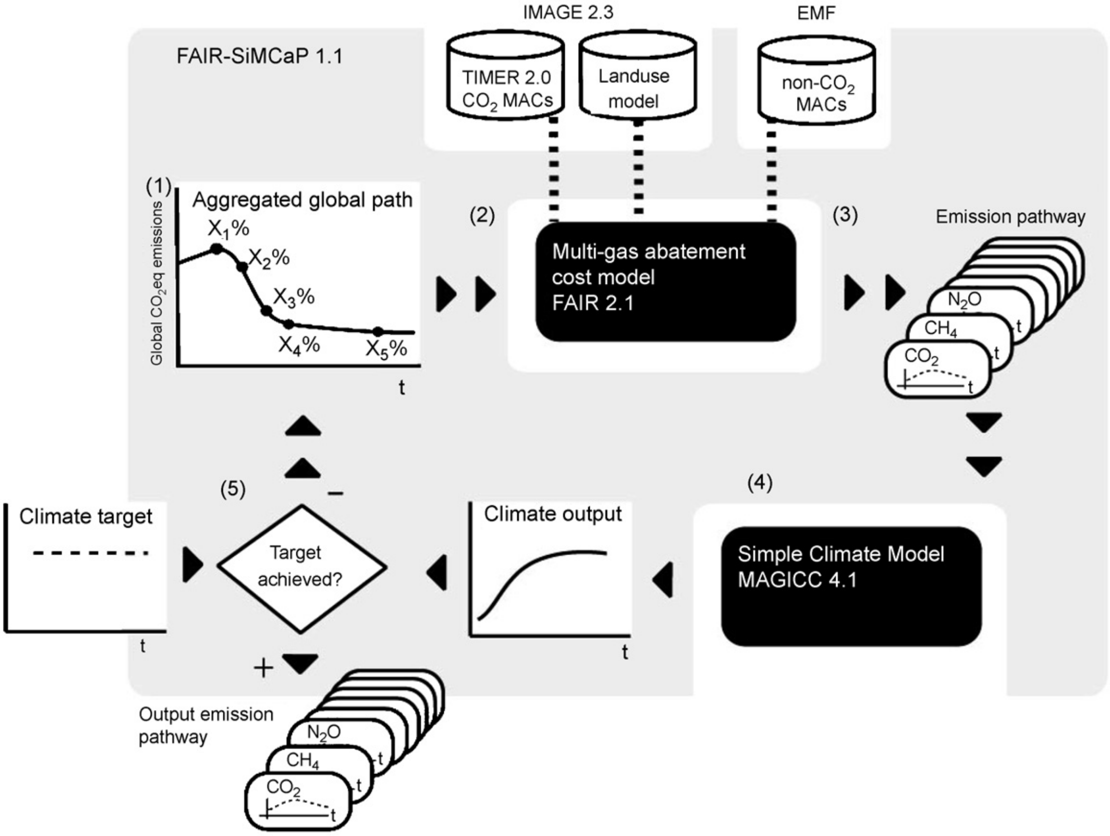

Fig. 1. The FAIR–SiMCaP 1.1 model. The calculated global emission pathways were developed by using an iterative procedure as implemented in SiMCaP pathfinder module. MAGICC was applied to calculate the global climate indicators, the multi-gas abatement costs and the FAIR 2.1 model to allocate the emissions of the individual greenhouse gases and the IMAGE 2.3 and TIMER 2.0 model for the baseline emissions scenarios along with the MAC curves. *Note*: the numbers refer to the four steps as explained in the text. *Source*: adapted figure from den Elzen and Meinshausen (2005).

a situation where states take full advantage of the flexible Kyoto Protocol mechanisms (emissions trading) (see den Elzen et al., 2005). For this purpose, FAIR makes use of (time-dependent) MAC curves (see Section 2.3 and Appendix A), and baseline scenarios, i.e., potential GHG emissions in the absence of climate policies, from the integrated climate assessment model IMAGE[9] and the energy model, TIMER 2.0.[10] In the calculations we assume full participation of all regions after 2012, including the USA.[11] Note that the costs are only for abatement; climate damage is avoided and ancillary benefits are not included in such cost estimates (see Section 2.3; Edenhofer et al., 2006).

3. The GHG concentrations and global mean temperatures are calculated using the simple climate model MAGICC 4.1. In this study, we applied default settings as used for the IPCC Third Assessment Report (TAR), for example, with regard to aerosol-forcing assumptions and temperature-related feedbacks on the carbon cycle. One exception is the estimation of probabilistic transient temperature implications, where the climate sensitivity

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[9] The IMAGE 2.2 model is an integrated assessment model consisting of a set of linked and integrated models that together describe important elements of the long-term dynamics of global environmental change, such as agriculture and energy use, atmospheric emissions of GHGs and air pollutants, climate change, land-use change and environmental impacts (IMAGE-team, 2001). IMAGE 2.3 is an updated version of IMAGE 2.2, differences being the possibility to explore impacts of biofuels and carbon plantations.

[10] The global energy model TIMER, as part of IMAGE, describes the primary and secondary demand and production of energy and the related emissions of GHGs on a regional scale (17 world regions). TIMER 2.0 is an updated version of TIMER 1.0 (de Vries et al., 2002). The main differences are additions with respect to hydrogen, biofuels and modelling of the electric power sector (van Vuuren et al., 2006a).

[11] Whether the USA will take any stronger action after the first commitment period (2008–2012) is of course highly uncertain. There are, however, a number of reasons to assume that the USA could join a post-2012 regime aiming at emission reductions. Several states and cities are already implementing climate policies. Moreover, several proposals have been discussed in the US Congress that involve climate policies, and they may still reflect increasing support for climate policy. Drivers for such increasing support may include an awareness of climate change impacts (e.g., the discussion on whether Hurricane Katrina was caused by climate change) but also energy security policies.

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varies according to published PDFs. This estimation takes into account the dependency between climate sensitivity, ocean diffusivity and aerosol forcing in order to match the historical temperature evolution (with a method according to Meinshausen, 2006).

4. The parameterisations of the CO_2-eq emission pathway (step 1) are optimised within the iterative procedure of the SiMCaP model (repeat step 1, 2 and 3) until the climate output and the prescribed target show sufficient matches.

2.2. Baseline scenarios

The baseline scenarios used in this study are based on the set of SRES scenarios (Nakicenovic et al., 2000). This set explores different possible pathways for GHG emissions on the basis of two major uncertainties: (1) the degree of globalisation versus regionalisation and (2) the degree of orientation on economic objectives versus an orientation on social and environmental objectives. Recently, the storylines of the SRES scenarios have been re-implemented into the IMAGE 2.3 model. Here we use the IMAGE/TIMER SRES B2 scenario (van Vuuren et al., 2006a) (hereafter known simply as the B2 scenario) as the central baseline scenario, while the IMAGE/TIMER SRES A1b and IMAGE/TIMER SRES B1 scenarios are used to show the impacts of different baseline assumptions. The B2 scenario represents a medium emissions scenario. The A1b scenario, in contrast, represents a world with fast economic growth, and correspondingly higher emissions early in the scenario. The B1 scenario describes a world characterised by strong globalisation in combination with environmental protection and correspondingly lower emissions. For the central B2 baseline scenario, energy sector CO_2 emissions continue to rise for most of the century due to increasing coal and gas use, peaking at 18 GtC in 2080 (making the scenario a medium–high baseline compared to existing literature) (van Vuuren et al., 2006a). Total Kyoto GHG emissions also increase, from 10 GtC-eq at present to 23‘GtC-eq in 2100 (Fig. 2). As a result, the baseline reaches a CO_2 concentration of about 730 ppm CO_2 and a GHG concentration of 850 ppm CO_2-eq by 2100. Fig. 2 also shows the results for the A1b and B1 baselines.

2.3. Abatement costs

Costs are calculated here on the basis of marginal abatement curves, which indicate the costs of reducing an additional emission unit. These costs constitute one measure of the costs of climate policy, capturing direct costs of abatement action but not taking into account the costs related to a change in fuel trade or macro-economic impacts (including sectoral changes or trade impacts). In the literature, different costs metrics are used to describe the costs of climate policy: in addition to abatement costs or the increase of energy system costs (used by both partial

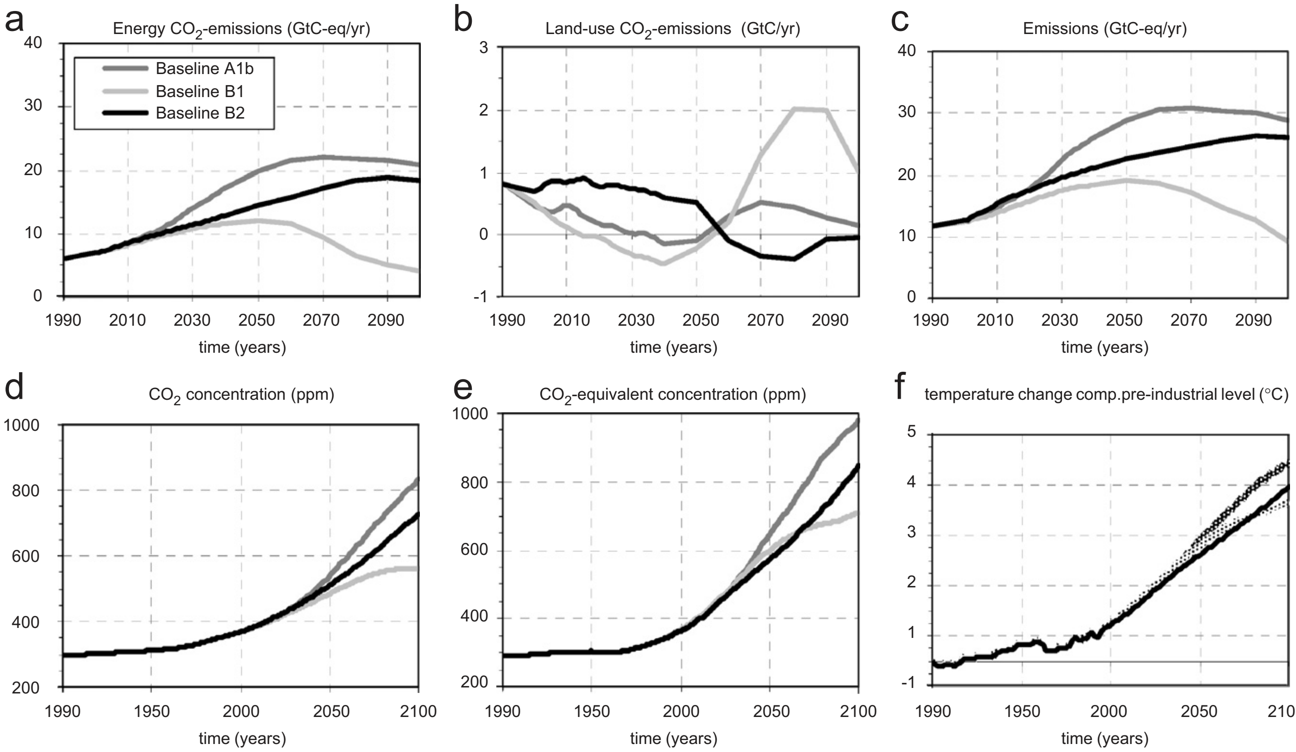

Fig. 2. Comparison of the emission, concentration and temperature increase for the B2, A1b and B1 baseline scenarios. The upper panel shows the annual global energy-related CO_2 emissions (a), land-use CO_2 emissions (b) and total CO_2-equivalent emissions (c) for the period 1990–2100. The lower panel shows the CO_2 (d) and CO_2-equivalent (e) concentration, and the temperature increase compared to pre-industrial (f) (assuming a climate sensitivity of 3 °C) for the period 1900–2100.

