Policy options to respond to rapid climate change

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ABSTRACT

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Ongoing research on climate change indicates that we cannot rule out the possibility of extreme climatic changes, beyond current IPCC scenarios. The thinking about policy responses to address these risks is still in its infancy. This study explores the possibilities for responding to extreme climatic changes in an integrated, systematic fashion. It distinguishes four main categories of emergency response options: drastic emission reduction, carbon dioxide removal, solar radiation management and enhanced adaptation to unavoidable consequences. These options may also become relevant if natural or social systems would turn out to be more vulnerable than until recently assumed or if current mitigation efforts would be unsuccessful.

Keywords: extreme climate change, drastic emission reduction, mitigation, emergency response options, geoengineering, carbon dioxide removal, solar radiation management, enhanced adaptation, extreme climate policies

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Preface

This report has been commissioned by the Netherlands Environmental Assessment Agency (PBL) to the Wageningen University as part of a larger project 'News in Climate Change and exploring the boundaries'. This project is carried out by the PBL, Wageningen University and the KNMI (Royal Netherlands Meteorological Institute) at the request of the Dutch Minister for the Environment, Jacqueline Cramer. The overall project is led by Leo Meyer from the PBL. The authors acknowledge the constructive comments on earlier versions of this report from Fons Baede (ex-KNMI), Arie Bleijenberg (TNO), Mart Bles (CE Delft), Bram Bregman (KNMI), Heleen De Coninck (ECN), Paul Crutzen (Max Planck Institute for Chemistry), Marius Enthoven (ex-VROM), Eric Ferguson (ex-TNO), Wouter Kersten (Tilburg University), Jip Lenstra (ECN), Bert Metz (ex-PBL), Arthur Petersen (PBL), Alan Robock (University of Wisconsin), Sible Schöne (Klimaatbureau), Jeroen van der Sluijs (Utrecht University), Aad van Ulden (ex-KNMI), David Victor (Stanford University), Bastiaan Zoeteman (Tilburg University).

Summary

Ongoing research on climate change indicates that we cannot rule out the possibility of extreme climatic changes, beyond current IPCC scenarios. The thinking about policy responses to address these risks is still in its infancy. This study explores the possibilities for responding to extreme climatic changes in an integrated, systematic fashion. It does not address the likelihood of such extreme changes. The vast majority of available or proposed technologies or practices to respond to an accelerating climate change can be classified in four categories: drastic emission reductions, carbon dioxide removal, solar radiation management, and emergency adaptation. These options may also become relevant if natural or social systems would turn out to be more vulnerable than until recently assumed or if current mitigation efforts would be unsuccessful.. Drastic emission reduction options are well-known today, but involve controversial policies. As an additional measure, carbon dioxide can be removed from the atmosphere through natural and artificial methods. These methods vary in terms of effectiveness, energy and space demands, and environmental and societal risks. Solar radiation management options have a rapid effect once deployed, but research, development and international agreement about implementation may take some decades and involve potentially large risks. Emergency adaptation is the last resort and could include radical in addition to incremental options. Trade-offs exist between response options: if one option would not be successful, others with possibly other difficulties and risks may be required. Because of different time delays none of the emergency options can be fully effective within a few decades. Emergency climate policy could be developed in parallel to current climate policies and raises new governance questions and new ethical questions. To enhance their preparedness to extreme climate change, individual countries should consider broadening their portfolio of policy options. Much is yet unknown, and better understanding of the dynamics of tipping points and development of early warning systems and monitoring is needed, as well as research that further explores and expands the menu of emergency response options.

Samenvatting

Uit wetenschappelijk onderzoek blijkt dat de mogelijkheid niet kan worden uitgesloten dat het klimaat sneller verandert dan voorheen gedacht. Het denken over beleidsopties om met deze mogelijkheid om te gaan staat nog in de kinderschoenen. Deze studie onderzoekt de verschillende mogelijkheden op een geïntegreerde systematische wijze. Het rapport gaat niet in op de waarschijnlijkheid van extreme klimaatverandering. De meeste opties kunnen in vier categorieën worden ingedeeld: drastische emissiereducties, verwijdering van koolstofdioxide uit de atmosfeer, beïnvloeding van de stralingsbalans van de atmosfeer, en noodaanpassing. Mogelijkheden om broeikasgasemissies drastisch te beperken zijn bekend, maar maatschappelijke weerstand en technologische uitdagingen zullen moeten worden overwonnen om effect te sorteren. Natuurlijke of kunstmatige methoden om koolstof uit de atmosfeer te halen verschillen in haalbaarheid en wat betreft de benodigde energie en ruimte. Opties om de stralingsbalans te beïnvloeden kunnen snel effect sorteren, maar ontwikkeling van en internationale overeenstemming over de veelal controversiële opties zouden enige decennia kunnen kosten. Het opvoeren van de adaptatieinspanningen, waarbij wellicht ook meer radicale opties moeten worden meegenomen, is een laatste toevlucht als de andere opties niet afdoende zouden blijken te zijn. De noodmaatregelen kunnen ook relevant worden als ecologische en maatschappelijke systemen kwetsbaarder blijken dan tot voor kort verondersteld, of als het niet lukt de mondiale emissies voldoende en voldoende snel te beperken. Beleidsopties gericht op het omgaan met extreme klimaatverandering zou vooralsnog parallel aan de reguliere klimaatbeleidsontwikkeling kunnen worden onderzocht. Vaak roepen deze opties nieuwe ethische vragen op en vragen met betrekking tot de institutionele organisatie ervan. Individuele landen kunnen hun portfolio van mitigatie- en adaptatiemaatregelen geleidelijk uitbreiden om klaar te zijn voor een meer extreme klimaatverandering, mocht deze optreden. Om de mogelijkheden van knikpunten in het klimaatsysteem beter te begrijpen en vroegtijdig te kunnen herkennen is meer gericht onderzoek en monitoring nodig. Ook is verder onderzoek nodig naar de mogelijkheden en risico's van maatregelen die zouden kunnen worden ingezet bij een snelle klimaatverandering.

Background and context

- *Ongoing research on climate change indicates that we cannot rule out the possibility of extreme climatic changes, beyond current IPCC scenarios. Such extreme changes, both faster and graver in consequence, would require drastic policy measures.*
- *Four main categories of options are available to respond to extreme climate change and impacts: drastic emission reduction efforts, carbon dioxide removal (CDR), solar radiation management (SRM) and adaptation to the unavoidable consequences. These have hardly been explored in an integrated, systematic fashion yet.*
- *It would make sense to start exploring such options in a second, parallel track of policy development, specifically geared at responding to extreme climate change. Doing so would avoid a situation in which uninformed decisions could prevail and policy responses could be inadequate or even harmful.*
- *Emergency response options could also be appropriate if natural or social systems would turn out to be more vulnerable to climate change than until recently assumed, or if the currently debated mitigation policies would turn out to be ineffective.*

Background

Up to recently, the main climate policy questions related to the reality of the climate problem, the impacts of climate change on humans and the natural environment, the share of human activities in causing it, and possible initial responses. The IPCC has documented the increasingly convincing evidence of climatic change in a series of assessment reports. The IPCC has generally focused on what most scientists agreed about and on the remaining differences in views and scientific uncertainties. After the closing date for inclusion of new scientific information for the IPCC's Fourth Assessment Report (AR4) in 2006, several new publications hinted at the possibility that climate change and sea level rise may develop faster and to higher levels than was previously assessed in the AR4, while other publications suggested that the climate response might be weaker. For this report, we considered the consequences of the former possibility. If the climate would change less than projected by the IPCC, some may consider the mitigation efforts up to now to have been wasted, but others would stress these mitigation efforts benefit other areas, including energy safety, employment and environmental sustainability. Therefore, for this report, such a possibility has not been analysed.

Why is it important to consider climate change beyond the ranges assessed by the IPCC? From global to local levels, currently both mitigation and adaptation policies which are being developed and implemented to address climate change, usually take the ranges of projected future changes in temperature, precipitation and sea level rise from the Working Group I report (IPCC, 2007a) as a starting point. The attention often focuses on the general picture of these ranges, or selected climate scenarios within them, not specifically on the outer ends of these ranges.

There are many uncertainties with respect to temperature change, two key dimensions of which are reflected in the axes of Figure 1: the climate sensitivity[1]

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[1] Equilibrium climate sensitivity refers to the change in the global mean annual surface temperature following a doubling of the atmospheric equivalent carbon dioxide concentration.

and factors determining radiative forcing[2] (including natural and manmade emissions, and other forcing factors). If both the climate sensitivity and the factors determining radiative forcing turn out to be at the low end of the IPCC range or below it, there is no reason to change current policies when they also serve other purposes, otherwise policies might even be relaxed ('best case scenario', bottom left quadrant).

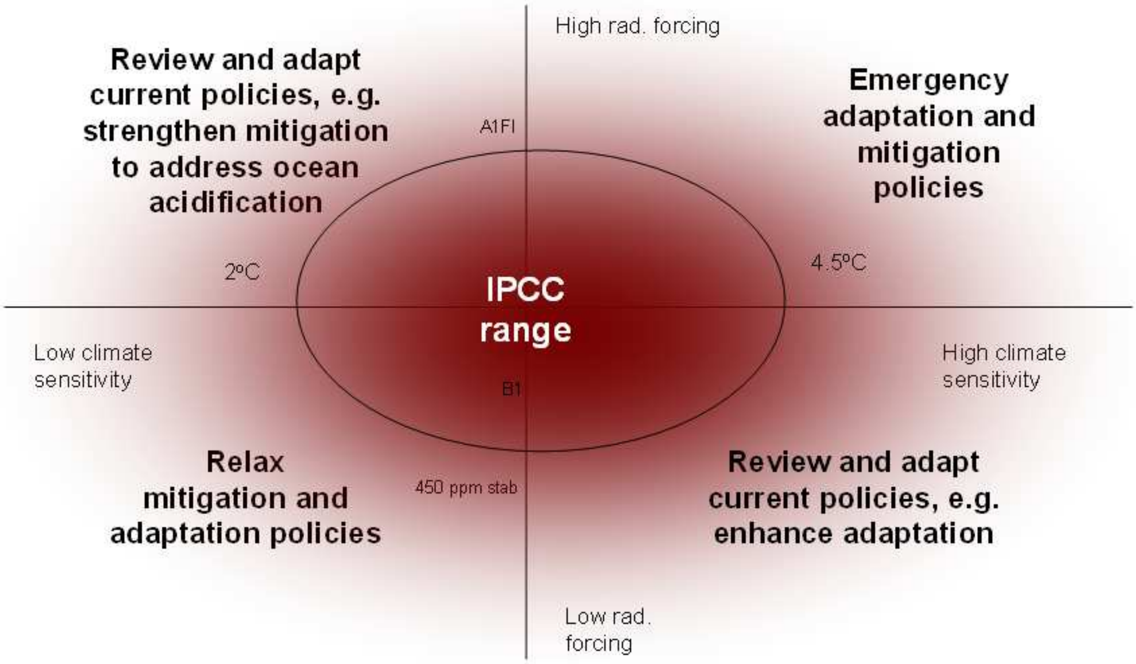

Figure 1. Climatic changes beyond the range covered by the IPCC (colored ellipse) demand different policies or revision of current policy

If the climate sensitivity would end up being at the low end of the IPCC estimates or below (hence relatively low temperature changes), but the forcing at the high end or above (e.g., relatively high CO_2 concentrations), there may be reasons to review and maybe adjust the menu of mitigation and adaptation options, for instance, strengthen policies aimed at reducing ocean acidification through decreasing carbon emissions (top left quadrant). In the opposite case, radiative forcing would be lower than projected, but climate sensitivity higher, and the mix of climate policies may be revised in favour of additional adaptation efforts (bottom right quadrant). For this report, the focus is on potential policy responses in the 'worst case' (top right quadrant), where both radiative forcing and climate sensitivity would turn out to be high. In this report, we considered scenarios at or beyond the boundaries of the IPCC AR4 projections as 'extreme' climate change. Where the rate of climate change associated with such extreme scenarios is important, we also used the term 'accelerating' or 'rapid' climate change. For this report, we explicitly have not assessed the likelihood of such a situation. Because of the large uncertainties and the impossibility of assigning probabilities to extreme climate change scenarios, worst case policies cannot be meaningfully addressed by a quantified risk approach (e.g., Kattenberg and Verver, 2009). However, to give a rough idea, Schneider

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[2] Radiative forcing is the change in the net, downward minus upward, irradiance (usually expressed in W/m2) at the tropopause due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the sun.

(2009) noted that IPCC (2007a) estimated that it is likely (66-99% probability assessed by the authors) that global mean temperature in the highest (A1FI) scenario would be between 2.5 and 6.4 °C by 2100, or would have a chance of 5 to 17% that it would be above 6.4 °C. Schneider also noted that the number and intensity of abrupt events and the possibility of irreversible damages increases non-linearly with warming, and that a 5 to 17% chance is well above the threshold, above which people usually take out insurance. In this context, it is also important to note that for a global mean temperature increase of 6.4 ºC, temperature changes will actually be higher in many regions. The likelihood of the A1FI scenario cannot be assessed, but Schneider noted that since the A1FI scenario was published about ten years ago, global emissions have increased more or less in line with this scenario, which, of course, is no guarantee that they will continue to do so.

In case the climate would change as in the top-right quadrant, the 'worst case scenario', the dynamics of the world's response will be very different from the current orderly – albeit not yet very effective - negotiations of the UNFCCC. The danger that may have to be faced might not involve the climate, but a break-down of the international order (Ferguson, personal communication). As will be discussed later in this report, nations may move from negotiation and collaboration to the pursuance of narrow self-interest with all political and maybe even military means at their disposal. On the positive side, the financial and economic crisis that started in 2008 illustrates that in times of crisis very rapid political steps appear to be feasible that would have been inconceivable just a few months before. We hope that such a breakdown of the global system will never occur as a result of climate change, but the report addresses options that could be considered IF climate change would indeed accelerate.

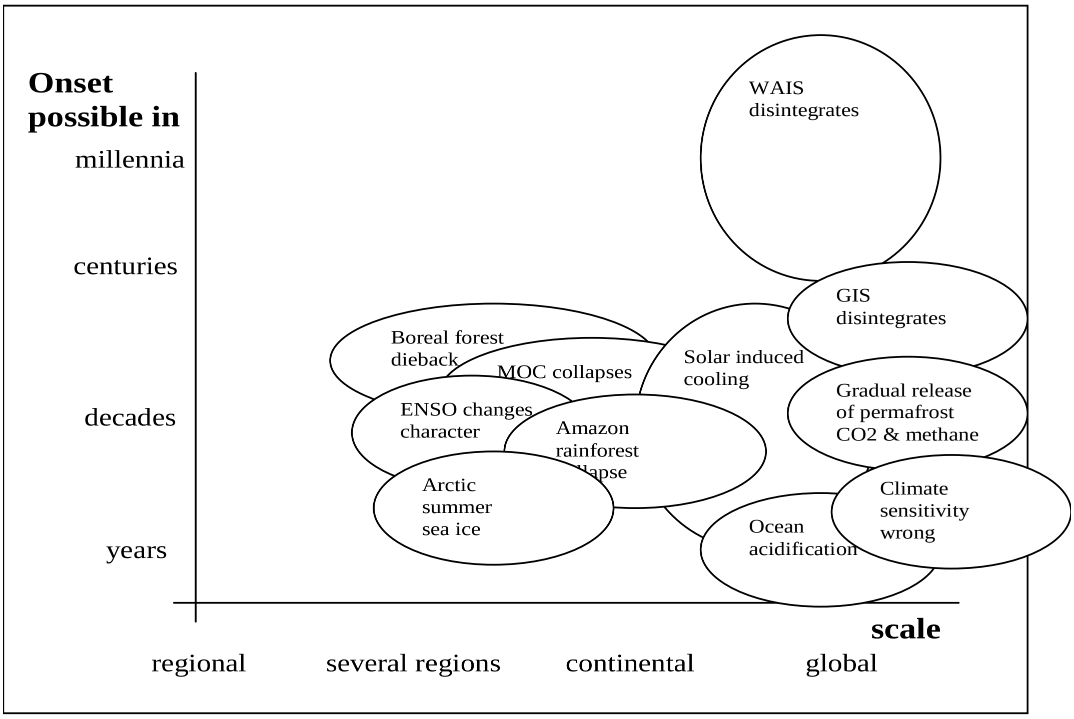

Figure 2. Various events may be triggered by increasing global warming with different spatial and temporal scales (source Kattenberg and Verver, 2009)[3]

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[3] WAIS = West Antarctic Ice Sheet; GIS = Greenland Ice Sheet; MOC = Meridional Overturning Circulation; ENSO = El Nino Southern Oscillation; 'climate sensitivity wrong' refers to the possibility, that the current estimates of this key factor (range between 2 to 4.5 oC) would turn out to be incorrect.

Kattenberg and Verver (2009) assessed which feedbacks and other factors in the climate-ocean-biosphere system could lead to such extreme, rapid climatic changes. They also assessed under which conditions such changes could take place, moving the world into the top right quadrant of Figure 1. They discussed various types of global and regional extreme climatic changes and tipping points that would lead to rapid and high sea level rise, temperature change, precipitation change, and possibly ecological diebacks. Different factors that would move the climate system into this quadrant have different spatial and temporal dimensions (see Figure 2). At present, knowledge is insufficient to determine in a quantitative fashion at which level of climate change particular tipping points may be passed, how they are interacting, and how serious or irreversible the results are. Aiming at stabilising climate change at the lowest possible levels would reduce the chance of thresholds being passed, and enhanced monitoring of indicators relevant for tipping points would increase our early warning capability.

Risk approaches

Does it make sense to account for the possibility of extreme and rapid climatic change in policy development, even if the uncertainties are very large? Because of the large potential impacts, the answer is yes. The risks of extreme, rapid climate change are real, even if they cannot be quantified, particularly because neither the probability nor the adaptive capacity of society can be meaningfully quantified. The resulting kind of uncertainty can be described as 'recognised ignorance': we know that climate change could accelerate, but we cannot predict how and when this might happen, nor how ecological and societal systems may respond. Figure 3 gives a subjective, qualitative assessment of likelihood and impacts, where the risk (a function of likelihood and potential impacts) increases from the bottom left to the top right of the graph.

The figure gives some rough, subjective idea about which events may represent larger risks than others, but in considering the level of the risks and how to deal with them, it should be noted that there are large differences in perception of uncertainty and risk between different stakeholders, and even between different scientists. For example, the formulation of the findings of the IPCC Working Groups reflects the very different risk perspectives of the scientific communities involved (see Box 1). And even if there would be agreement within the scientific community about the evidence, there would still be disagreement between different actors on how to act, because of different risk perspectives (Dessai and Van der Sluijs, 2007). While risks cannot be quantified, the factors determining them can be addressed: the potential impacts can be reduced and the adaptive capacity can be enhanced. For example, when considering adaptation options with high investment needs, it may be wiser to increase resilience or adaptive capacity which may be cheaper, and hence avoid investments that eventually may be unnecessary. Another option is 'anticipating design, for example, in the case of dykes, constructing a foundation that would also be adequate for larger dykes in the future, may those become necessary because of higher flood or sea levels (Dessai and Van der Sluijs, 2007). Such approaches are discussed more extensively further on in this report.

Text box 1: Different perspectives on risks, according to IPCC Working Groups

IPCC WG I projects global sea level rise to be in the range of 0.18 to 0.59 metres, between 2090 and 2099, relative to 1999 levels (IPCC, 2007a). According to WG II, 'there is medium confidence that at least partial deglaciation of the Greenland ice sheet, and possibly the West Antarctic ice sheet, would occur over a period of time ranging from centuries to millennia for a global average temperature increase of 1 to 4 °C (relative to 1990–2000), causing a contribution to sea level rise of 4 to 6 metres or more' (IPCC, 2007b). While these outcomes are consistent and based on the same data, the working groups convey very different messages (Webster, 2009). While WG I does discuss the option of larger and more rapid changes, for example, in the context of positive carbon cycle feedbacks or changes in ice flows; however, these changes were not included, because 'understanding of these effects is too limited to assess their likelihood or to provide a best estimate or an upper bound for sea level rise' (IPCC, 2007a). By contrast, taking a risk management perspective, for WG II the lack of understanding or agreement was no reason not to seriously highlight low-probability, high-impact effects of climate change, or impacts that may occur on longer timescales.

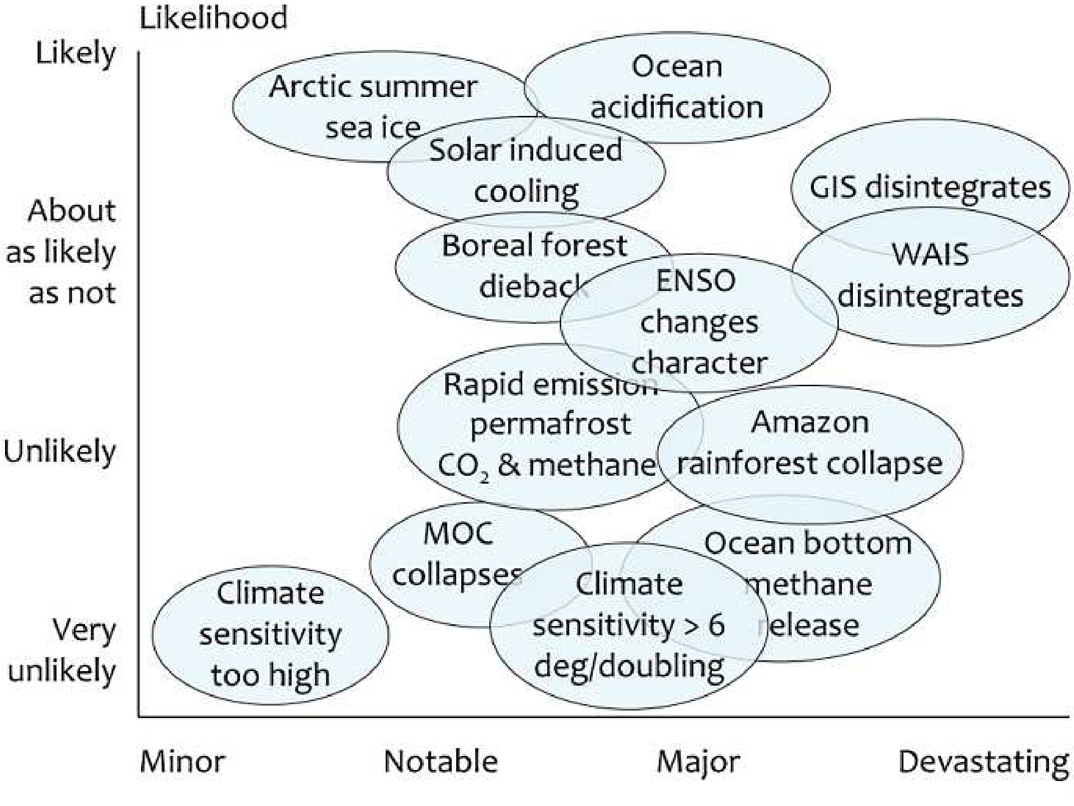

Figure 3. Probability and impact estimates for the 'high temperature' centennial timescale (i.e. 4 to 8 °C warming in 2200). The size and shape of the ovals are arbitrary and do NOT indicate uncertainties in impact and likelihood (Source: Kattenberg and Verver, 2009)

Objectives

The main objective of this study was *to identify appropriate policy options if new data or improved knowledge would provide growing evidence that the climate will probably change, according to the high end of the IPCC climate projections or beyond.* We note that the associated policy options would also be appropriate in two other situations. Firstly, they may become relevant if natural or social systems would turn out to be more vulnerable than until recently assumed, and impacts of climate change would materialise faster or would be much more serious than projected, even if the climate would not change faster than projected by the IPCC. Several authors have hinted at this possibility (Smith et al., 2007; Hansen et al., 2008; Leemans et al., 2009), which suggests that the EU climate goal of 2 °C may, in fact, entail larger risks than was foreseen at the time this goal was set. Secondly, the drastic policy options discussed in this report could also be taken into account if the current national and international (EU, UNFCCC) negotiations would turn out to be unsuccessful. For example, the Royal Society (2009) recently evaluated geoengineering[4] options – not in the context of extreme climate change, but in a context of the current mitigation policies possibly being unsuccessful (Brumfiel, 2009).

The UNFCCC and EU discussions have become very specialised and detailed on the basis of the knowledge embodied in the IPCC assessment reports. Moreover, the characteristics of a response to extreme or rapid climate change, beyond the IPCC projections, are likely to be different from the dynamics of the current policy debate which is based on the expectation of a gradual climate change. We, explicitly, did not limit policy option to present options for climate mitigation and adaptation, as these are generally incremental improvements on existing technologies and practices, but also include options requiring more fundamental system changes, and also currently controversial measures, such as geoengineering. Therefore, to not complicate the current climate policy negotiations, the options in this report could also be further explored in parallel, in the context of a separate climate emergency response strategy.

Methodology and scope

The above objective was addressed through literature review, expert brainstorming sessions and interactions with experts and policymakers, during a number of national and international meetings in 2009. In addition, drafts were reviewed by a national advisory group and by a number of additional national and international reviewers. The project benefited from interaction with the organisers of a meeting of a high-level political think tank on 'Preparing for a worst case climate change scenario'. This think tank was invited by the Dutch Government, in the early summer of 2009, to review the potential implications of rapid climate change (background document: Zoeteman and Kersten, 2009). The present report includes a critical inventory of the most important options for setting policy and research agendas. A full, comprehensive analysis, such as one including modelling analyses, was beyond the scope and resources of this report. We focused on the options themselves, rather than on potential policy instruments for their implication. Much of the literature on extreme climatic changes and how to respond to them has a time horizon of a century or more, but if and when observations would

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[4] There are various definitions of geoengineering. The IPCC defines it in a climate context as 'technological efforts to stabilise the climate system by direct intervention in the energy balance of the Earth for reducing global warming'. In this report, we also included technological carbon sequestration options, such as air capture and ocean fertilisation. However, following the main literature, we did not include large-scale carbon sequestration in forests or managed ecosystems in the term, unlike the Royal Society (2009), which also includes afforestation.

confirm that climate change is really accelerating, policymakers would need to respond within years rather than decades. Therefore, it is useful to start thinking about the possibilities well in advance, and this report provides an overview of the options to support this thinking process.