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and full equilibrium models) also gross domestic product (GDP) or consumption losses are reported (full equilibrium models). Both methods have their strengths and weaknesses. In fact, both methods are used in literature as valid approaches. To mention just a few examples of the abatement costs approach: it is used by the work of the MESSAGE model of IIASA (see Rao and Riahi, 2006), the work of the POLES model (Criqui et al., 1999), and also forms a separate element of the IPCC TAR assessment (Hourcade and Shukla, 2001), etc. The strength of the abatement costs approach is that it is relatively simple and flexible and focuses on the direct cost factor: additional costs for energy and abatement technology. Studies have shown that these direct costs are probably the largest costs factor. The weaknesses of the approach will be discussed below.

Macro-economic costs (GDP or consumption losses) are more comprehensive (as they also capture indirect effects within the economy) but are also much more uncertain (as a result, for instance, of uncertainties with respect to distribution effects, revenue recycling and impacts on investments), see IPCC TAR (Hourcade and Shukla, 2001; Morita and Robinson, 2001) or Repetto and Austin (1997). For instance, an important indirect impact may occur via altering investment patterns: some studies indicate that abatement action may lead to crowding out of more productive investments and thus less economic growth; at the same time, others claim that climate policies could lead to more investments (Hourcade and Shukla, 2001; Edenhofer et al., 2006). A similar issue exists with respect to tax revenue recycling, which can influence macro-economic costs based on the efficiency of re-investment. An overview of GDP impacts at a global scale in different models is available from Edenhofer et al. (2006) and the IPCC TAR (2001). In conclusion, macro-economic costs are more comprehensive—but also more uncertain, and abatement costs is still a good proxy of the total direct costs of climate policy. It should be noted that differences between macro-economic costs measures and abatement costs may become in particular important if not all parties participate in climate policy (see for instance, Lasky, 2003). As we assume full participation in this study, here we assume abatement costs to be an useful costs metric.

The MAC curves as used for this study are described in detail in Appendix A. In brief, costs estimates for non-CO_2 gasses are based on the EMF-21 study (Weyant et al., 2005). Their curves have been made consistent with the baselines used here and adopted to account for technology change (the original curves were developed for 2010). The curves for carbon plantations were developed from the IMAGE model (see Strengers et al., 2006). Finally, for CO_2 emissions from the energy system MAC curves were derived from the TIMER model. Here, it has to be noted that costs strongly depend on the pathway based on (1) technology change and (2) limited rates of change. In the FAIR model this was captured by two sets of curves that are scaled on the basis of timing of climate policy (as explained in more detail in Appendix A). In the calculations, these are scaled on the basis of the actual reduction path. By using one common baseline and three coupled models (TIMER, FAIR and IMAGE), a consistent set of information on baseline emissions and costs are generated. van Vuuren et al. (2006a) show that this leads to outcomes that are consistent across the three models; moreover, they also compare the outcomes with other studies showing that the costs estimates compare well to those of other studies, i.e. Azar et al. (2006), Rao and Riahi (2006), our earlier work of FAIR and IMAGE/TIMER (van Vuuren et al., 2005) and EMF-16/IPCC TAR (Hourcade and Shukla, 2001). Obviously, costs estimates do strongly depend on the assumptions about abatement potentials and reduction costs. van Vuuren et al. (2005) therefore also discuss the implication of uncertainties for overall costs—showing that the uncertainty range may well be 50% or more. In addition to annual abatement costs (as % of GDP), in this study we also use the net present value (NPV) of abatement costs over the 2000–2100 period. This represents the cumulated costs over that period—but discounted over time, divided by NPV of GDP (the cumulated, discounted GDP). Here, the GDP is exogenous in this modelling system, i.e. irrespective of the abatement.

While the methodology does provide useful insights into abatement costs and is relatively simple and flexible—we also realise that this methodology has a number of limitations (e.g., den Elzen et al., 2005). First of all, as already indicated these costs do not account for the costs related to a change in fuel trade or macro-economic impacts. Furthermore, the MAC curves have been created outside the system. This disadvantage is partly overcome by scaling different sets of MACs on the basis of actual reduction pathways in order to account for path dependency with respect to technology development and timing, as described above. Still this method can only capture part of the relevant dynamics (some of the processes that cannot be captured are carbon leakage and technology transfer). Another factor which has not been captured here in our cost estimates are so-called co-benefits: the reduction of air pollutant (or pollutant abatement costs) as a result of the systemic changes in the energy system.

3. Multi-gas emission pathways and envelopes and their resulting abatement costs

3.1. Methodology

A set of criteria has been defined for the development of the emission pathways:

1. *CO_2-eq concentration stabilisation target*—The emission pathways need to meet long-term CO_2-eq concentration (radiative forcing) stabilisation targets of 450 ppm (2.58 W m^{-2}), 550 ppm (3.65 W m^{-2}) and 650 ppm CO_2-eq (4.5 W m^{-2}) at around 2200, 2100 and 2150, respectively. For the stabilisation level at 450 ppm, we

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allow an initial peaking (or overshooting) up to 510 ppm (about 3.2 W m^{-2}).[12]

2. *Criteria for the level of emission reduction*—For each moment in time, the required level of emission reductions (by GHG) needs to be met by a corresponding level of emission reduction potential (derived from the expert models).
3. *Criteria for the rate of emission reduction*—The emission pathways take into account the constraints on the rate of the emission reductions reflecting technical and political inertia that prevent the global GHG emission levels from changing dramatically from year to year or from decade to decade. Fast reduction rates would require the early retirement of existing fossil-fuel-based capital stock, which involves high costs. In a certain way the current energy production system is 'locked' into fossil fuels, and changing this infrastructure takes time (see e.g. Gritsevskyi and Nakicenovic, 2000). But changing society and making political decisions is also a time-consuming process. Criteria on the rate of reduction are not included in the MAC curves. Therefore, following Swart et al. (1998) in their analysis of the 'safe landing' approach of emission corridors, we account for this inertia by simply assuming the following two constraints on the emission pathways (excluding LULUCF CO_2 emissions)[13]:
   - the global emission reduction rates should not exceed an annual reduction rate of x% year^{-1} (default) for all default pathways;
   - the annual trend change (change from 1 year to the next) cannot change by more than y percentage points per year (default values). For example, if emissions have risen 2% from year t to year $t+1$, emissions can only rise by $2-y$ to $2+y$ from year $t+1$ to year $t+2$.

We analysed 40 SRES non-climate policy and 18 available post-SRES mitigation scenarios (Swart et al., 2002) to identify the maximum rate of reduction in these scenarios—and to explore whether these rates are dependent on the stabilisation target. The results are shown in Fig. 3, which indicate that with only a few exceptions are maximum rates of reduction in emission scenarios usually less than 3%, and that the maximum rate is indeed somewhat dependent on the stabilisation target. Based on this, we chose the values ranging from 2% to 3%, depending on the final concentration stabilisation target. In addition, the change in reduction rate (i.e., the second derivative of emissions) of all runs is constrained to below 0.25 percentage points per year.[14] This is consistent with the assumption that too rapid changes over time are costly. Although most scenarios are only reported on a decadal basis, their relatively smooth trajectories more or less support the quantitative assumption made here, implying that a decade will be needed to go from constant emission level to the maximum reduction rates. These three criteria do not define unique pathways, as there are still many pathways that may lead to the same concentration stabilisation target, and may also meet the criteria for the rate of emission reductions. Mainly due to the long residence time of CO_2 in the atmosphere, it is rather the aggregated emissions that define the concentration stabilisation level than the time of emitting. Significant differences in the timing of required emission reductions allow many alternative pathways. This is shown by the emission envelopes, which we calculate here, by systematically varying the parameters of the parameterised global CO_2-eq emission pathway (see Appendix B). Within these envelopes, we define three types of emission pathways:

- *Default pathways*—The timing of the mitigation of these pathways is characterised as medium (not early; not delayed response), and the reduction effort is spread as much as possible over the century, thereby leading to as low as possible maximum global abatement costs (as a percentage of GDP). The default pathways are chosen (more or less) on the basis of the lowest maximum costs, as illustrated for the 550 ppm target in Fig. 4.
- *Delayed response pathways*—Here, the timing of mitigation is based on delayed response, with emissions being reduced less in the short term. The advantage is evidently buying time to prepare societies for strong mitigation policies—and also reducing short-term costs as shown in Fig. 4. However, costs are going to be higher in the long run compared to the default and early action pathways, as the latter pathways profit from induced technology development and an earlier signal of change to the energy system (and thus a more gradual response). Here, the central delayed response pathway is chosen as the one with the highest emissions and lowest relative costs in 2020.
- *Early action pathways*—Here, the response is as fast as possible, with either the rate of emission reductions restricted by the maximum annual trend change, or the emission reduction itself restricted by the maximum reduction rate. Both cases lead to pathways with an early peak of global emissions. We have two central pathways for this group: (i) the *early action/rapid change* (*RC*) *pathway*, with the highest maximum relative costs (above default) before 2050 as a result of the fast and high reductions in the first half of the century and (ii) the *early action/average change* (*AC*) *pathway*, with the

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[12] As the resulting SO_2 emissions are lower in this study compared to earlier emissions, the peak in concentrations is (temporarily) about 10 ppm higher around the peaking date, here we assume a 10 ppm higher peaking. For the emission envelopes we allow a variation of −2% to +1% in the final concentration stabilisation target. For 450 ppm the peaking may not exceed 515 ppm.

[13] Höhne (2005) used the same two constraints in his analysis of CO_2-only emission envelopes. In our earlier analysis, we only used the first constraint.

[14] More specifically, for 550 ppm 2% and 0.25 percentage point, and for 450 ppm 3% and 0.4 percentage point.