Responding to extreme or rapid climate change is usually framed in the context of geoengineering options (see, for instance, Boyd (2008), Schneider (2008) and the Royal Society (2009)). These studies however did not compare these options with others, but merely stated that geoengineering should be considered as a last resort, when greenhouse gas emission reductions would not suffice. In a modelling experiment, Wigley (2006) addressed the relationship between solar radiation management through sulphur injections in the stratosphere and global mitigation requirements. However, he did not evaluate the options other than by considering their radiative effects, nor did he elaborate on the policy consequences. The Royal Society (2009) assessed the current state of knowledge about solar radiation management and carbon dioxide removal, and has recommended policymakers to consider the appropriate balance between the relative contributions of mitigation, adaptation, and both carbon dioxide removal and solar radiation management. Our report supports the evaluation of such an appropriate balance by systematically evaluating a wide range of options.

Different categories of climate emergency response options

For the purpose of this report, we have structured possible emergency response options into the four categories below. In practice, possibly all of them, or combinations between some of them, would be needed, and some yet unproven options beyond these four have been suggested.

a) Drastic emission reduction;
b) Removing greenhouse gases from the atmosphere;
c) Influencing the radiative balance of the earth ('solar radiation management' or SRM);
d) Enhanced adaptation.

In Chapter 2, a summary of these options is provided. In Appendices A to C of this report, fact sheets provide more detailed descriptions. Figure 4 shows the relationship between these four sets of options and the factors causing rapid climate change described in Kattenberg and Verver (2009). The potential of deep greenhouse gas emission cuts (a) has been the subject of a huge body of literature. We have not reviewed this literature in any detail, but instead focused on options that can be associated with an emergency situation, when criteria such as economic feasibility are valued differently. In such a situation, options that would imply premature replacement of capital investments, or that would be politically unacceptable in the curre nt situation, may become realistic options. Options (b) and (c) are often referred to as geoengineering. With the exception of carbon sequestration in forestry or other land-use options, which we excluded from the definition of geoengineering, in this report. These have not yet been considered in any serious way in the formal deliberations about national and international climate policy. However, geoengineering options already have been extensively discussed in the scientific and technical literature, for a very long time, for example, in the context of weather modification. We have dealt with adaptation (d) in a way similar to drastic mitigation, and have not focused on adaptation options that are currently included in climate response programmes, but rather on those options that currently are considered to be premature or too expensive.

For all categories, different grades were considered: higher cost options in the current menu of options that can probably be introduced through regular economic, regulatory or voluntary policy instruments, options that require more serious political enforcement against societal resistance, and options that are not yet on the menu, such as geoengineering. Here should be taken into account that, because of the often speculative nature of many of the emergency response options, reliable and comparable information about costs is, as yet, mostly unavailable. At the same time, there are likely to be conflicting views on the priority options: on the one hand, these should primarily be effective as quickly as possible, while on the other hand, options which imply a more fundamental transformation of our production and consumption patterns and associated energy system may carry less risks and have a longer-term effect.

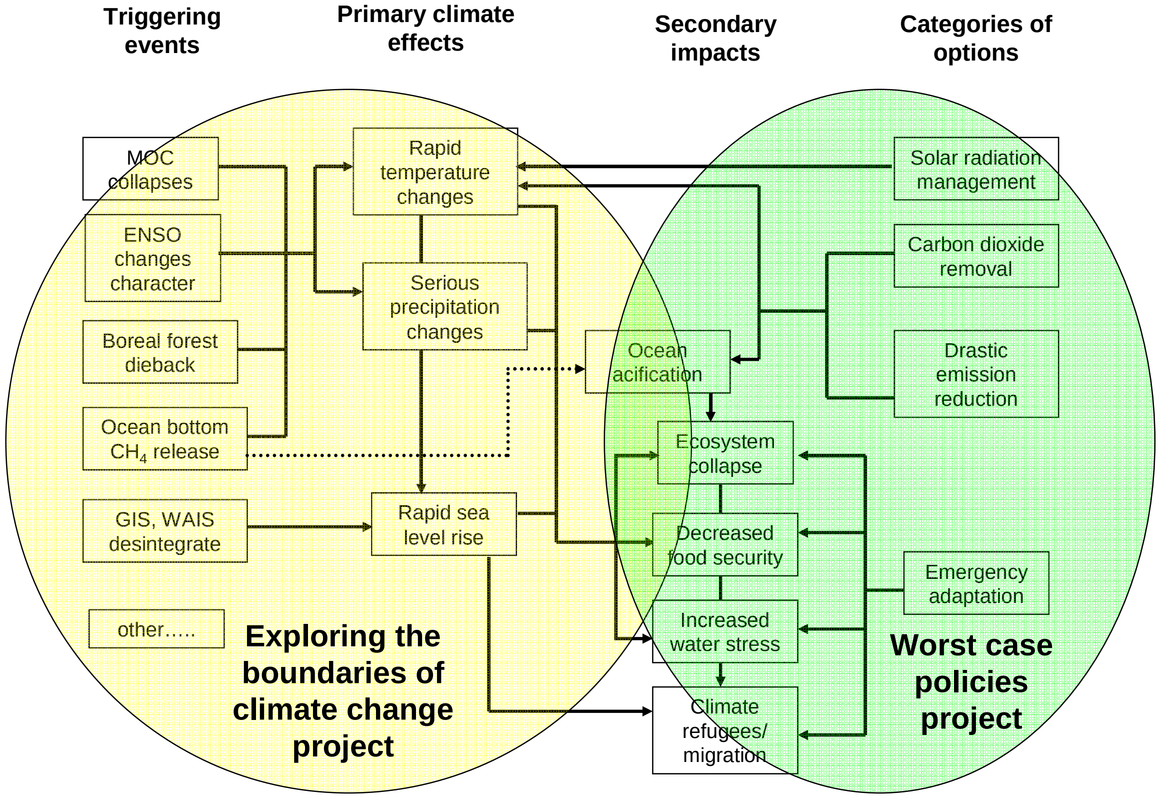

Figure 4. Relationship between different factors with the potential of inducing rapid climate change and emergency response options; and their coverage in the present 'Worst case policies' report and an accompanying 'Beyond the boundaries' report (Kattenberg and Verver, 2009)

Criteria for evaluation of options

In order to evaluate the various options, we distinguished four criteria: effectiveness, feasibility, environmental risks, and political implications[5]. In the fact sheets of Appendices A to C, all options are described taking these four criteria into account.

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[5] An assessment of geoengineering options, performed by the Royal Society (2009), coincided with the writing of our report. The Society used four quite similar, overlapping, but more limited technical criteria: effectiveness, timeliness, safety, and costs. We included 'timeliness' under 'effectiveness' assuming that options are not effective if untimely, and 'costs' under 'technical, economic and social feasibility'. In addition, we paid attention to political and governance criteria, which the Royal Society also discussed in some detail, but did not include in its criteria.

- *Effectiveness.* There are various factors that determine the effectiveness of the options. For drastic emission reductions, removal of greenhouse gases from the atmosphere and solar radiation management, the effectiveness is determined by the degree to which human-induced climate change is counteracted. This effectiveness is determined by how fast the option can be implemented in practice, at which scale it can be deployed, how quickly the climate system responds to the measure, for how long it should be maintained, and what the net effect on the greenhouse gas balance is - some options require a large amount of energy which may be produced through fossil sources, requiring additional mitigation. For enhanced adaptation, the effectiveness is determined by the extent to which the impacts of the rapid climate change are avoided or addressed.

- *Feasibility.* The feasibility of an option has technical, economic and social components. The *technical* feasibility is dependent on the level of development. For example, the option can be a creative idea, it can be based on established theory, possibly it has already been analysed with models, prototypes may have been developed or tests could have been performed. Often, some idea exists about the remaining technical challenges. The *economic* feasibility is determined by the costs of implementing the option (development, investment, maintenance), and the costs or benefits of side effects and spillovers. The *social* feasibility is assumed to be related to two factors: societal acceptance and behavioural barriers. In a situation of accelerating climate change societal acceptability of currently controversial options may increase, but some lack of acceptance is likely to continue to play a role. There may be large differences between different regions and social groups, as the example of nuclear energy illustrates, and it is likely that societal acceptance will change over time, as a possible climate emergency situation would unfold. While for many of the options in this report there has not yet been any public debate, for evaluating those options some subjective judgment is required. In general, options can be easier and thus faster implemented if less behavioural change is required. Feasibility is not a constant factor, it depends on the political priority of the issues at stake: in an emergency situation options can become ‘feasible’ while in a situation of gradual climate change they are not.

- *Environmental risks and co-benefits.* This criterion relates to the risks or co-benefits for natural systems. These can include direct or indirect climate effects other than radiative forcing, such as known and unpredictable regional climate impacts; changes in greenhouse gas concentrations; and other positive or negative environmental or ecological side-effects, such as air pollution, ecosystem or agricultural impacts, and resource depletion. Under this criterion, we also consider the level to which an option may lead to irreversible effects and if a rebound effect could occur. For example, if particular options (such as those influencing the atmospheric radiative balance) would be discontinued, climate change would be unmasked and even accelerate further.

- *Political implications.* Depending on the type of option, international agreement and control may be required during its development and implementation, or governance requirements and responsibilities may be limited to the local or national level. It may be an advantage if effective options do not require international coordination, unless there are risks involved extending to countries beyond those taking action. Some options may be vulnerable to aggressive action, or conversely could be applied to inflict intentional harm. A generic concern is that many of the options, if regarded attractive by some actors, could possibly ease the urgency of mitigation. Ideally, under this criterion, requirements for effective policy instruments would also be included, but current knowledge about the effectiveness of specific policy instruments in a climate emergency situation is insufficient to distinguish between the options.

We did not assess the various options with the intention to select the best one. In an aggravating emergency situation it is likely that a combination of different options would be appropriate. The preferred menu of options could change, over time, as on the one hand, further Research,Development and Demonstration (RD&D) may make options more effective or cheaper, while on the other hand, they may ultimately be ineffective, have unexpected undesirable side-effects, or eventually become unnecessary. In addition, the development of a portfolio of response options and preferences for different options will also depend on risk perspectives and perceptions, which could also change over time. We also recognised that the criteria are not independent. Effectiveness, for instance, or real or perceived environmental risks can affect feasibility. In the next chapter, the main characteristics of the four options have been summarised, while details are elaborated in the appendices of this report, structured according to the four criteria. Because the main objective of this report is to address policy implications of rapid climate change, Chapter 3 highlights governance and ethical questions. These are particularly important for policy development, but are often overshadowed by a focus on the technical and economic characteristics of response options, which are described in more detail in Appendices A to C of this report. In the fourth and final chapter, the information is synthesised in support of a number of possible ways forward for Dutch and international policy.

Four categories of options to respond to extreme climate change

- ***Drastic emission reduction** options are well-known today, but may call for policy measures that are neither voluntary nor kind. They often imply fundamental system changes, profound innovations and lifestyle changes rather than incremental improvements in current consumption and production patterns, slowing their introduction and increasing the appeal of other emergency response options. Reduction of emissions of short-lived substances and behavioural changes may be the fastest option. Additional options would be required to reach a low-carbon economy, but these would require more time. These could include accelerated introduction of carbon capture and storage (CCS) and nuclear and renewable energy.*
- ***Carbon dioxide removal** (CDR) can be realised in terrestrial and marine ecosystems (e.g., by changes in land use and forestry, enhanced oceanic carbon uptake, or aquatic sequestration via algae), or by artificial methods (e.g., 'air capture', enhanced mineral weathering). Particularly, marine sequestration can have known and unknown ecosystem effects, and its permanency still needs to be unambiguously demonstrated. Artificial methods have as yet unattractive energy and economic characteristics.*
- ***Solar radiation management** (SLR) can provide immediate emergency cooling, but entails often unknown consequences. The risks of stratospheric aerosol injections and space reflectors are larger and raise even more ethical questions than those of cloud seeding and terrestrial albedo modifications. Solar radiation management does not prevent ocean acidification. Its deployment, if ever, should be seen as a temporary measure, until greenhouse gas concentrations are stabilised through mitigation.*
- ***Emergency adaptation** would be required If the types of options above would not work. Adaptation options beyond those considered today are possible but can have major social, economic and environmental implications, and there are limits to adaptation.*

Basically, there are four categories of emergency response options: reduce emissions, remove greenhouse gases from the atmosphere, directly influence the radiative balance of the atmosphere, or adapt to the (remaining) consequences. In this chapter, the most important options have been summarised under the four categories. Chapter 4 presents an evaluation of these options in more detail against the other options, taking into account the various criteria. In Appendices A to C of this report more detailed fact sheets are included for the first three categories of options, including a comprehensive reference list. Detailed assessment of 'drastic' adaptation options was beyond the scope and resources of this report. The four categories addressed are not exhaustive and new types of ideas emerge on a regular basis, such as facilitating excess heat flows from the bottom layers of the atmosphere to the stratosphere through giant chimney-like constructions (Runneboom and Feller, 2008). Initiatives, such as Richard Branson's Earth Challenge Prize, may generate new solutions. In the limited time frame of this project, we focused on those options for which we identified substantive discussions in the scientific literature.

A. Drastic emission reduction

When climate change impacts are stronger or occur faster than expected, bringing ongoing GHG emissions to a minimum would be a first priority. Currently, most economic activities contribute (in)directly to GHG emissions. Moving to a low-carbon economy has proven to take time and resources. However, options that provide deep emission reductions are known and available in all sectors, albeit at high costs. Some options involve stepping up current efforts, while others are more drastic and could potentially be disruptive. In the mind set of policymakers and experts alike, the preference is to look at stretching existing efforts to a maximum, rather than looking beyond the usual toolbox of options. Drastic and effective policies can be unpopular, as they may lower comfort, push privacy boundaries and personal freedoms, or be difficult to monitor and implement. This section explores such options for drastic emission reductions.

The current ambition for GHG reduction in the Netherlands, codified in the 'Clean and Efficient' white paper (EZ, 2007), is to reduce GHG emissions by 30%, relative to 1990 levels, by 2020. A 30% emission reduction is already seen as quite ambitious. So the question arises what 'drastic' emission reductions would mean in the context of the Dutch national policy landscape. For this report, we considered a case in which the often mentioned 80% reduction required by 2050 (IPCC, 2007c) would need to be achieved by 2020. Furthermore, we assumed that all reductions would have to take place nationally and that national targets were the result of an internationally agreed effort to strongly mitigate emissions.

The descriptions below present emission reduction options per sector. After the technical options, policy instruments are discussed with a distinction between extending current practice and implementing more drastic policy strategies.

Power supply
The supply of power is currently responsible for around 25% of global GHG emissions[6] (WRI, 2008). To drastically reduce the emissions from energy supply, there are two general approaches: switch to low-carbon energy sources or use carbon capture and storage (CCS) to prevent emissions from entering the atmosphere. Low-carbon energy supply can be achieved by using renewable energy sources or fission of nuclear material.

- Many countries are currently moving to modest levels of renewable energy (i.e. tens of percentage points). At present, there is no mix of renewable energy sources available to replace the entire fossil-based energy system. With sufficient innovation and technological progress, however, it is expected that renewable energy can eventually completely replace traditional fossil fuel. Short-term barriers include costs, intermittency and the associated requirements of the transmission network.
- Nuclear energy is readily available as a low-carbon alternative to fossil-fuelled base-load generation. Short-term barriers include high capital intensity and significant lead times of up to a decade, until a new power plant is built, making it less suitable for rapid drastic mitigation. Nuclear energy has several serious disadvantages compared to renewable energy, in the long term, including unavoidable proliferation risks and nuclear waste. Nuclear fusion is not an available technology.
- Power generation from fossil fuels without releasing the emissions into the atmosphere can be achieved by using carbon capture and storage (CCS). Combined with bio-energy, it even offers the potential for negative-emission

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[6] Note that there is a potential overlap between sectors and end uses. Emissions from energy supply should not be attributed to use in industry or buildings.

power production. While having a potential contribution to reducing emissions, CCS is not considered off-the-shelf technology, and numerous barriers, including costs, public perception and geological storage potential, exist before the option can be implemented.

Current efforts to reduce emissions from energy production are mostly based on government procurement, regulation and financial incentive schemes. Policies can be extended considerably, using sufficient means, possibly moving to a situation where well over 50% of the power supply is based on renewable sources. Most serious low-carbon futures however, involve complete decarbonisation of the energy sector.

Drastic measures on the energy supply side include very strict emission regulation, mandatory renewable energy shares for consumer and industrial supply (progressive shares), mandatory CCS for new power plants, and complete government-induced rethinking of the energy infrastructure to accommodate renewable energy. In a situation in which emission reductions greater than 80% need to be realised in the power sector by 2020, decommissioning existing capital stock (e.g. coal and gas fired plants) and obliging CCS with biomass seem inevitable.

Transport
With over 14% of global GHG emissions, transport is notoriously difficult to address, policy-wise, because of the number and diversity of actors involved and the relation with 'personal freedom' of mobility. The technical potential in the medium term is substantial, especially for private transport: when electric or hydrogen cars are introduced on a large scale, technically this can result in 50 to 90% emission reduction, provided it is supplied from low-carbon power production.

Reducing the carbon intensity for road transport per kilometre, however, would require large infrastructural adjustments outside the (time) scope of a drastic mitigation scenario. Relatively mild carbon standards for new vehicles are already considered and in some countries implemented. However, considering options beyond decreasing emissions per unit of vehicle-kilometre travelled, would be needed. Options that affect overall mobility and behaviour may offer more rapid solutions.

Introducing the infrastructure needed for large-scale use of electric vehicles is relatively easy, but implementation will put heavy pressure on the power grid (especially in peak hours). A significant increase in public transport availability will require large investments and inevitably involves inertia, due to urban planning constraints.

Drastic mitigation options for air transport may include banning air freight and severely limiting personal air travel. Long-distance freight transport can be obligatorily shifted to rail and water, leaving road transport only for short-distance connection. Policy measures for air and sea transport are effective mainly if agreed internationally, while road and rail transport policies can be national. Personal transport can be limited by extremely progressive ('explosive') fuel taxes, prohibiting personal ownership of cars with internal combustion engines and impose aggressive parking policies. Each of these transport-related options is likely to affect economic growth and (perceived) personal freedom.

Buildings and appliances

Emissions from the building sector represent 17% of total global GHG emissions (including power use in buildings) and represent both building-related and non-building-related emissions. Emissions in the first category stem from construction and provision of heating, cooling, ventilation and hot tap water. Non-building-related emissions are mainly associated with the use of electrical appliances. Technical options to reduce emissions from the building sector include better insulation, application of renewable energy options for water and space heating, and more efficient appliances.

Current policies are mostly targeted at providing standards, information and financial incentives for *new* residential and commercial buildings. Regulation enforcing energy efficiency will often be economically attractive and is not expected to cause major implementation difficulties. *Existing* buildings are more difficult to address effectively by policy, given the long lifetime of existing buildings, high cost of replacement, social barriers and, in some jurisdictions, legal restrictions on changing regulation on existing property. Significant improvements in efficiency of electrical appliances do not require extreme measures, but could be achieved by internationally coordinated regulation: stringent appliance standards could be implemented within the course of five years, effectively banning all energy-intensive consumer goods from the shelves (although not from people's living rooms!). Drastic measures will be needed to improve energy efficiency of existing buildings: mandatory energy scans and associated sanctions, either financial incentives for changing old appliances for newer, more efficient ones, or obligatory refurbishing of housing. Buildings represent a major capital stock in any society – rebuilding to new standards will require substantial resources.

Industry

Excluding power production, industrial activity contributes roughly 25% to global greenhouse gas emissions. Although very diverse by nature, industrial emissions are largely related to energy use (85%). Sectors with the highest emissions include production of iron and steel, paper and pulp, cement, and chemicals. Each of these sub-sectors has specific opportunities for process optimisation and integration, but some efforts are valid in all sectors: the use of efficient motors, heaters and the like, and overall procedure enhancement and insulation.

Current policy measures, such as strong economic incentives and strict regulation, are expected to be very effective and industry is expected to respond fast and straightforward. International coordination is important, as many industrial sectors are especially vulnerable to competition issues (putting companies out of business may prove counterproductive). Common cap-and-trade policies are likely to be inadequate, as these are aimed at slow transition towards lower emissions through own investments and long-term carbon price.

Drastic measures in industry should necessarily be taken in an international context, to prevent the production from shifting towards regions with less strict regulation – with no net effect on emissions. Most realistic yet drastic short-term measures for industry are very tight (energy/material) efficiency standards, both for new and existing installations. This can go as far as prohibiting certain base materials and promoting bio-feedstock. In the short term, tight regulation concerning (excessive) packaging of goods can be implemented without problems.

Agriculture, Forestry and Land-use change (AFOLU)

AFOLU is the single largest contributor to greenhouse gas emissions, with 30% of global GHG emissions. Consequently, the technical abatement potential is large, particularly in non-OECD countries. Land-use change from forest to agriculture (CO_2), fertiliser application (N_2O), and cattle and rice production (CH_4), are the main sources of emissions and the human diet is a dominant factor. Some unsustainable practices in biofuel production, such as the clearing for ethanol production from sugar cane in Brazil, also contribute substantially to the increase of GHG emissions.

Strict bans on deforestation, implementation of large-scale afforestation programmes, and forest and peat land management programmes could harness a large part of the potential against relatively low cost (see also the section on carbon dioxide removal below). Important characteristics are the high number of relevant actors, sovereignty issues, and the dispersion of emission sources, which make designing and implementing mitigation policies a large challenge.

Drastic mitigation is possible, in principle, but in addition to financial and technical promotion, institutional capacity in areas vulnerable to change is paramount, and it is questionable whether this can be addressed in the short term. Influencing dietary choices involves efforts to enhance social acceptance contrary to the prevailing association in many cultures between increased consumption of meat and diary and increasing wealth. Dietary choices may need to be regulated higher up in the food chain, such as through production standards.

Short-lived gases, methane and black carbon (soot)[7]

Several non-CO_2 GHGs and soot account for over one-third of current anthropogenic radiative forcing (IPCC, 2007a). This includes several substances with much shorter atmospheric lifetimes than the long-lived CO_2: methane, tropospheric ozone, black carbon and several F gases all have lifetimes from several years up to several decades. In various world regions efforts are already underway to reduce emissions of several of these substances or their precursors to reduce air pollution. An extensive menu of end-of-pipe technologies is available, providing opportunities for drastic mitigation that do not involve rapid retirement of industrial capital stock or lifestyle changes. Soot emissions from industry, power production and transport can be abated effectively by end-of-pipe technologies such as filters. However, several of the available options do not only abate soot, but also other aerosols and their precursors (nitrates, sulphates) that have a cooling effect.

In addition, forest management to reduce fires could also greatly reduce soot emissions, although soot from open biomass burning is difficult to abate. Rapid phase-out of CFCs controlled by the Montreal Protocol, or bans on substances, such as the refrigerants HCFC-22 and HFC-134a and foam blower HFC-152a, could be introduced. Methane emission reductions in addition to those mentioned under AFOLU include those from the energy sector and from landfills.

Implementing the options: time delays and policy instruments in emergency circumstances

Most of the above options have in common that under normal circumstances they will take time to change because of inertia in existing production and consumption systems, notably energy supply systems. During this implementation period, CO_2 and other

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[7] Ozone, possibly the third most important contributor to radiative forcing, is formed in complex chemical interactions involving carbon monoxide, NOx and volatile organic compounds.

GHGs will continue to be emitted into the atmosphere (and remain there for decades to centuries and more). Three non-exclusive exceptions that will not contribute to the GHG build-up are (a) demand reduction, (b) mandatory emission reductions of short-lived substances with direct or indirect radiative effects, and (c) application of CCS.

All three options allow for continued reliance on fossil fuels, and can be implemented quickly and independent of an overall transition. CCS requires underground storage, which has some unresolved uncertainties. Reducing energy demand would involve behavioural changes – effectiveness and speed depend on enforcement options available in a climate emergency situation.

Can we speed up the implementation of (drastic) emission reductions? According to the IPCC, there is sufficient potential to reduce global GHG emissions below current levels in the coming decades at moderate costs, while in the longer term, costs to stabilise concentrations between 445 and 710 ppm CO_2 eq are estimated to be between a 3% decrease in GDP and a small increase compared to the baseline (IPCC, 2007c). Mobilising this potential from a scientific assessment and turning it into effective policy is clearly a non-trivial matter. A case in point is the apparent negative costs associated with many energy efficiency options which are not implemented because of various non-economic barriers.

In order to realise the projected potential, a policy framework is needed that addresses this type of non-economic barriers. Some relevant policy approaches that may be considered are:

- *Scale up current policy.* The first step could be to push current policy to the extremes. For example, increase feed-in support and preferential access to renewable energy, tighten the European Union Emission Trading System (EU ETS) caps, and strictly enforce all energy standards.
- *Government coordination of energy and industry.* On the supply side of the economy, governments could reverse privatisation and resort to coordination and control over energy and industry infrastructure and operation, just as governments increased control over the banking sector during the recent financial crisis.
- *Government interference with energy demand.* Some policy measures are effective, but rather uncomfortable as they limit freedom and consumer choice, and interfere with individuals' privacy. Examples are personal travel and transport budgets, obliging households and industry to use certain appliances (or discard others), limiting hot water use and space heating or cooling, and imposing dietary restrictions.
- *Overarching cross-sectoral coordination.* The national and international climate policies have been developed in a piecemeal sector-by-sector approach focusing on improvements of individual technologies. This prevents a serious discussion on transitions at a systems level, not limited by national boundaries (e.g. mobility rather than car efficiency, food security rather than crop yields).