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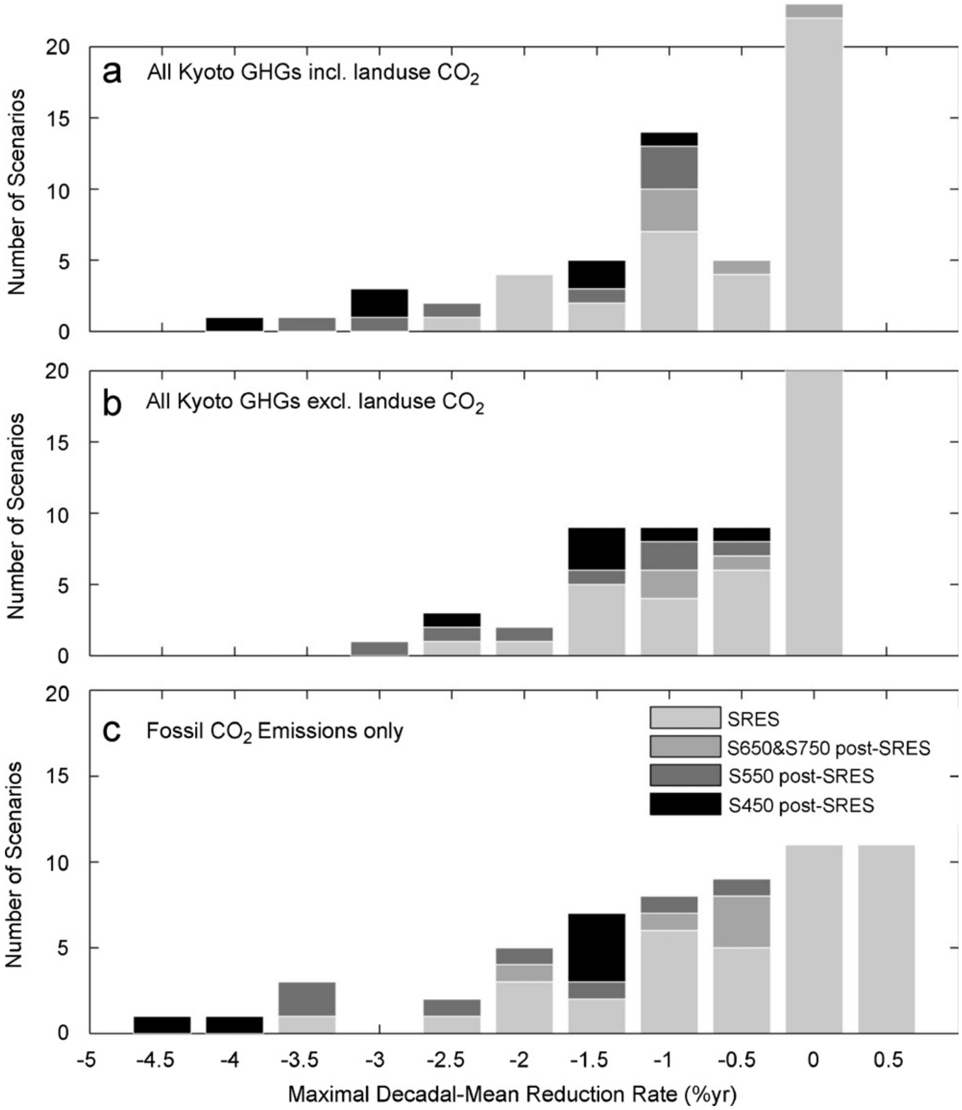

Fig. 3. Maximum decadal mean reduction rates in percentage per year for global emissions of (a) all Kyoto GHGs incl. land-use CO_2, (b) excl. land-use CO_2 and (c) energy-related CO_2 emissions for 40 SRES scenarios (Nakicenovic et al., 2000; Swart et al., 2002) and 18 post-SRES scenarios (Swart et al., 2002). *Note*: the maximum reduction rates for each scenario are here estimated as follows: the decadal emission changes (E_d/E_{d+1}) for each SRES and post-SRES scenario are calculated from 1990 to 2100 and the average annual emission change (in % year^{-1}) for each decade '*d*' is then derived as $R_{annual} = (\exp(\log(E_d/E_{d+1})/10) - 1) \times 100$. The maximal reduction rate is then the minimal value for R_{annual} for each scenario. The post-SRES scenarios were designed to stabilise at different CO_2 concentration levels, namely 450 ppm CO_2 (S450), 550 ppm CO_2 (S550), 650 and 750 ppm CO_2 (S650 and 750).

lowest maximum costs (below default), but with fast increasing costs in the coming two decades (Fig. 4).

The four pathways (*default*, *delayed response* and two *early action* pathways) lead to approximately the same concentration stabilisation target (long term), but their CO_2-eq concentrations in 2100 may differ, with the lowest concentrations for the early action RC pathways (see Fig. 7a–c). As we want to compare the abatement costs and reductions of these four pathways, we oblige the delayed pathways to lead to the same temperature increase in 2100 as the default pathway (see Fig. 7d–f).[15] For reporting reasons we show only the different representatives of the group (see Fig. 4); furthermore, the emission pathways of the three groups are simply represented as grey lines, which together form the emission envelope.

3.2. Emissions

Fig. 5 shows the central default, delayed and early action emission pathways and their envelopes for the three baseline scenarios, as well as the three concentration stabilisation targets.

3.2.1. Default pathways

The global GHG emissions (including LULUCF CO_2) for the default emission pathways at 650, 550 and 450 ppm

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[15] This holds for all pathways, except for the early response RC pathways, as this pathway leads to lower concentrations and temperature increase projections over the time horizon considered up to 2400.

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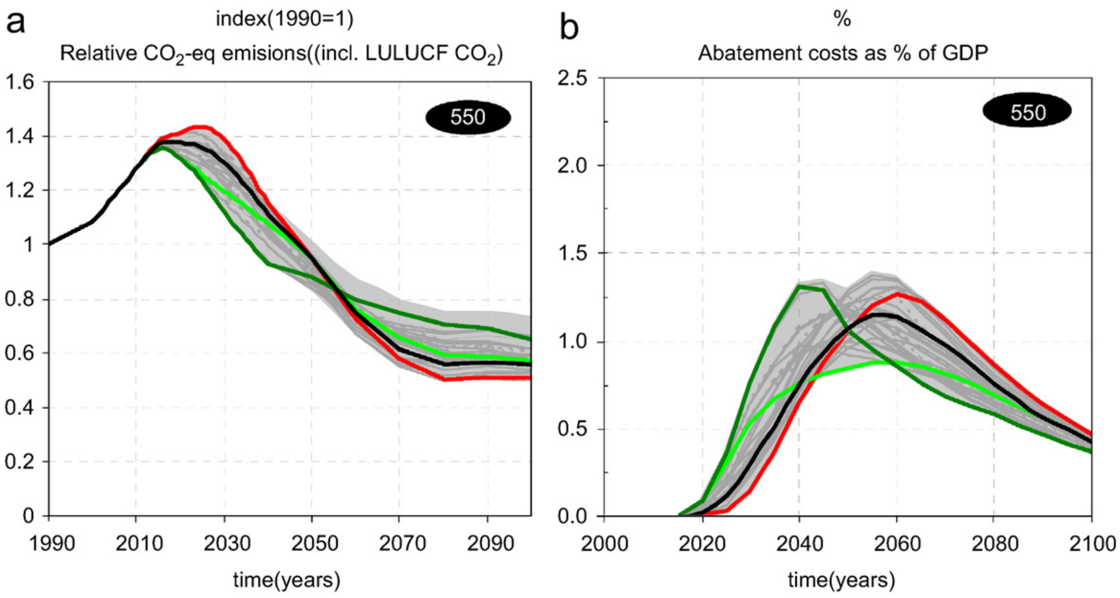

Fig. 4. Global emissions relative to 1990 levels including LULUCF CO_2 emissions (left, a) vs. the global abatement costs (b) for the default (bold), early action/rapid-change (RC (dark green)), early action/average-change AC (light green), delayed response (red) emission pathways and all pathways (grey) (forming the envelope) at 550 ppm CO_2-equivalent concentrations for the B2 baseline scenario.

Table 1
The uncertainty range and the default change of global GHG emissions (including LULUCF CO_2 emissions) compared to 1990 levels for the different multi-gas pathways for stabilising at 450, 550 and 650 ppm CO_2-eq concentration for the three baseline scenarios (in %)[a]

Baseline	B2		A1b		B1	
	Range	Default	Range	Default	Range	Default
2020						
450 ppm	[14;24]	22	[3;9]	8	[0;20]	7
550 ppm	[32;41]	37	[32;18]	26	[13;23]	19
650 ppm	[35;50]	41	[30;43]	35		
2050						
450 ppm	[–45;–23]	–33	[–52;–42]	–50	[–60;–40]	–45
550 ppm	[–7;0]	–5	[–28;–13]	–18	[–40;–20]	–25
650 ppm	[21;57]	32	[5;42]	24		
2100						
450 ppm	[–74;–55]	–71	[–75;–65]	–72	[–77;–67]	–73
550 ppm	[–49;–26]	–44	[–59;–42]	–47	[–57;–41]	–49
650 ppm	[–25;–3]	–12	[–18;–8]	–21		

[a] The uncertainty range presented here needs to be considered carefully in the context of the envelope, choosing lower reductions in the beginning needs to be compensated by higher reductions later on and vice versa.

CO_2-eq need to be reduced in 2100 by 55%, 70% and 85%, respectively, from their B2 baseline levels (see Fig. 5, left panel and Table 1). Under the 650 ppm CO_2-eq pathway emissions can still slightly increase and stabilise at a level 40% above current emissions in the next 3–4 decades—followed by a slow decrease. For the 550 ppm CO_2-eq pathway, however, emissions need to peak around 2020, directly followed by steep reductions in order to avoid overshoot of the 550 ppm CO_2-eq concentration level. The emissions are approximately 5% below 1990 levels in 2020. For stabilisation at 450 ppm CO_2-eq, short-term reductions become even more stringent, with global emissions peaking around 2015 at 30% above 1990 levels. Global GHG emission reductions increase up to 35% below 1990 levels in 2050.

3.2.2. *Delayed response versus early action pathways*

The delayed pathways make it clear that running along the upper boundary of an envelope does not bring you to the concentration stabilisation target (see also Figs. 4 and 5, left panel). The early high emissions of these pathways, forming the short-term upper boundary of the

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envelope, will have to be offset by low emissions later on, forming the long-term lower boundary of the envelope. An opposite pattern can be seen for the early action pathways. The early low emissions of the early action RC pathways, forming the short-term lower boundary of the envelope, can be compensated by higher emissions in the long term, forming the long-term upper boundary of the envelope.

The transient evolution of CO_2-eq and the CO_2 concentrations for the four pathways do not differ much. Thus, even if there is a net increase in terrestrial and ocean carbon in a scenario with temporarily elevated CO_2 concentrations and temperatures (e.g., Wigley et al., 1996), the effect in case of our pathways will be very limited. In other words, the cumulative emissions for the four different pathways for each stabilisation level do not vary much. For example, the cumulative emissions of the pathways within the envelope for the B2 baseline scenario and the 550 ppm target differ by -2% and $+1\%$ of the cumulative emissions of the default pathway. If we were to allow a higher overshoot, the effect could become more prominent, but would also lead to a higher rate of temperature increase, which in turn is likely to reduce the carbon uptake of the biosphere and the oceans.