B. Removing greenhouse gases from the atmosphere

This category of options not only allows for removing those GHGs from the atmosphere of which future emissions are impossible to avoid, but also for removing GHGs which have been emitted in the past. Dependent on the type of option and the scale at which it is applied, these options can limit GHG concentrations complementary to emission reductions. They can have significant space and energy requirements, but generally do not require changes in production and consumption patterns. Although some biological options (such as algae) could also remove GHGs other than CO_2 from the atmosphere, we focused on carbon dioxide removal, CO_2 being by far the most important gas in this context. There are various possibilities, some of which have already been applied or tested on various scales, while others still have to be developed further before they can be deployed. Some options (such as sequestering carbon in a way that allows it to be used as biofuel, or storing it through CCS techniques) can be combined with drastic emission reductions, but have been placed in this category.

Land use and forestry

Options to sequester carbon through terrestrial ecosystems have been analysed extensively in the scientific literature and discussed politically for a long time. Indeed, carbon sequestration through land-use change and forestry is included at present in national and international climate mitigation schemes. It can have many positive side-effects, but can also have risks, for example, for biodiversity and local livelihoods in case of large-scale plantation forestry. In a situation of accelerating climate change, carbon sequestration should be maximised, for instance, by large-scale afforestation programmes, not in the least because of synergies between mitigation, adaptation and other sustainable development objectives. A novel idea beyond the options usually considered today is the afforestation of the world's deserts using desalinated water for irrigation. In theory, the potential of this option is limited to the available land, but if grown biomass is used for fuel and the emitted carbon stored, the benefits would be continuous. Using biomass as fuel has been placed in the section on drastic emission reduction.

Aquatic carbon sequestration (algae)

CO_2 (and other GHGs) can also be drawn from the atmosphere through sequestration by algae in open aquatic systems or, more effectively, bio-reactors. The algae can be used as bio-energy, replacing other (fossil) fuels. Controlled systems are more efficient than unmanaged systems. Using flue gases from power plants or other large point sources rather than air would increase the sequestration effectiveness (see section on drastic emission reductions). Existing small commercial units for algae production produce only limited quantities of high value products and, hence, the volume of CO_2 that they sequester is not of great importance; none of current pilot projects for biofuel production is at a commercial scale yet, but upgrading could produce large volumes of algae and would, therefore, have a more significant carbon sequestration potential. In this area, there are many technical challenges to address.

Enhanced ocean sequestration

This option mostly refers to the enhancement of the 'biological pump' which draws down carbon sequestered in biomass from the top to deeper layers of the oceans, or of the 'solubility pump', transferring and redistributing inorganic carbon into the ocean. The most studied option is adding nutrients to stimulate primary productivity. These can be macronutrients, such as nitrogen or phosphorus, or micronutrients, such as iron, facilitating more efficient usage of existing macronutrients. Tests with iron fertilisation have been implemented, but the potential to influence CO_2 concentrations effectively for a long time remains very uncertain. Other possible ways to enhance ocean carbon uptake are to bring up nutrient-rich deep water, for example, by using pipes, or kinetic wave energy, or by enhancing oceanic uptake of CO_2 by adding alkaline substances, such as limestone, but their feasibility still has to be proven. Because of the unknown risks, an international moratorium has been agreed until 'scientists better understand the potential risks and benefits of manipulating the oceanic food chain' (Tollefson, 2008). Shell has recently revived the exploration of a separate chemical option to increase alkalinity of the ocean and subsequent carbon uptake through liming of the ocean.

Biochar
Biochar is a black carbon, produced by pyrolysis of biomass, allowing for carbon sequestration and long-term storage. It can be produced from wood, or from waste, which otherwise would release carbon dioxide. It is claimed to have additional positive environmental and economical effects, because it is a by-product from energy production and can be used as soil additive to improve soil quality and fertility. Co-production of biochar and energy involves a conflict of maximising them, simultaneously. Control of toxic substances, which are produced during pyrolysis, is required, dependent on the combination of feedstock and production conditions.

Air capture
Proposed artificial air capture systems remove CO_2 from the air and deliver a pure CO_2 stream for sequestration and disposal. These schemes all use some 'sorbent' material (mostly a sodium hydroxide (NaOH) or calcium hydroxide ($Ca(OH)_2$) solution) which reacts with CO_2 and binds it. After that, CO_2 is removed from the sorbent by using, for instance, a chemical reaction, heating or vacuum. Various designs are currently developed and tested. They all require much energy, but further development may decrease energy requirements. The proposed technologies vary from 'artificial trees' to making use of minerals, such as olivine. The problems with disposal could be avoided, if these devices are built at suitable places with large enough storage capacity and far enough from human settlements and vulnerable infrastructures.

The aquatic sequestration and air capture technologies would work most effectively for high concentrations of CO_2, that is, for flue gases, and, hence, could also be considered as part of our option category of drastic emission reductions. The above options appear to have in common that they can be implemented by individual countries, generally without major implications for other countries. However, the options which use the biospheric carbon sequestration capacity have various known or unknown ecological effects. Mechanical options raise major questions with regard to energy requirements, costs, efficiency and public acceptance. The rate at which the options can remove carbon from the atmosphere is limited, therefore, there will be delays in influencing carbon concentrations and radiative forcing.

C. Influencing the radiative balance of the atmosphere (solar radiation management)

The most direct and rapid way of counteracting the effects of increased GHG concentrations is to influence the short wave solar radiation. This category of proposed solutions has an immediate effect masking global warming, but also has many as yet unknown risks. These options are usually proposed in case other options would not work quickly enough, or appear not to be feasible. In an emergency situation, these options could be considered to be legitimate to avert negative impacts from climate change, and at least theoretically might be deployed unilaterally by a country or group of countries and even by some large commercial or private bodies. In order to avoid a rebound effect of rapidly increasing temperatures from unmasked high GHG concentrations, they should be implemented until the concentration of greenhouse gases reaches the desired low level, to be achieved through parallel emission reduction or sequestration measures.

Injections of aerosols or aerosol precursors *into the stratosphere*
Various proposals to inject aerosols or reflecting particles into the atmosphere have been made and to a limited extent analysed in modelling studies. Because of the relatively long residence time (approximately two years), injection into the stratosphere would be most appropriate. The aerosols or precursors, such as SO_2 or H_2S, could be carried to the stratosphere on balloons, rockets and airplanes, or by artillery guns. Evidence of cooling after large volcanic eruptions has proven that this option can be effective. However, there are many known and unknown side-effects, including ozone depletion and regionally different effects on precipitation and other climate variables.

Reflectors in space
Another idea to directly influence the albedo of the earth would be to launch space-based ‘sunshade’ shields, situated at the Lagrange point between the earth and the sun at a distance of about 1.5 million kilometres from our planet, averting the incoming solar radiation from the earth. They could be either large (e.g., a single 2000 km diameter shield of thin aluminium foil) or small reflectors (e.g., a cloud of many transparent metre-sized spacecraft). While the aerosol option, described above, would require periodic renewal, the space reflectors would have a longer lifetime. At the same time, theoretically, they could be removed or turned off immediately if undesirable effects would occur. This apparent benefit is also a large risk, because the system would be very vulnerable to intentional or unintentional damage. Costs of these options are as yet estimated to be very high, although innovative solutions are sought to reduce them.

Cloud modification through sea water injection
Another idea concerns low-level maritime stratocumulus clouds, that could be seeded with seawater aerosol in order to increase their solar reflectivity by enhancing the overall droplet surface area or the longevity of clouds. Next to global applications, also a limited deployment of this technology has been proposed to counteract regional impacts, e.g., to cool vulnerable regions such as regions with coral reefs and polar ice[8], but since regional climate change effects are very uncertain, the effectiveness of such regional applications is uncertain, both from a global and regional perspective. Remotely controlled unmanned spray vessels could be used, with limited additional energy requirements. The implementation of this technology will modify the distributions and magnitudes of ocean currents and regional and local meteorology: temperature, rainfall, wind and land–ocean temperature contrast. This option is sometimes suggested to be reversible because the lifetime of droplets is just a few hours or days at the most, but like the other albedo options, it does not avert ocean acidification and would have to be maintained until the atmospheric GHG concentration was brought back down.

Albedo changes of terrestrial systems
By increasing the reflectivity of surface areas, global warming could be counteracted. Proposals have been made to change the albedo of deserts, cropland, urban areas, and oceans. Floating foils or solids could change the ocean’s albedo, but the instability of the sea’s surface and the unknown effects on marine ecology make this a rather farfetched option, which was not further explored for this report. Because of their size and relatively low asserted ecological and economic value, deserts may be the most attractive

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[8] A. Robock (personal communication) suggested, however, that there is so little sunlight in the polar regions, that it is a minor factor in the energy balance and that clouds can actually warm the surface due to their longwave properties.

type of land cover in this context, even if the albedo change to be gained is relatively minor. The world's deserts would be covered with highly reflective, inexpensive, recyclable, tear-resistant and easy to install and maintain material that may have to be replaced every couple of years. In agriculture, new crop varieties may have a higher albedo but similar nutritional value as current varieties. The albedo of the expanding urban areas can be influenced through lighter roofs and surface pavement. It is as yet unknown what the regional climatic effects of large-scale application of this option would be. Evidently, there will be effects on local ecosystems and peoples in the regions themselves, as well as elsewhere (e.g. spreading of fertile Saharan dust would be blocked). Similar to the other options influencing the albedo, ocean acidification would continue and the option would be irreversible – until GHG concentrations would be brought back down.

The potential of several of these options has been demonstrated in analogue situations in the past – for example, cooling from volcanic eruptions, stratospheric dispersion from radionuclides, and terrestrial albedo effects from current land cover differences – but for the purpose of counteracting climate change they can still be considered to be in the very early stages of research and development. The risks of the aerosol and space shades appear to be larger than those associated with modification of clouds and terrestrial surfaces, but all options have the problem that they do not change the concentration of GHGs in the atmosphere and, hence, do not prevent ocean acidification and have to be maintained as long as is needed, until the concentrations will have been brought down, by emission reductions or carbon sequestration. In this context, they can be regarded as temporary emergency response options. The unknown risks pose ethical questions, which are described in more detail in the next chapter.

D. Emergency adaptation

Even if the categories of options A to C would be implemented successfully, for most options it will take some decades before they could have their full effect, because of the time needed for the development and large-scale deployment, and, for emission reductions and carbon dioxide removal, the delays in the climate system (see also Chapter 4 and appendix D). Behavioural changes can be implemented very quickly, provided that public resistance can effectively be overcome in an emergency situation. Because of the more direct link between people's behaviour and their climate resilience, this may be easier than for mitigation where the effects of changing behaviour are dependent on what others do. A swift implementation of the options A to C seems rather unlikely and, therefore, an assessment of the implications for adaptation to residual climate change impacts in the case of accelerating climate change is essential. Here, we distinguished between (a) local impacts in the Netherlands, and (b) global impacts and related risks for the Netherlands. It should be noted that while (a) has been the subject of a large body of research and assessments, (b) is as yet relatively unexplored. The latter may not only be important in case of accelerated climate change, but also for climate change as projected by the IPCC. Not withstanding a focus on Dutch policies, the generic nature of many of our findings may also make them relevant to other countries.