3.2.3. *Emission envelopes*

The envelopes show that there is indeed a large spread of emission paths leading to the same concentration levels, but the spread of emission pathways decreases for the lower concentration targets (see also Figs. 5 and 6, left panel). More specifically, for the lower concentration targets there is a limited space for emissions, going from early action to our default assumptions and finally delayed response. The envelopes for both 450 and 550 ppm CO_2-eq show that emissions are required to peak before 2015 and 2025, respectively, with strong emission reduction following. Our calculations show this phase (striving to reach these concentration levels) to be the most difficult in climate change policy, even when assuming full participation of all countries under a climate regime. Without participation (in some form) of the major GHG emitters, the 450 and 550 ppm targets are outside our reach, as were shown by den Elzen and Meinshausen (2005). Fig. 6 (left panel) also shows that the envelopes of 450 and 550 ppm CO_2-eq do not overlap (after 2015), which suggest that there are no emission pathways initially following 550 ppm (early action) and then turning to a 450 ppm pathway. For 650 ppm, the emissions may peak at 2030–2040 at the latest, although for a delayed response strategy (with higher short-term emissions) this peak also occurs before 2025. Here, we see some overlap between the emission envelopes of 550 and 650 ppm (Fig. 5).

These conclusions have to be qualified of course for cases in which the limits applied here are relaxed; this affects the maximum emission reductions and changes in reduction rates from year to year. Furthermore, we want to emphasise again that these envelopes are not necessarily what they are considered to be as what they are, i.e., envelopes around a set of pathways. Following the upper or lower boundary of the envelope for the whole time period does not lead to the concentration target. The envelope better reflects the idea that following the lower boundary in the beginning can be compensated by following the upper boundary later. Early reductions can be compensated with more relaxed reductions later, and vice versa.

3.2.4. *Baseline*

The emission pathways and resulting emission envelopes are baseline-dependent. For example, compare the columns in Figs. 5 and 6 (see also Table 1). This is a direct result of the differences in: (i) initial (starting point of the pathways in 2010) emissions and their growth and (ii) MAC curves and (iii) LULUCF CO_2 emissions. For example, in (i) the pathways under the B2 scenario have higher short-term (2020) emissions, and medium-term (2050) emissions, although their emissions are lower in the second half of the 21st century (see Fig. 5). For example, in (ii) there are no feasible delayed pathways for the 450 ppm target for the high-growth emission scenario A1b, resulting in a small emission envelope compared to the other two envelopes for 450 ppm. For the B2 scenario, these LULUCF CO_2 emissions (iii) show a temporary increase at the end of the century due to a rapid introduction of biofuel in the transport sector. Therefore, these emissions form a large part of the total emissions from the pathways at the end of century, which needs to be compensated by lower emissions in the medium term.

3.2.5. *Comparison with earlier study (den Elzen and Meinshausen, 2005, 2006)*

In general, the reductions for the Kyoto GHG emissions including or excluding LULUCF CO_2 emissions are very similar. However, our earlier study showed that the reductions excluding LULUCF CO_2 were about 10–15% higher than the reductions in the Kyoto GHG emissions including LULUCF CO_2. This is because of the much higher LULUCF CO_2 emissions for the updated baseline scenario due to the additional deforestation emissions from the biofuel plantations. Other differences with the earlier study, such as the updated baseline emissions and MAC curves, have only a minor effect on the emission pathways. Another difference is that in our earlier study the initial (2010) growth of about 1–1.5% year^{-1} (depending on the baseline) was assumed to decline relatively rapidly after 2010 to 0.5% year^{-1} for all concentration stabilisation targets. This is different for the 550 and 650 ppm CO_2-eq pathways in this study, since here we apply a boundary of how fast emission reduction rates can change from year to year. However, the boundaries for the 450 ppm stabilisation pathway are more or less in line with the assumptions of our earlier study.

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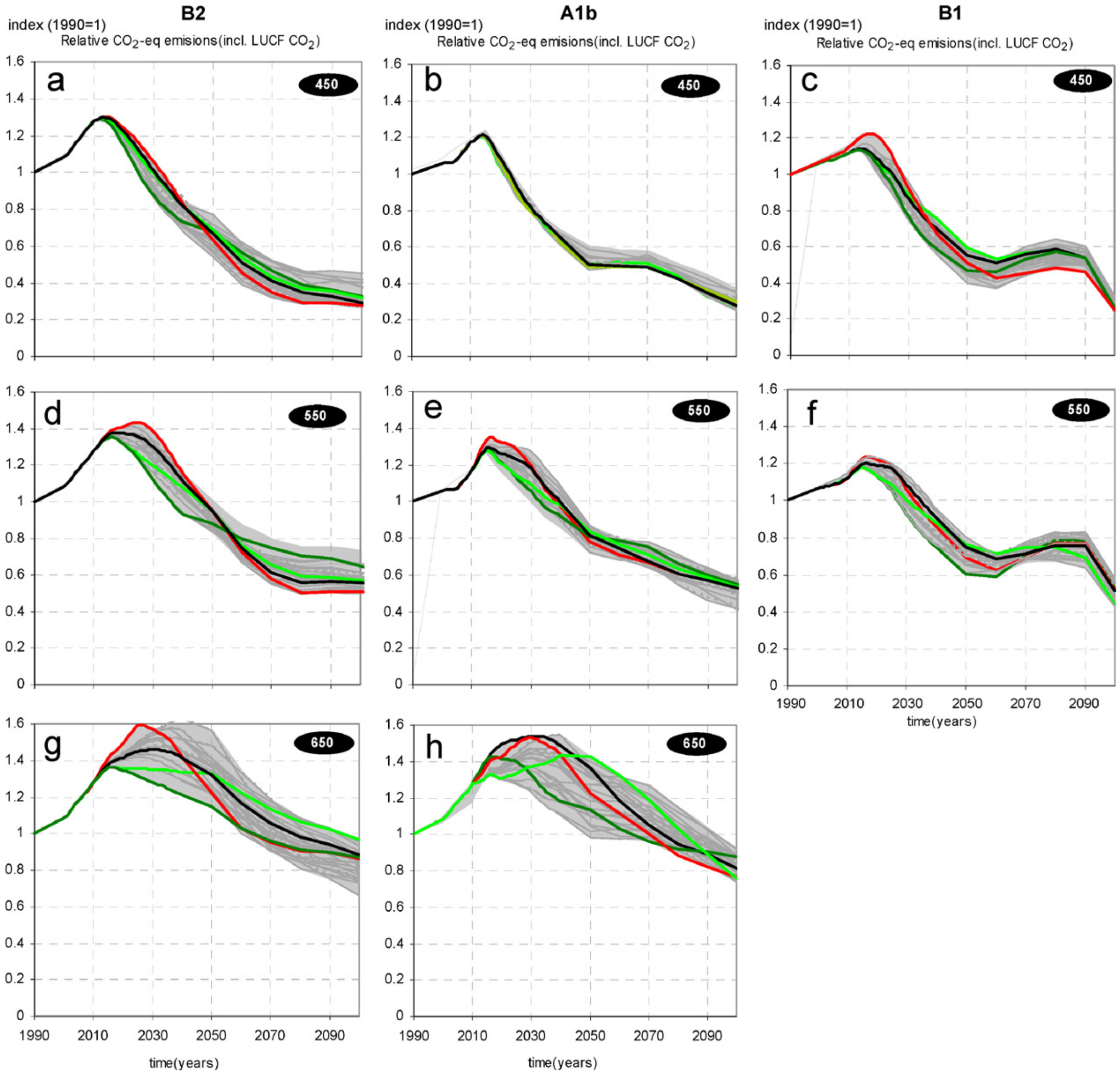

Fig. 5. Comparison of the global emissions relative to 1990 levels for the global emission pathways, i.e. default (black), delayed (red) and early action (green) pathways and envelopes (set of grey lines) at 450 (upper, a–c), 550 (middle, d–f) and 650 (lower, g, h) ppm CO_2-eq concentration for the B2 (left panel, a, d, g), A1b (middle panel, b, e, h) and B1 baseline (right panel, c, f) scenarios. *Note*: for the A1b baseline scenario there was no delayed pathway possible, and for the B1 baseline scenario, there were no feasible pathways towards 650 ppm.

3.2.6. Abatement across different gases

Initially, a substantial share of the reduction is, for all emission pathways, achieved by reducing non-CO_2 gases, while only 10% of the reductions comes from reducing energy-related CO_2 emissions (not shown here) (see also van Vuuren et al., 2006a). The disproportional contribution of non-CO_2 abatement is caused mainly by relatively low-cost abatement options that have been identified for non-CO_2 gases (e.g., reducing methane emissions from energy production and N_2O emissions from adipic and acidic acid industries, and halocarbons). After 2015 ever more reductions need to come from CO_2 in the energy system—up to 80% in 2100. This shift simply reflects that non-CO_2 gases represent about 20% of total GHG baseline emissions. In addition, some non-CO_2 GHGs (including several sources for land-use related CH_4 but in particular N_2O emissions sources) cannot be reduced fully due to limited reduction potential. The share of non-CO_2 abatement declines somewhat further in the 450 ppm stabilisation—compared to the 650 ppm stabilisation. The use of carbon plantations shows an increasing contribution to about 1 GtC annually in 2100 for all targets due to increasing land availability.

3.3. Global costs

Fig. 8 shows the resulting abatement costs of the pathways as a percentage of world GDP (see also Table 2). Although our relatively simple cost calculations

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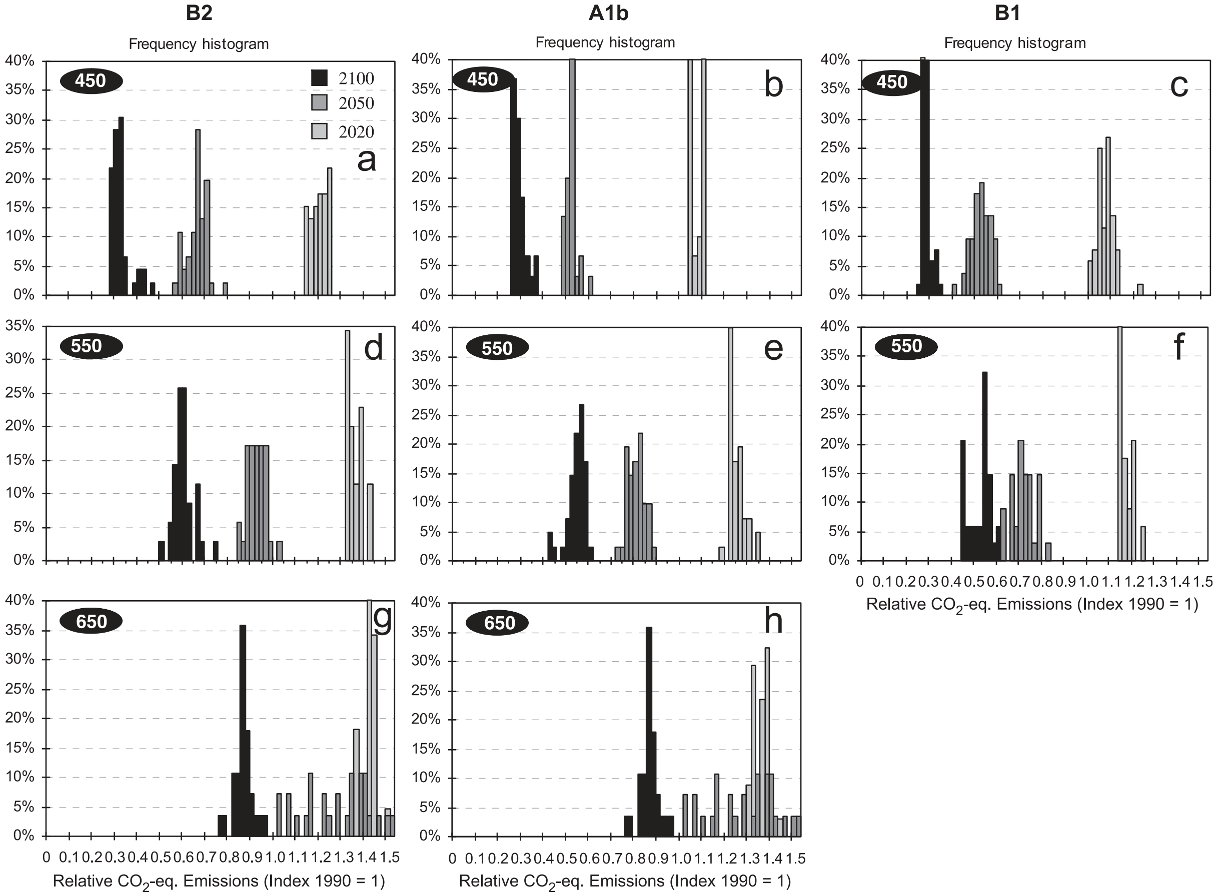

Fig. 6. The frequency histograms of the global emissions relative to 1990 levels for the emission pathways as presented in Fig. 5.

are meant to be explorative (see Section 3.1) the following findings have emerged.