Key questions in the context of this section are: in which way would adaptation policy today be different if extreme, rapid climate change would explicitly be taken into account? When do we have to step up adaptation efforts? Do we need separate emergency plans? The PBL (2009) provided an overview of the impacts and possible response options for ’regular’ climate change, and we used the structure of this report also below. It should be noted that of the four categories of options, only A to C have been explored in detail and summarised in the appendices A to C. A full analysis of emergency and more radical adaptation options is yet to be done.

a. Adapting to direct impacts in the Netherlands

- *Ensuring water safety.* The safety of the Dutch water systems along the major rivers and coast line against flooding can be ensured during this century with the current methods of sand suppletion and reinforcement of the dykes, at a rate of sea level rise of 1.5 metres per century (Delta Commission, 2008; PBL, 2009). This rate is about twice as high as assessed by the IPCC, which did not take into account new insights into the potential accelerated deglaciation of Greenland and West Antarctica. This allows sufficient time to assess the implications of such high (or higher) rates of sea level rise in the next century, particularly with regard to investments that are meant to have a lifetime beyond a century, such as new urban or industrial developments. More radical options, such as managed retreat from the most vulnerable areas, changed prioritisation regarding the planning of new urban settlements, or even floating cities, do not seem to be urgent at this time.
- *Safeguarding fresh water supply.* Salt water intrusion threatens agriculture and natural ecosystems, summer droughts present risks for the availability of sufficient fresh water for human consumption, industry and agriculture, and for the functioning of water transport systems, and high water temperatures affect aquatic ecosystems and cooling water availability. The capacity of the Netherlands to adapt to these threats is limited (PBL, 2009). Different responses are possible, some of which offering more flexibility than others, when the uncertainty of long-term climate change is taken into account (PBL, 2009). For example, closing off the Nieuwe Waterweg to protect the province of South Holland’s fresh water supply would not only have negative implications for river transport, but would also be difficult to change later on, while increasing the IJsselmeer level to increase fresh water supply offers more flexibility. Currently controversial options, such as fundamental changes in agricultural practices or particular spatial reservations for water storage, may become more acceptable under extreme climate change.
- *Protecting nature.* Adaptation options aimed at natural ecosystems are limited, but nevertheless possible: nature areas can be linked nationally and internationally, overall environmental conditions can be improved, and in spatial planning more use can be made of natural gradients and the existing physical systems (PBL, 2009). From a global point of view, other options may be considered if the climate would change faster than projected. For example, significant expansion of reserves or restoration or creation of new habitats would go beyond the current emphasis on defensive protection and linking of existing nature areas. For certain situations, captive breeding and translocation of species is suggested, but this would be limited to a number of individual species and, thus, could result in serious and unpredictable modifications of complex ecosystems.
- *Climate-proofing urban areas and protecting health.* For urban areas, addressing water problems in cases of high intensity rainfall or droughts, as well as health problems related to the urban heat island effect and possible new infectious diseases, are the main problems. Various spatial (e.g., parks and water retention areas in cities, floating housing areas) and non-spatial (e.g., cool building designs, heat emergency plans, tightened air pollution control) response options are available,

but so far these have not been considered in the context of extreme climate change, whereby temperature increases of 6 °C or more in this century may not be excluded and the frequency and length of heat waves is likely to increase.

- *Climate-proofing transport and energy networks.* The vulnerability of national and international infrastructural, energy and communication networks has not yet been assessed. The economy and human well-being are increasingly dependent on the functioning of these networks, which are also increasingly interconnected internationally. Possible impacts include flooding of low-lying infrastructure, damage to or changed stability of infrastructure due to heat or intensive rainfall, shifts in cooling water demand and possibilities for disposal, changes in electricity demand, and water transport problems with low water levels (e.g., Swart and Biesbroek, 2008).

b. Adapting to indirect risks resulting from global climate impacts

- *Integrating climate into trade policies.* The Netherlands may be low-lying, but its wealth and long history of managing water systems make the country less vulnerable to direct climate change impacts than many other countries. Projected climate change impacts will have a global impact on agriculture, hence on prices of food and non-food products, and hence on agricultural trade. In particular, food trade is projected to increase as a result of climate change, with increased dependence of most developing countries on food imports (IPCC, 2007). On the flipside of these negative impacts are the opportunities for export of knowledge and innovative adaptation technologies, for example, delta-technology and high-tech agricultural practices, such as drought and salt-tolerant crop varieties, or urban farm towers. If, as part of a response to projected or extreme climate change, the role of biofuels in the world energy supply increases, there will also be consequences for the Dutch agricultural sector. Furthermore, drastic emission reductions to address accelerated climate change will also have a major effect on world energy prices and, hence, have large implications for international and national economic development. How these possibilities could be taken into account in economic, trade, energy and agricultural policies, has not yet been systematically analysed.
- *Supporting vulnerable countries through development cooperation.* Although problems other than climate change currently dominate the vulnerability of developing countries, in general, climate change is likely to exacerbate them, especially for those regions which are particularly vulnerable, such as semi-dry and low-lying coastal areas. Although climate change is not part of the Millennium Development Goals, it is likely to make reaching them more difficult, and to subsequently maintain or improve the conditions subsequently. Integrating climate change in development cooperation is required for reaching development cooperation goals in the coming decades, particularly if the climate were to change even faster than projected.
- *Avoiding or managing refugees.* Already a share of the global numbers of refugees is suggested to be connected to climate and environmental problems. While climate change is likely to continue to be just one of many reasons for people to flee their homes, it is projected to become a factor of increasing importance (e.g., EACH-FOR, 2008; Kollmanskog, 2008). Whether climate change will result in large international migrations of poor people is as yet quite uncertain, because of the lack of a direct relationship between the level of exposure to climatic risks and the likelihood of associated migration (McLeman and Smit, 2005). Nevertheless, Europe and the Netherlands may also be confronted with an increasing number

of refugees in case of a changing climate, and it would be useful to explore which role the Netherlands could play, internationally, to address the problems. Rather than a sign of failing adaptation, controlled migration may also be seen as an active adaptation option (Guillaume, 2009).

- *Avoiding or managing security implications of rapid climate change.* In a changing climate, increased tensions related to resource scarcity and associated increased commodity prices are likely. Already, the UN Security Council, the United States (e.g., see CAN, 2007) but also the Netherlands (Dutch Ministry of Defence, 2009) have recognised this threat. Security issues can be related to energy, food and water security. For example, major security issues are involved in the structure of the world energy system which may or may not continue to be dependent on energy from often instable regions. Physical or economic food shortages and water scarcity can lead to an increase in the numbers of refugees (both internally displaced people and international refugees) and associated risks of conflicts. Recent (public) military assessments have focused on reduction of vulnerability to climate change of politically unstable regions and military installations, but do not yet indicate specific measures to address climate-induced conflicts, may these arise.
- *Preventing impacts.* From an engineering point of view, similar to the above options to remove GHGs from the atmosphere or influence the radiative balance of the atmosphere, proposals also have been made to prevent particular impacts *after* the climate has changed. For example, ocean acidification may be addressed by liming the ocean, the strengths of hurricanes and other storms might be reduced by seeding clouds, and even a fully artificial environment may protect mankind from an inhospitable outside climate. A long history of weather modification attempts in countries, such as the United States (see e.g. Fleming, 2007) and China, and a small number of projects to create and maintain an artificial environment (e.g., the 'failed' Biosphere 2-project, discontinued in 1994 and now a tourist attraction, see Marina and Odum, 1999), were all unsuccessful. Less extreme forms of ecological engineering are being considered. Because of the uncertainties and the serious ethical questions related to these options, we did not analyse these options in any detail.

In general, the Netherlands appears to be on track to increase its resilience against climate change, especially with respect to vulnerabilities in the water safety system, in the coming century – a period for which the Delta Commission has already considered changes more extreme than projected by the IPCC. Following the recommendations of the National Adaptation Strategy, the Netherlands will also adequately prepare itself for projected climate change impacts in most other areas. The Netherlands being a frontrunner in many, notably water-related adaptation options, is likely to be in a good position to export knowledge and technologies. At the same time, the country does not seem to be prepared for potential indirect consequences from climate change impacts elsewhere in the world.

Governance issues of emergency climate policies

- *Emergency climate response options involve new ethical questions that will have to be addressed, including the issue of intentional modification of the earth system; known and unknown risks; possible global effects of action by one or a small group of actors, including possible military implications; and the desirability of research.*
- *Views on geoengineering options vary with world views: some may consider them as definite solutions ('technological fix' proponents), others as a temporary emergency measure that at least justifies research (risk managers), and some are strictly against any further development and research (environmentalists).*
- *Countries which are particularly vulnerable to climate change, but have relatively limited global influence, such as the Netherlands, could stimulate exploratory discussions on controlled and coordinated research on emergency response options.*
- *New institutions or new coalitions may be more effective in dealing with the challenges of an emergency climate response than current multilateral institutions which focus on consensus building and gradual change, but may raise questions about the level of democratic control.*

Emergency policies and governance

The emphasis in the descriptions of the four categories of options in the previous chapter and Appendices A to C (the fact sheets) is on their technical and economic aspects, reflecting the emphasis in the literature. Especially, since many of the options are either controversial at present or require major system changes, also governance and ethical considerations are important for the successful development of policy strategies. These subjects are covered in this chapter. Here, 'governance' refers to the set of national and international management and leadership arrangements, required for successfully responding to extreme climate change. We have first summarised governance implications for the four categories of options, and then specifically elaborated on the ethical aspects of what may be the most controversial set of options: solar radiation management.

A. Drastic emission reduction

Governance of drastic emission reduction options is determined by the economic effects of the options, the policy level of intervention (from domestic to multilateral) and the degree to which the options interfere with personal freedoms and disrupt markets. Drastic emission controls can only be effective when implemented, coordinated and enforced at the global level. Current governance problems related to international negotiations in the context of the UNFCCC will be exacerbated, as the required drastic emission reductions are likely to involve rapid structural economic changes, premature retirement of capital stock and lifestyle changes.

Emergency policies may differ between countries, leading to discontinuities in price levels, regulations, and tax systems, which could be at odds with a level playing field for economic actors (Ferguson, personal communication). Enforcement and sanctions – imposed on countries or other actors not adhering to emergency agreements – would become major issues. The mandate of existing organisations, such as the UNFCCC, but potentially also other currently more powerful organisations such as the WTO and UN Security Council, may need to be expanded. However, many current institutions are characterised by slow consensus-forming processes, which cannot adequately respond to emergency circumstances, and new institutions may be required. Questions related to the level of democratic control of new institutions have to be considered in such circumstances. Specific arrangements may be required for the energy sector. The Agreement on an International Energy Program (IEP, see IEA, 2008) to address oil crises in an internationally coordinated fashion may be an interesting source of ideas[9], even if the nature of the climate problem surpasses the characteristics of usually more short-lived oil crises. While currently international agreements such as the Convention on Long-range Transboundary Air Pollution (CLRTAP) address air pollution at the continental scale, a new Global Atmospheric Pollution Convention could address air pollutants, including short-lived greenhouse gases not covered by the UNFCCC, at the global level. Such a Convention may also provide a framework for addressing the issue of solar radiation management through aerosol injection into the stratosphere (see below).

B. Removing greenhouse gases from the atmosphere

Terrestrial carbon sequestration (forestry and land management, including biochar production) can be pursued by a limited number of nations with sufficiently large available land areas. International political issues may be related to the question of whether, and if so how, countries should be compensated for managing their lands for the global benefit. But these problems appear to be limited, compared to the other options discussed. Local and regional implications for forestry and land management options are discussed extensively in the literature (e.g, IPCC AR4). Schellnhuber (2009) noted that with the world economy and population continuing to grow and a number of international crises (climate, water, food) developing, land becomes an increasingly scarce resource. He provocatively suggested that international management may be required for an optimal use of land, for example, earmarking the world‘s most fertile land as ‘Global Agricultural Commons’. While such ideas may look far-fetched and infeasible at present, increasing multiple pressures may change this in the future. In order to use land-use and forestry options effectively to address extreme climate change at the global level, many social, economic and political barriers will have to be removed, because dependent on the type of measure, the sovereignty of countries and land owners may be at stake. However, the options have already been discussed in a UN context (climate change, biodiversity and land degradation) for quite some time, and reasons other than climate change make them attractive. This may still make land use and forestry options a feasible and meaningful part of a climate emergency response programme.

Artificial sequestration methods (air capture, enhanced mineral weathering) could also be done unilaterally. Apart from the considerable energy requirements, risks associated with air capture appear to be primarily related to CO_2 disposal. Some questions relate to the inclusion of sequestration options other than those currently included in the UNFCCC in national GHG accounts, for example, questions of how carbon is sequestered through mechanical means technically measured and accounted for in carbon credit systems, and how monitoring is arranged? Such questions could be of limited importance in an emergency situation.

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[9] The IEP not only calls for 60 days emergency oil reserves, but also requires participating countries to have plans for contingent oil demand restraint, evaluated by a Standing Group on Emergency Questions which reports to a Governing Board which decides on a majority basis.

Ocean sequestration could also be pursued unilaterally. Some companies have been established, hoping to already be able to earn carbon credits. However, ocean fertilisation, even if it would draw carbon effectively from the atmosphere, can involve important yet unknown risks to marine ecosystems and geochemical cycles, which would affect other parts of the world, and thus would require international agreement and control. For this reason, in 2007, 200 countries agreed under the Convention on Biological Diversity on a moratorium on adding nutrients to the ocean in order to stimulate algal growth, with the exception of approved small-scale research in coastal waters (UNCBD, 2007). In 2008, the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter decided that ocean fertilisation is not scientifically justified (IMO, 2007). Nevertheless, if this type of carbon capture would eventually be allowed, similar questions regarding the accounting of air capture would have to be addressed, which would be minor in an emergency situation.

C. Solar radiation management

Changing the albedo of the earth through injection of stratospheric aerosols or reflectors in space has global consequences, but can be done unilaterally, because it may be considered relatively inexpensive, compared to emission reductions or ambient air capture (Barrett, 2006; Bles, 2009; Bickel and Lane, 2009). Different from mitigation, changing the albedo may also be perceived as relatively easy to implement, because it only addresses climate change without targeting other social or environmental goals, and it does not require difficult changes in production and consumption patterns (Virgoe, 2008). Several authors have stressed that because of largely unknown effectiveness and risks, international agreement on research, development and possibly eventually deployment would be highly desirable (Ricke, 2008; Victor, 2009; Schneider, 2009), particularly, as the private sector could also enter this area because of the required technological capabilities.