3.3.1. *Default pathways*

The costs as a percentage of GDP increase for lower concentration stabilisation targets; however, it can also be seen that these costs increase much more rapidly in time. For the 450 and 550 ppm pathways, costs such as percentage of GDP reach a maximum level between 2020 and 2040 (1.2% of GDP for 550 ppm and 2% for 450 ppm).[16] This re-emphasises our earlier conclusion that this time period (2020–2040) is evidently one of the most crucial periods for emission reductions. In fact, given the lags between climate policy drafting, implementation and actual emission reductions, the period before 2020 is politically equally important—certainly if one attempts to reach the lower concentration stabilisation targets. The costs very much depend on the participation of countries in emissions trading. Here, full participation is assumed. This implies that only if the participation of countries adopting absolute targets and taking part in the emission trading can be broadened, will our cost calculations be correct. The costs will be higher (or concentration targets will not be reached) when major emitting countries delay their participation. In the default pathways (but also alternative pathways) the relative cost (as a percentage of GDP) actually declines again after 2040. This decline is caused by: (1) decline of the marginal price at the end of the century, (2) the stabilising emission gap between baseline and the emission pathway (in particular for 550 and 650 ppm) and finally (3) GDP growth outstrips the growth in calculated abatement costs for most of the pathways (see Fig. 8). The decrease in marginal prices is on its turn determined by a number of factors including (1) the required early reductions in order to allow meeting the long-term goals, (2) reductions in abatement costs as result of technology change and (3) the reduction in baseline emissions by the end of the century (as a result of dropping population levels).

3.3.2. *Delayed response versus early action pathways*

The cost pathways over time are shown after an initial rapid increase in costs, with the early action pathways resulting in the lowest average maximum (relative) costs

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[16] The trajectory of the carbon tax also depends on the fact that we constrain our CO_2-equivalent concentration not to exceed the final peaking concentration target earlier in the century (or if they do, by a margin as small as possible). Given population and GDP trajectories, targets may be just as binding early in the century as latter in the century.

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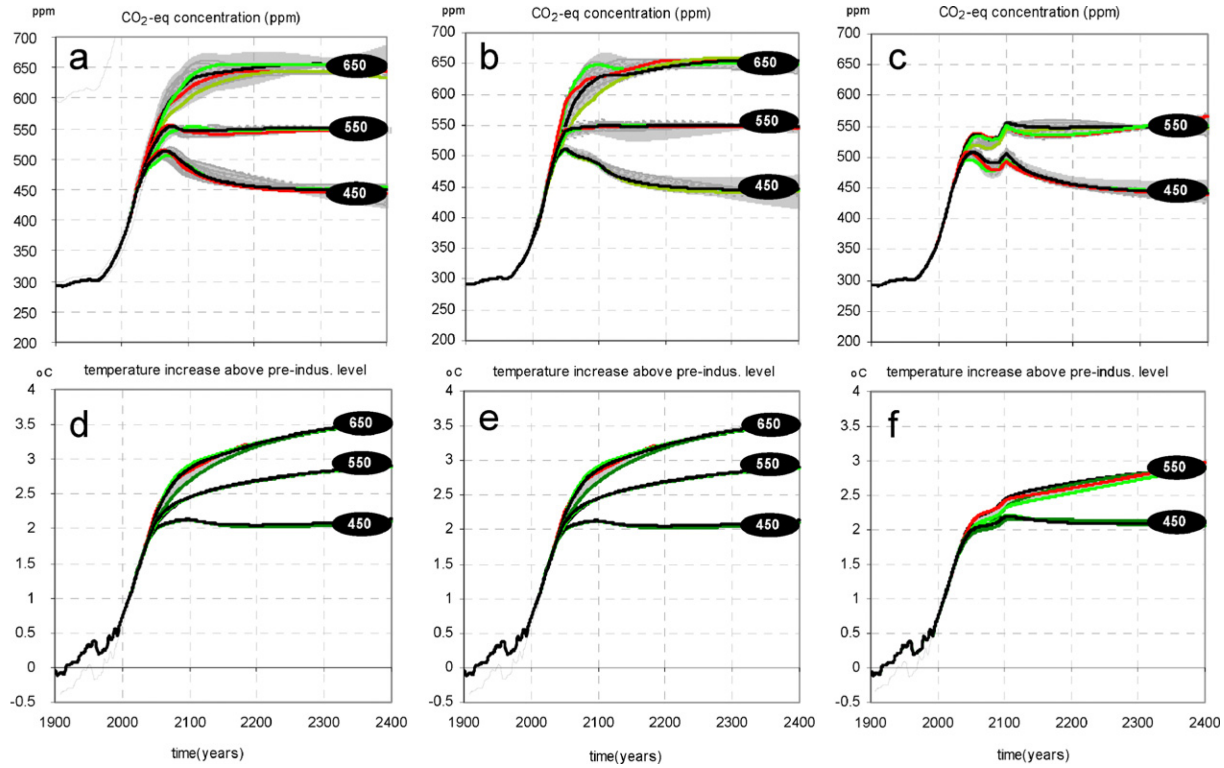

Fig. 7. The CO_2-equivalent concentration and temperature increase above pre-industrial levels (assuming a climate sensitivity of 3 °C) for the global emission pathways, i.e. default (black), delayed (red) and early action (green) pathways and envelopes (set of grey lines) for the three stabilisation levels for the B2 baseline (a), A1b baseline (b) and B1 baseline (c) scenarios.

benefiting from lower reduction rates, an earlier signal of change to the energy system and technology development. The delayed pathways, in contrast, avoid the early rise in costs, but see higher maximum costs during the 2020–2040 period. The default pathways result in maximum costs somewhere in between those two (see Fig. 8). More specifically, the peak of the global costs for the B2 scenario is the lowest for early action AC (0.8% and 1.6% of GDP for 550 and 450 ppm, respectively), followed by the default pathway (1.1% and 1.8%), the delayed response (1.3% and 1.9%) and, finally, the early action RC pathway (1.3% and 2.2%). The NPV of abatement costs as a percentage of the NPV of GDP for the B2 baseline scenario varies between 0.2% of GDP for stabilisation at 650 ppm and 1.0% of GDP in the 450 ppm case (with a discount rate of 5%, Fig. 9a).[17] For the A1b scenario, the NPV of abatement costs are somewhat higher and for B1, lower. We can now compare the NPV of abatement costs for the early, default and delayed pathways under different discount rates (Fig. 9b). No discounting shows that for the 450 and 550 ppm stabilisation targets early action (both variants) leads to the lowest NPV of costs, followed by the default case; the delayed pathway leads to the highest NPV of abatement costs (Fig. 9b). The 650 ppm target gives a similar pattern, except that the early action RC pathway now gives similar costs as the delayed pathway. This result is, again, caused by technology development and the longer time needed for the energy system to respond. Under the discount rate of 5%, the differences between the early action AC, default and delayed pathways are small. The early action RC pathway leads to the highest costs.

More specifically, discount rates less than 2% would favour early action RC pathways for the 450 ppm target, discount rates less than 8% would favour early action AC pathways and to a lesser extent the default pathway. Finally, discount rates more than 8% would favour delayed response—on the basis of economic arguments alone. For the 550 ppm target, this will depend on the scenario. For the B2 scenario, the discount rates of less than 1% would favour early action RC, 1–3% early action AC, 3–4% default pathways and more than 5% delayed pathways (Fig. 9b). However, for the A1b scenario there are higher discount rate thresholds, less than 2% early action RC, 1–3% early action AC, 3–9% default pathways and more than 9% delayed pathways. For the 650 ppm target, the discount rates of less than 2% would favour early action RC, 2–5% default pathways and more than 5% delayed pathways.

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[17] van Vuuren et al. (2006a) have showed that these costs estimates compare well to those of other studies. More specifically, Azar et al. (2006) and Rao and Riahi (2006) also discuss similar cost levels as a function of concentration targets (again only for CO_2) for considerably lower levels. The costs of this study are similar to our earlier work of FAIR and IMAGE/TIMER (van Vuuren et al., 2005), and in between the lowest and the highest estimate of EMF-16/IPCC-TAR (Hourcade and Shukla, 2001).

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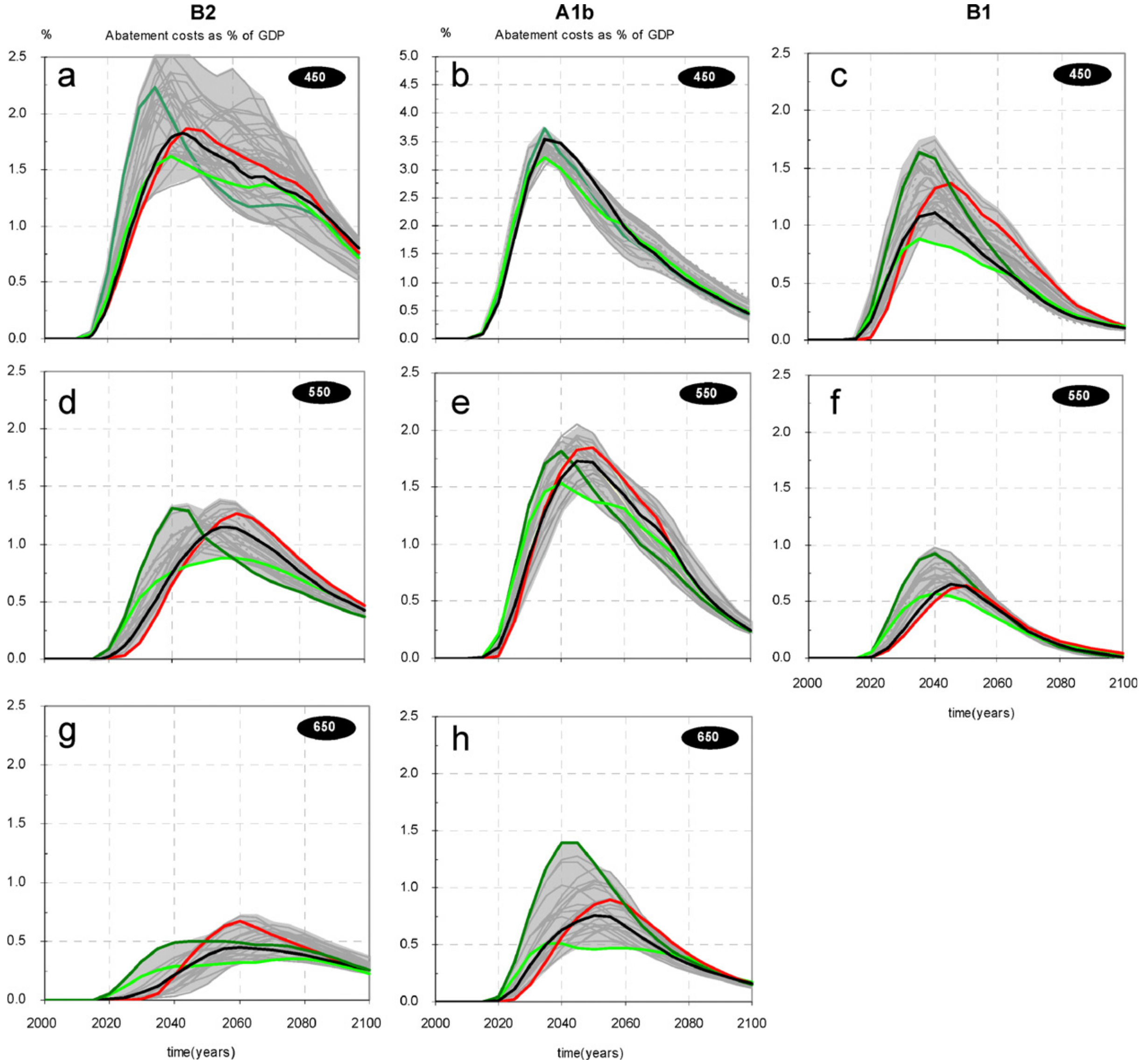

Fig. 8. Comparison of the global abatement costs as % of GDP for the global emission pathways, i.e. default (black), delayed (red) and early action (green) pathways and envelopes (set of grey lines) at 450 (upper, a–c), 550 (middle, d–f) and 650 (lower, g, h) ppm CO_2-eq concentration for the B2 baseline (left panel, a, d, g), A1b baseline (middle panel, b, e, h), B1 baseline (right panel, c, f) scenarios. Note that a different scale is used for the A1b-450 ppm case.

Table 2
Comparison of climate risks vs. abatement costs for the different multi-gas pathways for stabilising at 450, 550 and 650 ppm CO_2-eq concentration

Stabilisation (ppm CO_2-eq)	Peaking (ppm CO_2-eq)	Climate risks[a]		Abatement costs[b]	
		Probability (%) of limiting warming to below 2 °C for pathways with (and without) stabilisation after peaking		Cumulative costs (NPV) as % of GDP	Maximum costs as % of GDP
		Central estimate[c]	Range		
450[d]	510	54 (54)	14–67 (14–67)	1.0 (0.9–1.2)	2.0 (1.6–2.6)
550	550	26 (34)	1–40 (3–48)	0.5 (0.4–0.6)	1.14 (0.9–1.3)
650	650	10 (12)	1–21 (2–23)	0.15 (0.1–0.3)	0.45 (0.4–0.7)

[a] Climate risks: the probability of exceeding 2 °C warming above pre-industrial levels up to 2400 for the 'IPCC lognormal PDF' and the range across 11 climate sensitivity uncertainty distributions.

[b] Abatement costs: the NPV of abatement costs as a percentage of GDP (using a discount rate of 5%) and maximum costs as a percentage of GDP.

[c] Based on IPCC lognormal PDF (Wigley and Raper, 2001).

[d] This is in fact an overshooting scenario.

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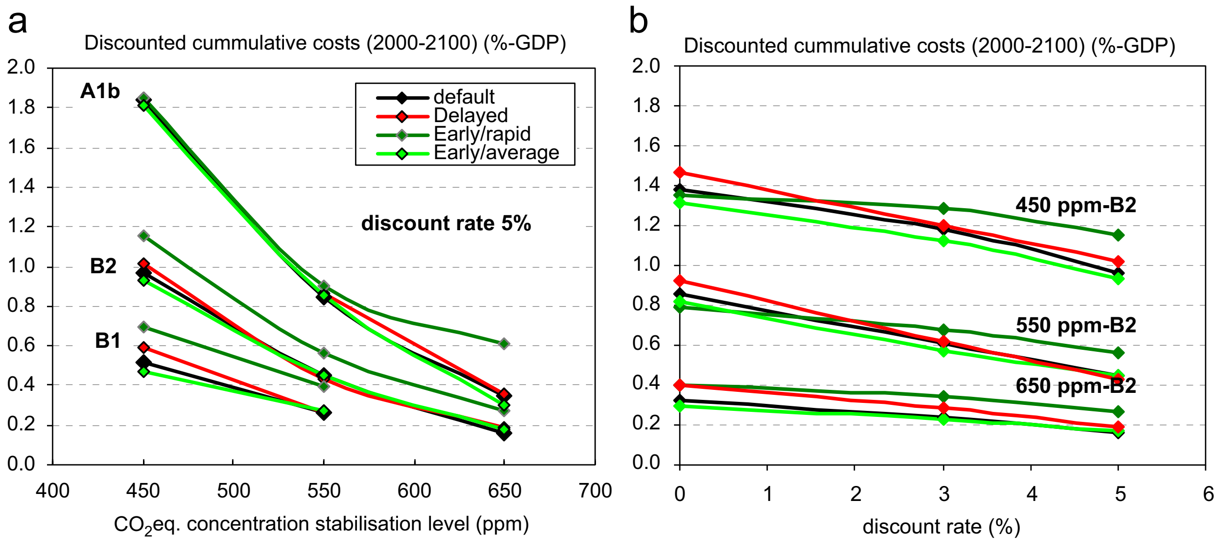

Fig. 9. Net present value of abatement costs for different stabilisation levels, starting from different baseline scenarios for discount rate (5%) (a), and as a function of the discount rate for the B2 baseline (b).

3.3.3. *Cost of the envelopes*

The costs of the complete set of emission pathways show an even wider range than the range already seen for the early action, default and delayed pathways, especially for the 450 ppm target. In general, the costs peak later for the higher concentration targets, but the date of the peak shows a wide range. For example, this can be before 2030 (early action RC) for the B2 baseline and the 550 ppm target, but may also be as late as 2070 (early action AC), although a maximum around 2050 is more likely. For the 450 ppm target, the latest date is much sooner (2050). The maximum level itself can also vary considerably: for the B2 baseline and the 550 ppm target, this range is between 1% and 1.7%, whereas for the 450 ppm target it can vary between 1.5% and almost 3%.

3.3.4. *Baseline*

Fig. 8 also shows the global abatement costs to be even more influenced by the baseline emissions than the stabilisation level, as also concluded by the IPCC. The A1b costs are higher than the B2 costs, while the B1 costs are below this stabilisation level for each concentration stabilisation level. This is a direct result of the lower reduction objective, the high technology development rate and the resulting lower marginal price. The economic assumptions also obviously influence the relative cost measures, such as GDP losses or abatement costs as a percentage of GDP. The NPV of the abatement costs shows a similar trend, as indicated in Fig. 9.

Finally, it should be noted that it is interesting to study the same profiles as well using macro-economic models to obtain additional insights in the indirect costs.

4. Probabilistic temperature increase projections

The different multi-gas emission envelopes for the different concentration stabilisation targets analysed in Section 3 lead to clearly different temperature increases, both during this century and in the long term. Fig. 7d–f show the resulting temperature increase projections using a single value for climate sensitivity (3 °C). There are a number of points to note here. Firstly, the early action AC pathway, default and delayed response emission pathways lead, as assumed, to very similar temperature increase projections by 2100. While temperature increase in 2100 is more-or-less similar, during most of the century delayed response has led to higher temperature increase than early action and default responses. Secondly, the early action RC pathways lead to somewhat lower temperature projections over the period of 2000–2200 compared to the temperature increase in the other three pathways, which is a direct result of their lower CO_2-eq concentration. Thirdly, although the CO_2-eq concentration stabilise for the 650 and 550 ppm cases before 2150, the warming continues beyond 2250. This is because of the large thermal inertia of the climate system, which, in turn, is largely determined by how rapidly heat is mixed down into the ocean. Fourthly, due to the inertia of the climate system, the peak of concentrations (510 ppm) before stabilisation at 450 ppm CO_2-eq does not translate into a comparable peak in global mean temperatures. In fact, the peaking concentration is the key factor that determines whether a 2 °C temperature threshold will be achieved or not, rather than the stabilisation level itself (see also Meinshausen, 2006).

It should be noted, however, that the temperature response of the different stabilisation scenarios depends to a considerable extent on the climate sensitivity. Taking into account the uncertainty in the climate sensitivity, we

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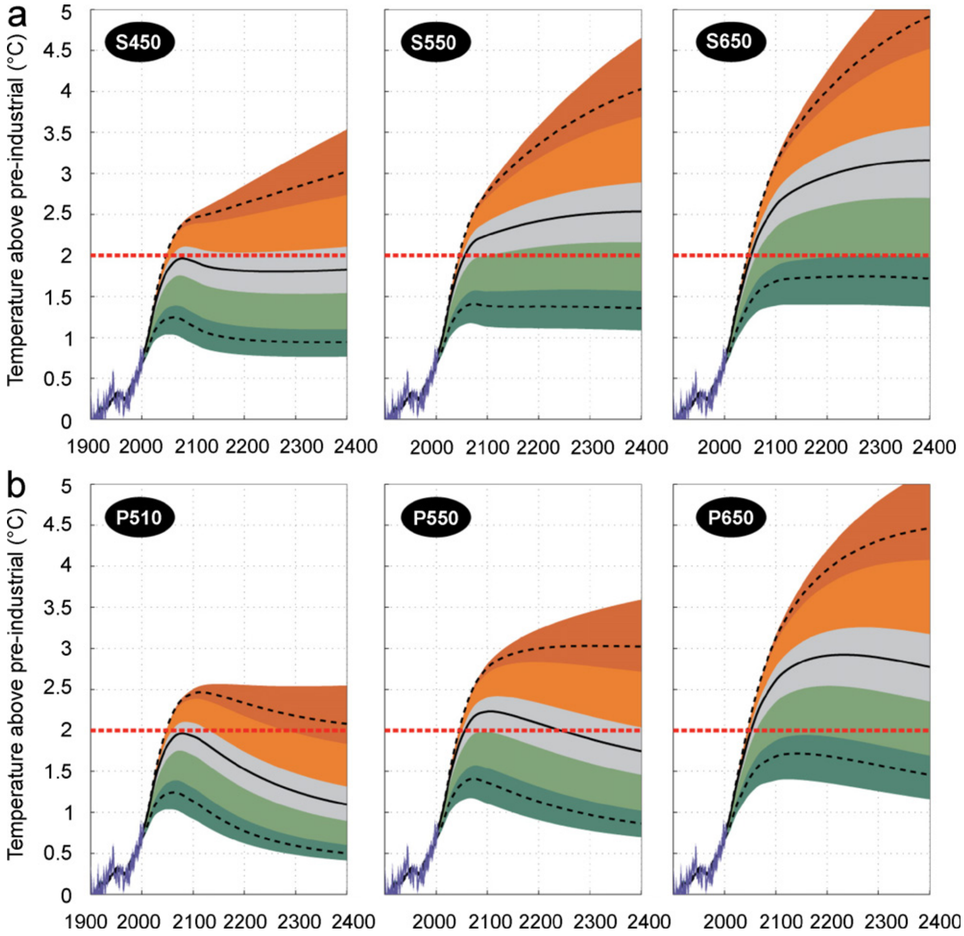