This set of options, in particular, may require governance arrangements beyond economy, technology and environment. The world has a long history of attempts to influence the weather, especially the United States and China. There are military interests in developing some geoengineering options, and new norms and control mechanisms may have to be developed urgently, since some experiments are already planned. Several military applications have been tried with, generally, much smaller effects than expected, if any (Cascio, 2008; Fleming, 2007). In 1977, the Environmental Modification Convention (ENMOD, 1977) agreed to prohibit weather modification for military purposes. This Convention – even if it addresses weather rather than climate modification – may have been one of the starting points for new negotiations to develop an international mechanism to control or manage solar radiation management (SRM) activities. In terms of (different perspectives on) risks and benefits, SRM may have aspects in common with nuclear technologies, and, hence, the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) also might provide interesting experiences. The NPT tries to further the goal of non-proliferation and act as a confidence-building measure between countries, with a safeguard system under the responsibility of the International Atomic Energy Agency. Another option is clearly the UNFCCC, of which the ultimate objective is to avoid dangerous interference in the climate system, something SRM may be at odds with. Sulphur injections into the stratosphere may be in conflict with the aims of the Convention on Long-range Transboundary Air Pollution (CLRTAP). Many large countries, such as the United States and the Russian Federation, which could theoretically take unilateral action, are party to these Conventions. China however is not a party to the ENMOD and LRTAP Conventions. Because existing processes and institutions such as the above may be inadequate to deal with this kind of option (Parsons, 2006), new arrangements may be required.

Changing the albedo of the earth by changing the reflective properties of land or clouds is similar to the stratosphere and space-based options in its albedo changing features, but can be applied regionally, having regional effects. Because of this, it may be perceived as less threatening than the options with more direct global effects. However, to make a difference, the scale of application should be large enough, and the interconnectedness of the global climate system implies that regional changes in reflective properties of land and clouds can have effects in other regions. Therefore, it seems that the governance implications are similar to the option discussed above. All raise serious ethical questions (see below).

D. Emergency adaptation

Finally, emergency adaptation options can also have very challenging requirements for national and international governance. Internationally, many of these are related to 'climate refugees', tensions or conflicts over scarce natural resources, such as water and land, which may be associated with climate change, and threats to the world's supporting ecosystems. Addressing the problems of large numbers of *climate refugees* is just one of the major issues that the world community would have to deal with, but one which already attracts attention. The number of environmentally induced migrants has been suggested to increase from about 24 million around the turn of the century to about 50 million by 2010, around 200 million by 2050, and 700 million after 2070 (Warner, 2009). However, because of the complex interactions, with climate just being one of the factors forcing people to move in a wide array of social, economic and environmental factors (Kolmannskog, 2008), predictions are hard to make. The EU project 'Environmental Change and Forced Migration Scenarios' is developing scenarios for environmentally forced migration (EACH-FOR, 2008). There are various international mechanisms to address the problems related to large flows of refugees or forced migrants, notably the UNHCR (UNHCR, 2008). The International Federation of Red Cross and Red Crescent Societies has established a special centre to address the climate risks for the poor (RC/RC, 2007). In 2008, the Climate Change, Environment and Migration Alliance (CCEMA) was established by the United Nations University (UNU), the International Organization for Migration (IOM), the United Nations Environment Programme (UNEP) and the Munich Re Foundation (MRF), to encourage the mainstreaming of environmental and climate change considerations into migration management policies and practices, and conversely, also add migration issues to the global environmental and climate change agendas (Mortin et al., 2008). It remains to be seen to what extent the current system can cope with increasing numbers of people. According to Kolmannskog (2008), existing law and protection possibilities should be further investigated to identify and address potential protection gaps in climate change-related displacement. WBGU (2006) recommended to consider a burden-sharing arrangement or quota system for refugees, related to a country's greenhouse gas emissions. Guillame (2009) suggested that migration could be an intentional adaptation option. Biermann and Boas (2008) proposed the establishment of a global regime to protect climate refugees, inter alia, because the numbers of people may overwhelm the capacity of the current institutions and systems, and the character of refugee problems would be different from current ones. They discussed the disadvantages of addressing the problem through existing refugee or security institutions and suggested a new UNFCCC Protocol on Recognition, Protection, and Resettlement of Climate Refugees and an associated Climate Refugee Protection and Resettlement Fund.

As to *security problems*, scarcity or increasingly unequal distribution of vital resources like water and food are likely to lead to conflicts, possibly violent. According to CNA (2007), climate change could be considered a 'threat multiplier for instability in the most volatile regions of the world' and, hence, should be integrated into national security and national defence strategies. Based on this report, the New York Times (8 August 2009) concluded that 'climate-induced crises could topple governments, feed terrorist movements or destabilise entire regions'. At the first UN Security Council meeting on climate change in 2007, delegates still differed in views on the role of the Council regarding climate change, but in 2009 picked up the issue again. This development adds 'security' to other aspects of prevention of 'dangerous interference with the climate system', which in article 2 of the UNFCCC is associated with natural adaptation of ecosystems, food security and sustainable economic development. At present, there is no common understanding on the long-term goals and the criteria to evaluate dangerous interference (Sprinz et al., 2007). The term 'dangerous' is inherently related to normative questions and cannot be reduced to a strict scientific meaning. And not only in the United States, but also in the Netherlands, the issue of climate change and security has been the focus of attention: an interdepartmental group is currently assessing the associated future risks (Dutch Ministry of Defence, 2009). The interest from the military may enhance the urgency of the problem, inject further impetus to the climate negotiations, and, as a consequence, to mitigation efforts, but also the historical interest in the military in engineering solutions (weather modification) may increase the attention for such solutions. It is unclear what this may imply for non-military governance of (extreme or projected) climate change.

In general, for all four categories of options, a key question is whether the slow and bureaucratic UNFCCC is still the most appropriate international mechanism in a situation of accelerated climate change which requires rapid response. Alternatively, other existing or new institutions may be required, parallel to the UNFCCC, to respond to the challenges in a peaceful and internationally coordinated fashion. In that case, a global effort can be imagined, but coordinated action by a smaller group of key countries could be faster and more effective. This would raise questions as to the desirable democratic control of the actions.

Solar radiation management and ethics

Climate change involves a large number of ethical questions (e.g., see Program on the Ethical Dimensions of Climate Change: Brown et al., 2006). Mostly, the scientific debate focuses on issues relating to the question of responsibility, fair allocation of emission rights and costs, access to technologies, or procedural equity. Although we recognised that all categories of options involve ethical questions, we focused on solar radiation management options, many of which pose a 'moral hazard', possibly reducing the pressure for emissions reductions, and raise new ethical and legal challenges. In the context of extreme climate change, the pertinent question may change from a mainly economic one: 'what level of dangerous anthropogenic interference with the climate system do we want to avoid at which cost' into a more ethical one: 'what level of dangerous anthropogenic interference with the climate system do we want to avoid by using which currently controversial and risky solutions?' Brown et al. (2007) distinguished four ethical issues related to aerosol injection into the stratosphere, which are also relevant for other types of SRM:

- *The difference between inadvertent and intentional interference with the climate system.* Different from the collective development of a world economy based on fossil energy with initially no knowledge about the climate effects, SRM involves intentional modification of the world climate, which would require attention in new or existing international treaties. Especially the interest of the military (Fleming, 2007; Tollefson, 2008) is an important consideration here.
- *Scientific uncertainties related to the deployment of these technologies.* SRM involves uncertainties with respect to the sensitivity of the climate system to the actions, the effects on the atmospheric composition, possible irreversibility, and the remaining impacts of CO_2 concentrations. Some options which are claimed to be reversible in the sense that they can be turned off quickly, are not reversible in the other sense that if turned off after some time, warming due to high levels of greenhouse gas concentrations would be unleashed. Ethical questions relate to the burden of proof (attribution of responsibility, level of proof required), the rights of protection or compensation of possible victims, and the appropriate use of the precautionary principle.
- *The issue that one or a small group of countries (or companies) can determine the 'optimal' climate for the planet.* What are the rights of those implementing the options, absent any democratically empowered institution? Here the status of the implementing group is important, for instance, the UN Security Council is an example of an established multilateral institution not elected democratically. At present, there do not seem to be any countries – or other actors – that have a clear motivation to act unilaterally[10]. However, this may change in emergency circumstances. In an emergency situation, it is likely that a strict multilateral institution, such as the UNFCCC with its unanimity rule, will be overruled by a 'coalitions of the willing' (Metz, personal communication).
- *The need for or desirability of further research.* Usually, SRM researchers acknowledge the various questions regarding associated risks, and call for more research to address the uncertainties. However, the mere decision to do research or not involves ethical questions. Such a decision may lead to less efforts to reduce emissions, to lower mitigation research budgets, impacts from the research on others, or deployment or tests without international consent.

The validity of these points varies between different types of options. The ethical challenges are the most serious for options that have potential long-lasting, maybe irreversible, large-scale effects and can be deployed by one or a small group of countries (e.g., stratospheric aerosols, space reflectors, ocean fertilisation). In addition, other options which may be reversible to some extent, have mainly regional implications, or require international cooperation to be effective (e.g., regional albedo changes), raise similar questions. The exception may be air capture of carbon dioxide, which can be implemented unilaterally, and has no effects on others, apart from the large energy requirements and risks related to the disposal of captured carbon.

Tests of some SRM options have already been proposed, and pressure to take them seriously can be expected to increase, because cost estimates for some options by proponents may be relatively low, at least if unknown side effects are not priced (Barrett, 2008; Bles, 2009; Bickel and Lane, 2009). A dilemma for those not in favour of these

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[10] Russia may expect less negative impacts than other countries, and may even experience some positive impacts, Europe - at least in the past - strongly favoured the precautionary principle, and other security and competitiveness concerns, and concerns about unpredictable effects on rainfall, may dominate in countries such as the United States and China.

options is that setting up or participating in research, as well as starting an international debate about them, has the implication that these options will enter the political agenda, from which they may be hard to remove. In the United Kingdom, the Royal Society (2009) recently published a climate engineering assessment, and in the United States, NOVIM (a group of experts, Blackstock et al., 2009) developed a blueprint for a major research programme, which also addresses conditions for research, field experiments and deployment.

Inherent to such ethical issues, different people have different views. Proponents of geoengineering as a technological fix may see these options as a solution that can at least partially counteract the radiative forcing of greenhouse gases, for example, by allowing for higher levels of stabilised concentrations than would be desirable without them. Such a view would decrease the urgency and importance of greenhouse gas emission reductions. On the other side of the spectrum are those who do not agree with any form of geoengineering, including research, because of the risks involved. These are usually in favour of what we have called drastic emission reductions. In between are those who see geoengineering options as a potential temporary emergency measure that may not be desirable, but perhaps unavoidable if major climate impacts are to be prevented. In the latter case, the options are to be maintained until greenhouse gas concentrations have been reduced through measures with less risks involved, but with longer lead times. Table 1 gives an overview of some arguments of geoengineering proponents and adversaries in the four categories of ethical questions described above. Countries which are particularly vulnerable to climate change, but have relatively limited global influence, such as the Netherlands, could stimulate such exploratory discussions on ethical questions, most urgently on controlled and coordinated, open research. Because once started, work on geoengineering may be hard to stop, international agreements on rules are urgent (Victor, 2008). At the same time it should not be forgotten that also other options, such as those for drastic emission reduction through controversial technologies or behavioural changes, have ethical implications, and should also be further explored.

Table 1. Selected arguments of geoengineering proponents and adversaries

	Proponents of geoengineering	*Adversaries of geoengineering*
Inadvertent vs. intentional	In an emergency situation this distinction becomes obsolete Also GHG emissions imply human modification of the earth system	The planet should not be gambled with in any circumstances There are unacceptable liability questions, military risks
Scientific uncertainties	We can act and learn Several options are reversible GHG induced warming also has unresolved uncertainties	There may be unacceptable, unknown, irreversible effects An 'optimal' climate can never be agreed on or achieved The burden of proof can most probably never be established
Unilateral vs multilateral	Coalitions are quite acceptable in an emergency situation, to avoid bureaucratic delays Side payments to countries which do not want to join are possible	Solutions with global effects without global control are unacceptable Agreement on compensation of possible victims will be difficult
Need for research	Research is essential to optimise effectiveness and reduce risks Research is crucial to having a 'plan B'	Research will move the attention away from emission reductions Research is undesirable, but if done at all, then only under very strict rules and international control

Assessment and discussion

- *Many technologies and practices for major carbon dioxide emission reductions or removal from the atmosphere are well-known today, but implementation will take up to decades, and an additional time lag exists due to earth system delays. The effects of solar radiation management (SRM) are more immediate, but the required research, development and deployment can also be expected to take some decades.*
- *Therefore, at present, none of the major emergency response options are expected to be available in time to effectively address rapid climate change in the coming decades, leaving adaptation as the main short-term solution.*
- *There is a trade-off between categories of options: the less drastic emission reduction proves to be viable, the more carbon dioxide removal and solar radiation management is needed to avoid increasing impacts in a situation of accelerating climate change. If drastic emission reductions and geoengineering both appear to be infeasible (technologically, economically or politically), enhanced efforts to adapt to the exacerbated consequences would be unavoidable.*
- *Recent insights and preliminary model calculations suggest that, theoretically, global GHG emission reduction rates of 4% per annum, or more, may be possible. In comparison, SRM can only match the effectiveness if applied globally and maintained over a long period of time. Discontinuation of such SLR would lead to immediate rapid temperature increases.*

In the appendices, the options are evaluated that are available to respond to rapid climate change against our of criteria. In a situation of rapid climate change, one single option is most likely insufficient, and the full portfolio of options would need to be considered seriously, in spite of the associated environmental, economic or ethical concerns. Depending on different perspectives on how the world may develop and how the changes should be managed, different combinations of options are likely to be preferred by different stakeholders. In this chapter, a summary is given in an overview of our assessment, on how the groups of options are interlinked, and how the international community may politically react to rapid climate change.