Fig. 10. The probabilistic transient temperature implications for the stabilisation pathways at 450, 550 and 650 ppm CO_2-eq concentration (upper row) and the pathways that peak at 510, 550 and 650 ppm (lower row). The FAIR–SiMCaP pathways shown are those for the B2 baseline scenario based on a climate sensitivity that assumes the 1.5–4.5 °C uncertainty range for climate sensitivity (IPCC TAR), being a 90% confidence interval of a lognormal distribution (Wigley and Raper, 2001). Shown are the median (solid lines) and 90% confidence interval boundaries (dashed lines), as well as the 1%, 10%, 33%, 66%, 90% and 99% percentiles (borders of shaded areas). The historical temperature record and its uncertainty from 1900 to 2004 is shown (blue-shaded band) (Folland et al., 2001; Jones and Moberg, 2003; Jones et al., 2001).

present the temperature in probabilistic terms for the default pathways under 450, 550 and 650 ppm CO_2-eq for the baseline B2. The assumed climate sensitivity uncertainty distribution for the temperature projections in Fig. 10 is constructed by assuming the conventional IPCC TAR 1.5–4.5 °C uncertainty range. This represents the 90% confidence interval of a lognormal distribution—called below 'IPCC lognormal PDF' (see Wigley and Raper, 2001). Aerosol forcing and ocean diffusivity are set to their respective maximum likelihood estimators for any given climate sensitivity to find a best match with historical global mean temperature observations (see "temperature constrained" method by Meinshausen, 2006). In these transient calculations, we included the solar forcing according to Lean et al. (1995, 2001) and volcanic forcing according to Ammann et al. (2003). Future natural forcing is assumed as the mean over the last 22 years (solar) and 100 years (volcanic). A set of alternative climate sensitivity PDFs (Andronova and Schlesinger, 2001; Forest et al., 2002; Frame et al., 2005; Gregory et al., 2002; Knutti et al., 2006, 2003; Murphy et al., 2004; Piani et al., 2005) has been applied to determine the probability that the analysed pathways are in line with the avoidance of a global warming of more than 2 °C relative to pre-industrial levels (Fig. 11).[18] The pathways aimed at a 650 ppm stabilisation have very small or zero chance of limiting warming to below 2 °C (refer to Fig. 10). The probabilities for staying below 2 °C are still very limited, 1–40% for the 550 ppm stabilisation pathways with (IPCC lognormal PDF: 26%). However, a peaking at 550 ppm without subsequent stabilisation could increase those chances marginally to 3–48% (IPCC lognormal PDF: 34%). For the stabilisation pathways that peak at 510 ppm and stabilise at 450 ppm, the chances are again slightly increased to 14–67% (IPCC lognormal PDF: 54%). Note that in this latter category of pathways, the peaking concentration level at 510 ppm, not

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[18] Note that the cited probabilities and likelihoods are only indicative. Furthermore, the underlying probability density distributions on climate sensitivity only reflect the fact that our knowledge is uncertain. The climate sensitivity is not a random variable.

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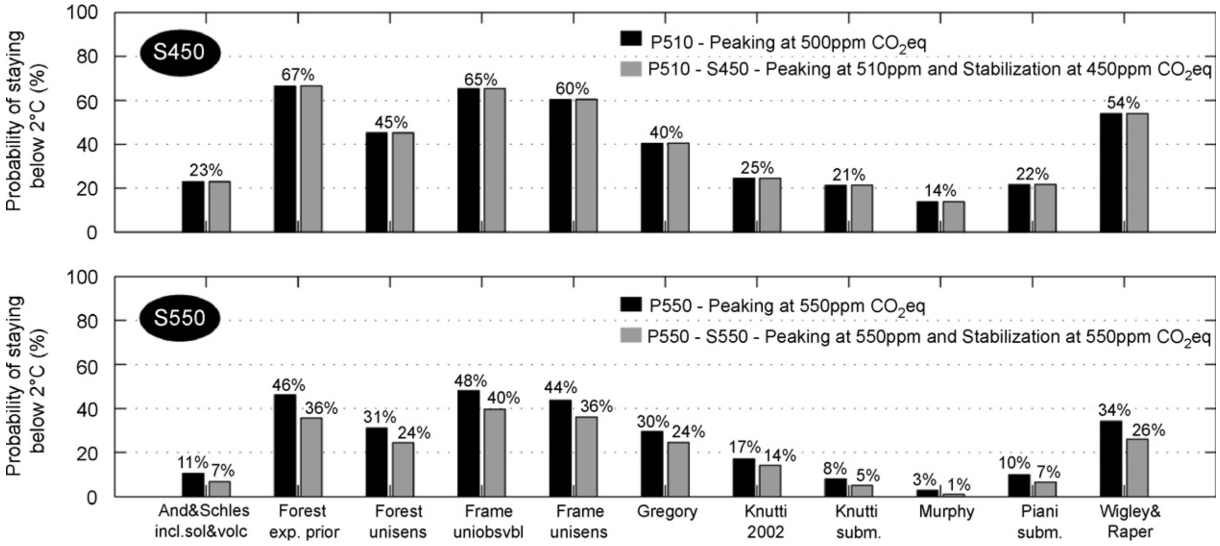

Fig. 11. The probability of staying below 2 °C global mean warming up to 2400 for the pathways that peak at 510 ppm CO$_2$-eq (upper panel) and those that peak at 550 ppm CO$_2$-eq for different climate sensitivity PDFs. Note that those pathways that stabilise and/or peak at 650 ppm have only negligible chances of meeting a 2 °C target (23% or below). The last two bars indicate the results for the IPCC-based lognormal PDF on climate sensitivity (Wigley and Raper, 2001), which corresponds to the transient temperature evolution shown in Fig. 10.

the stabilisation at 450 ppm CO$_2$-eq, is likely to cause the maximal warming over the time horizon from 2000 to 2400.

These results reconfirm two important points. Firstly, only a long-term stabilisation of 450 ppm CO$_2$-eq or below (400 ppm CO$_2$-eq) can be expected to avoid global warming of 2 °C or more with a medium likelihood. Secondly, policy and science should increasingly focus on the peaking level of concentrations in the 21st century rather than the ultimate stabilisation level. It can be inferred from our results shown above that a reduction in the ultimate stabilisation level below 450 ppm will not alter the probabilities of exceeding 2 °C—as long as the peaking level of concentrations is not lowered below 510 ppm.

As a word of caution, it should of course be noted that the above cited likelihood ranges should be taken as indications and are subject to change in the light of new evidence on the climate sensitivity and other important parameters, for example, the aerosol radiative forcing effects.

5. Conclusions

We have described a set of multi-gas emission envelopes (sets of emission pathways), which are compatible with GHG concentration stabilisation levels of 450, 550 and 650 ppm CO$_2$-eq (including all major GHGs, ozone precursors and sulphur aerosols), along with an analysis of their global reduction implications, abatement costs and the probability of meeting long-term temperature targets including the EU 2 °C climate target. The lower pathways presented allow overshooting, i.e., concentrations peak before stabilising at lower levels, for example, rising to 510 ppm CO$_2$-eq before dropping later on to levels such as 450 ppm CO$_2$-eq.

The emission pathways are calculated on the basis of a cost-optimal implementation of available reduction options over the GHGs, sources and regions. This closely reflects the existing international framework of pre-set caps on aggregated emissions and individual cost-optimising actors. We used time-dependent marginal abatement cost curves, including technological change and learning-by-doing as a function of the earlier abatements and accounting for the inertia in the energy system. Furthermore, a maximum reduction rate was assumed, reflecting the technical (and political) inertia that limits emission reductions (this rate is based on a large set of existing mitigation scenarios). In this way, the envelopes or pathways are assessed to be technically and economically feasible. In Section 2 we discussed a number of strengths and weaknesses of our approach. Overall, we find our results to be consistent with other costs estimates and to be a fair representation of direct costs estimates. These characteristics make these pathways different from many of the pathways published in the literature.

Within the emission envelope we distinguish three major types of pathways:

(1) the delayed response pathway following the upper boundary of the envelope as long as possible and so reducing emissions less in the short term;
(2) the early action pathways following the lower boundary as long as possible (RC), or only following the lower boundary for about 10–20 years (AC) and then starting to follow the upper boundary and
(3) the default pathways characterised as medium-term pathways (since they are neither early nor delayed), with the reductions spread out over time as much as possible, thereby avoiding rapid early reductions and rapidly changing reduction rates over time.

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The analysis of these emission pathways leads to the following conclusions:

- The emission envelopes show that a wide range of pathways can lead to the same concentration stabilisation target. However, the range decreases for the lower concentration targets. There is a limited space left for emissions for the 450 ppm target, going from early action to our default assumptions and finally delayed response. The envelopes for 450 and 550 ppm show that the emissions are required to peak before 2015 and 2025, and are followed by strong emission reductions. For 650 ppm, the emissions may even peak around 2030–2040. The envelopes of 450 and 550 ppm do not overlap after 2015, which imply that there are no pathways that initially follow 550 ppm (early action), and can turn into a 450 ppm pathway later on. The envelopes of 550 and 650 ppm show quite a bit of overlap, in particular up to 2030. After 2030, only the 650 ppm early action (RC) pathways can turn to the 550 ppm delayed pathways.
- The emission envelopes are dependent on the baseline emissions, in particular, the initial emissions and the baseline emissions of sources with limitations in the reduction potentials, in particular the land-use related sources of CO_2 and CH_4. For example, to reach 450 ppm stabilisation, the emission reductions compared to 1990 levels can be as high as 40–60% for the B1 baseline or as low as 25–45% for B2 in 2050.
- The costs of the envelopes show a wide range. The delayed pathways show lower costs in the short term, but in the long term these pathways are more expensive than the early action and default pathways, simply because the latter pathways benefit from induced technology development and an earlier signal of change to the energy system. The early action pathways gain even more from the earlier signal to the energy system. For example, the peak of the global costs as a % of GDP is the lowest for early action (AC) (0.8% of GDP for 550 ppm), followed by the default pathway (1.1%), the delayed and early action (RC) response pathways (1.3%). Comparing the NPV of abatement costs for the 550 ppm target and the B2 scenario shows that discount rates of about 4–5% or less would favour an early or default pathway; if economic arguments only are taken into account, rates in excess of about 4–5% would favour delayed response. For the 450 ppm target this threshold lies between 5 and 10%, and for 650 ppm for about 5%.
- The NPV of abatement costs for the default scenario increase from 0.2% of the NPV of GDP (5% discount rate) for 650 ppm and 0.5% for 550 ppm to 1.0% for 450 ppm. The costs themselves reach a peak of around 2% in the 2040–2070 period for the 450 ppm target, whereas for the 550 and 650 ppm targets this is only 1.1% and 0.4%, respectively.
- On the other hand, the chances of avoiding global mean warming of 2 °C and beyond are close to non-existent for 650 ppm (10%), very small for stabilisation at 550 ppm (26%) and roughly 50:50 for a peaking at 510 ppm and subsequent stabilisation around 450 ppm (54%). This assumes a climate sensitivity PDF that takes the conventional 1.5–4.5 °C uncertainty range as a 90% confidence interval of a lognormal distribution (Wigley and Raper, 2001). Thus, to achieve a certainty of at least 50% in reaching a 2 °C target, the CO_2-eq concentration needs to peak below 510 ppm in the 21st century.
- Reaching a 2° target with a higher probability would imply peaking at even lower concentration that 510 ppm CO_2-eq and/or reducing emissions after the peak concentration even faster in order to shorten the temperature overshoot period. For example, Meinshausen (2006) indicates chances for meeting 2° of up to 70–80% for CO_2-eq peaking levels of around 475 ppm. Here, we have not explored such profiles—but in literature some studies can be found that provide some insights on how scenarios may look like that aim for even lower targets (see e.g. Azar et al., 2006; van Vuuren et al., 2006a). Further research is needed on mitigation scenarios that meet a 2° target at higher probabilities.
- The analysis shows the post-2012 period up to 2030–2040 to be the most difficult phase of climate change policy, where the aim is to reach the lower and medium concentration levels (450 and 550 ppm), even assuming full participation of all countries under a climate regime, with rapidly increasing emission reduction rates and increasing abatement costs. It seems that emission pathways that focus on the 550 ppm target will soon lose the option of shifting towards stabilising at 450 ppm. Specifically, this could be as early as 2015, if the boundaries on maximum reduction rates assumed here are not exceeded. Hedging strategies may lead to relatively early action pathways focusing on 450 ppm, in order to leave as many options open as possible.

Appendix A. MAC curves

Different sets of MAC curves for different emission sources were used for the calculations and all updated conforming to our earlier study (den Elzen and Meinshausen, 2005, 2006).

The MAC curves of *energy- and industry-related CO_2 emissions* were determined with the energy model TIMER 2.0. This energy model calculates regional energy consumption, energy-efficiency improvements, fuel substitution, and the supply and trade of fossil fuels and renewable energy technologies, as well as carbon capture and storage. The TIMER MAC curves were established by imposing a carbon tax and recording the induced reduction of CO_2 emissions, taking into account technological developments, learning effects and system inertia. The carbon tax leads to use of zero or less carbon-intensive fuels and technologies and efficiency. As a result, CO_2 emissions will be decreased. As discussed in the introduction, the costs of climate policy

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may depend strongly on the timing. To capture some of the important dynamics here, two different tax profiles were used to explore the level of emission reduction in TIMER (in the 'response year'): one that assumes a linear increase in the carbon tax value of 2010 in the response year (linear tax) and one that reaches the maximum value 30 years earlier (block tax). The second profile results in more CO_2 reductions in the response year because the energy system has a longer time period to respond to the higher prices of carbon-intensive fuels. The two sets of time- and path-dependent response curves for various carbon tax levels are used in the FAIR model as MAC curves. A combination of the linear-tax and block-tax MAC curves is made, depending on the trajectory of the calculated actual carbon tax (international permit price) associated with the emission pathway. The responses recorded on the linear tax profile are used for a rapidly increasing tax, while the responses recorded on the block tax are used if the carbon tax follows a more constant tax level. To do this, the FAIR model looks back 30 years. It constructs a linear combination of the two types of response curves by comparing the tax profile in that period to the one assumed in the block or linear tax profile used in TIMER. In this way, it is possible to take into account (as a first-order approximation) the time pathway of earlier abatement, which is a new element compared to our earlier work. The method results in dynamics similar to those observed for the TIMER model itself, as described by van Vuuren et al. (2006a).

The MAC curves for *carbon plantations* were derived using the IMAGE 2.3 model (Strengers et al., 2006). In this model, the potential carbon sequestration of carbon plantations is estimated and compared, using a 0.5×0.5 grid, to the carbon sequestered by natural vegetation for land abandoned from agriculture. On the basis of grid cells that are potentially attractive for carbon plantations, carbon sequestration supply curves are established and converted into MAC curves by adding land and establishment costs. Besides these carbon credits from carbon plantations, the model also includes carbon credits from forest management based on a conservative, low estimate from our earlier study.

An extended set of data from the Energy Modelling Forum-21 project (EMF-21) (Weyant *et al.*, 2005) was used for the MAC curves for *non-CO_2 emission sources* (CH_4, N_2O and halocarbons). The original EMF-21 set, based on detailed abatement options, included abatement potential for a limited cost range of 0–200 US\$ tC-eq^{-1} up to 2020, and did not include technological improvements over time. Lucas et al. (2006) extended this set on the basis of a literature survey and expert judgements about long-term abatement potential and costs. The long-term potential is significantly higher than current potential as a result of the technology development process and the removal of implementation barriers.

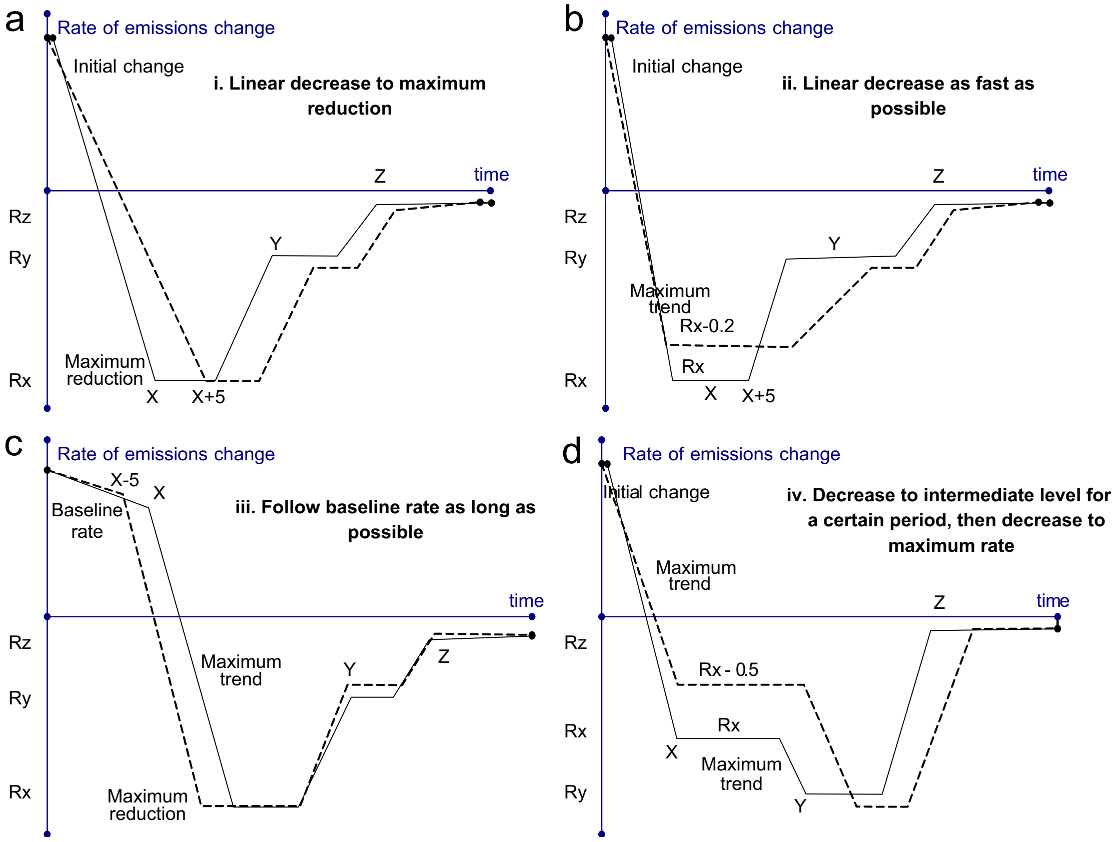

Fig. 12. The methodology for the development of emission envelopes; the four groups of emission pathways and their sketched reduction rates.

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Appendix B. Description of the emission envelopes calculation

The emission envelopes are calculated by systematically varying the parameters of the parameterised global CO_2-eq emission pathway, i.e., the yearly emission reductions (X_I, initial 2010 value, X_1,…, X_5) and years (t_1,…, t_5) at which the reduction rates change. Note that for each parameterised pathway we first calculated parameters X_1 and t_1 (assuming $X_2 = X_1$ and t_2) based on an iterative procedure to match the concentration with a concentration peaking profile, and secondly, we calculated the remaining parameters in the same way using the final concentration stabilisation profile (see den Elzen and Meinshausen, 2005).[19] The systematic procedure on the basis of four groups of emission pathways follows (see Fig. 12).

1. *Linear decrease to the maximum reduction rate at time t_1 (as early as possible)* stays at maximum level for at least 10 years (Fig. 12a). Repeat this for t_1+5, t_1+10 and so on. In this way, the first pathways are early action ones at the lower boundary of the envelope, but after many repetitions, the last pathways are delayed response pathways at the upper boundary.
2. *Decrease linearly as fast as possible to level X_1 (above maximum rate) at time t_1 (as early as possible)* stays at this level for at least 10 years (Fig. 12b). Repeat this for $X_1 + 0.2$, $X_1 + 0.4$ and so on. Similar to (i), we start with early action pathways and end with delayed response pathways.
3. *Follow the baseline rate as long as possible* (the concentration target can still be met) till time t_1, and then decrease as fast as possible to the maximum reduction rate (Fig. 12c). Repeat this for $X - 5$, $X - 10, \ldots, 2015$. Here we simulate from delayed response to early action pathways.
4. *Decrease first as fast as possible to time X_1 to intermediate level X_1* (between initial and maximum rate) for a certain period (defined by t_1 and t_2), and then decrease as fast as possible to the maximum reduction rate (Fig. 12d). Repeat this for variations in X_1, t_1 and t_2. The pathways belonging to group (iv) represent a large group of possible pathways (from early action to delayed response) in the envelope.

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[19] Note that the effective emission reduction rates will be different from the preset rates due to (a) smoothing of emissions pathways and (b) lower bounds for some reductions of gases, which affect lower emission pathways. These lower bounds can result if a certain baseline and target emission path is chosen, the emission gap of which is not fully covered by the chosen MAC curves. As well, the non-reducible fractions for N_2O and CH_4 emissions are fixed after 2100 (see footnote 8), which can lead to a gap in pre-set and effective reduction paths after 2100 for lower concentration pathways.

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