Table 2 provides an overview of the various options for responding to accelerating climate change, for the four criteria that we distinguished. In their assessment of geoengineering, the Royal Society (2009) included tables with scores for the various options and a summary graph with four dimensions. Notwithstanding suggestions from various reviewers of this report, we have not provided such a scoring, nor did we provided a comprehensive graphical overview, for the following reasons:

- The four categories of options include a variety of individual options that vary in terms of their effectiveness, feasibility and environmental and socio-economic implications;
- Moreover, the criteria are in fact composite criteria: one particular option may score positive for one aspect and negative for another;
- Scoring would also only represent current views of the scorers, ignoring that the evaluation is likely to change as the impacts of an accelerating climate change would gradually become more apparent and constraints on implementing particular options that may exist at present could disappear[11].

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[11] New insights or arguments may change attitudes. For example, while initially geoengineering options were primarily discussed as a global option to address a global problem, increasingly it is suggested that

- The information basis for providing scores is very uneven and scoring would be very subjective;

In addition to the qualitative synthesis in Table 2, we organised some of the options in the graphs and tables below for a limited set of the many relevant dimensions. For example, Figure 5 illustrates these spatial dimensions of some of the options, ignoring that at least some of the regionally applied options may have consequences for other regions or globally.

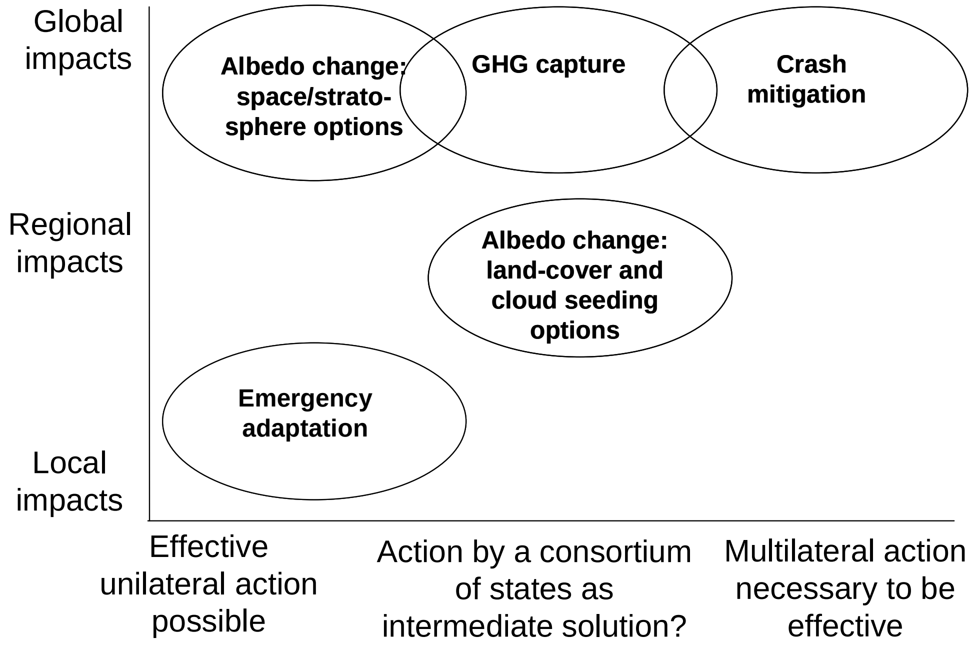

Figure 5. Response options and spatial scales of governance and impacts

Figure 5 also shows that, at least theoretically, some options need full international collaboration to be effective, while others can be effective also if one country or a small group of countries (or other actors, such as private companies) take action. Literature finds that the ethical questions related to the possibility of unilateral action are important. In reality, one may expect that, in an emergency situation, a small group of countries may step forward to take the lead in all options, not in the least due to the difficulties involved in and time necessary for UN-style international decision-making. This does not necessarily imply that high risk (geoengineering) options would be selected more easily, because there may be few individual countries (if any) which see a competitive advantage in taking such risks (see Chapter 3).

Time delays
The various options have different time delays:

- *Research, development and demonstration*: the time needed to develop the options, from conceptual idea to available technology or practice;

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some of these options may be applied regionally to address regional impacts. While this point of view downplays the risk of effects outside the region where the option is applied, such arguments might have the potential to make these options more acceptable.

- *Development and implementation of policy instruments*: the time needed to move from an initial policy initiative to the effective implementation of the policy, including the time needed to move from niche applications to full international deployment and in some cases the time required to gain public support or reach international agreement about their deployment;
- *Earth system delays:* the time needed to have the desired effect, which can be immediate for adaptation options, very rapid for solar radiation management options, and slower for options aimed at reducing emissions or concentrations.

Time delays in society and in the earth system differ between the various options, making an overall prioritisation difficult. Table 3 gives an assessment of the relative time delays, but does not say much about effectiveness and nothing about the feasibility of the options. The societal time lags can be influenced by policy, and can be reduced in a climate emergency situation. For example, solar radiative management options may have a rapid cooling effect, but will probably take some decades to develop, from the drawing board to actual application, and until the desirable international agreement about their deployment would be reached. Conversely, several drastic emission reductions may already be technically available, but even after they have been introduced, take some time to affect the radiative balance, because there is a small delay in changing the atmospheric composition and, subsequently, a larger delay to affect the earth system's heat balance. At present, none of the emergency options described in this report appears to be ready to counter an accelerating climate change, effectively, within a period of at least a few decades.

Interrelationships between options

The stylised Figure 6 provides a framework for comparing the potential contribution from the four categories of options. The middle thin line depicts the stylised level of 'impacts' that could be associated with a baseline scenario in which emissions increase for some time, to decrease in the course of the next century, comparable to the A1B scenario of the IPCC SRES. It is generally acknowledged that this scenario would not lead to stabilisation of greenhouse gas concentrations that is sufficiently low to avoid 'dangerous interference with the climate system', for example, by limiting the global average temperature to 2 °C, being the EU target. Therefore, the bottom of the range depicts a scenario in which these impacts would be decreased through the kind of mitigation policy considered today. If, in the coming decades, climate change would accelerate, depicted by the top of the range, we assumed that the world would continue to aim for a similar level of low impacts, as it would in a world without accelerated climate change (bottom of range). If stepping up mitigation efforts would not be sufficient to lower the impacts, additional options (carbon dioxide removal, solar radiation management) would be required, to lower the impacts and/or buy time to reduce atmospheric concentrations of greenhouse gases.

Table 2. Summary overview of emergency response options

	Effectiveness	**Feasibility**	**Environmental implications**	**Political implications**
Drastic emission reductions	• Generally, these options have the most sustainable effect • Most rapid effect: carbon capture and storage, reduction short-lived substances, behavioural changes • Other options: long transition time (30 years or more) • Some options have an energy penalty (CCS, biochar)	• Most options well-developed, some in demonstration phase • Requires fundamental transition • Economic costs suggested to be limited (<1-2 % of global GDP) • Some options require difficult behavioural or structural economic changes, or are politically controversial	• Most options have environmental co-benefits (e.g., air pollution abatement) • Some options entail environmental risks (biofuels, biochar, nuclear)	• Reduced dependence on fossil-fuel exporters can have positive and negative security implications • Some options (biofuels) may lead to land-use conflicts • Global cooperation is required • Boundary conflicts to be resolved for uncoordinated policies • Emergency policy instruments yet to be developed
Removing carbon from atmosphere	• Scale of application determines effectiveness • Effectiveness marine options questioned • Most options require decades to be fully deployed • Some options have an energy penalty (air capture, large-scale ocean fertilisation)	• Terrestrial ecosystem sequestration well-known, other options less mature • Until GHG concentrations are sufficiently reduced • Costs largely unknown, by some suggested to be limited (excl. negative effects) • No behavioural change required	• Some options (protection/enhancement of soils and terrestrial natural ecosystems) can have environmental co-benefits • Some other options can have environmental risks (e.g., biodiversity) depending on how they are implemented • Air capture has few effects	• Options generally have little societal risks, compared to other options • Some options can lead to land-use conflicts • No risks associated with unilateral application
Influencing radiative balance (solar radiation management)	• Stratospheric aerosols/space reflectors: global effect • Cloud modification/terrestrial albedo change: smaller effects • Shortest climate response time when deployed • Many options have energy	• Full implementation may require some decades • Costs estimated to be relatively low, depending on scale of application • Options to be maintained until GHG concentrations have reached safe levels	• Ocean acidification unaddressed • Acid deposition (for aerosols) • Effects on regional climate as yet largely unknown • Stratospheric aerosols have air pollution implications	• Unilateral deployment affects the power balance and may be susceptible to intentional damage • Ethical questions involved in intentional modification of the atmospheric system • Terrestrial albedo changes may involve land-use conflicts

	penalty		• Terrestrial albedo modification can have ecosystem effects	
Emergency adaptation	• Can be relatively quick, when other options do not work • Limits to adaptation: victims and damage cannot be avoided • Several options have energy penalty (cooling, irrigation, etc).	• Most adaptation options are known, but costs can be high • To be maintained until the climate is stabilised	• Coastal and river bank protection can have ecosystem implications • Migration can increase ecosystem pressures	• Developing countries may not have the capacity to adapt • Refugee and security issues to be addressed • Land-use conflicts likely after major sea level rise • Can be done by countries individually

Table 3. Author's assessment of the relative time lags associated with various emergency response options (the darker, the longer the delays; the table does not address the relative effectiveness, risks or desirability of the options)

	Option Time delays	RDD	policy	earth system
Drastic emission reductions	Move to high cost emission reduction options of current technology menu	░	░	■
	Behavioural changes; controversial technological options, such as nuclear, CCS	░	▓	■
	Fundamental infrastructural/economic transitions	▓	■	■
Carbon dioxide removal	Afforestation, reforestation, soil carbon enhancement		░	▓
	Mineral sequestration	▓	░	▓
	Ocean fertilisation	▓	■	▓
	Aquatic sequestration (algae)	░	░	▓
	Biochar	▓	░	▓
	Air capture	■	■	▓
Solar radiation manageme	Aerosol injections into stratosphere	▓	■	░
	Reflectors in space	■		░
	Cloud modification through sea water injection	▓	▓	░
	Terrestrial albedo changes (ecosystems)	▓	▓	░
	Terrestrial albedo changes (urban areas)	░	░	░
Drastic adaptation	Adaptation through available technologies (water safety, cooling, desalinisation, irrigation, etc.)			
	Adaptation through behavioural changes	░	░	
	Drought-resistant varieties	░		
	Fundamental infrastructural/economic adaptive transitions, relocations	▓	▓	

shading	**Relative RDD status**	**Policy: relative societal resistance**	**Earth system effect on**
■	Conceptual idea	Highly controversial; no effective instruments	Emission sources
▓	Model studies; few experiences	Controversial; some Instruments known	Concentrations
░	Prototype; some experiences/tests	Moderately controversial; limited experiments	Radiative forcing
	Technology/practice available	Non-controversial; already practiced	Impacts

Mitigation might be given priority, because of the unknown feasibility and risks of solar radiation management, reducing the need for such measures. Conversely, if solar radiation management would be applied, this would allow for much more time to successfully mitigate greenhouse gas emissions or capture carbon from the atmosphere. The impacts that cannot be avoided require adaptation. Also, without accelerating climate change, solar radiation management and/or emergency adaptation would be required if actual global emissions could not be kept below the level at which unacceptable dangerous interference with the climate system would occur, that is, if the agreement to be reached in Copenhagen would prove to be insufficient. In that case, emergency options, such as solar radiation management, could be considered to reduce the time and degree to which greenhouse gas concentrations would overshoot levels that would be considered safe. Options that draw greenhouse gases from the atmosphere, such as the capture of ambient air, appear to have less negative side effects than solar radiation management and have a longer response time. They could be considered an option, complementary to emission reductions (Bles, 2009).

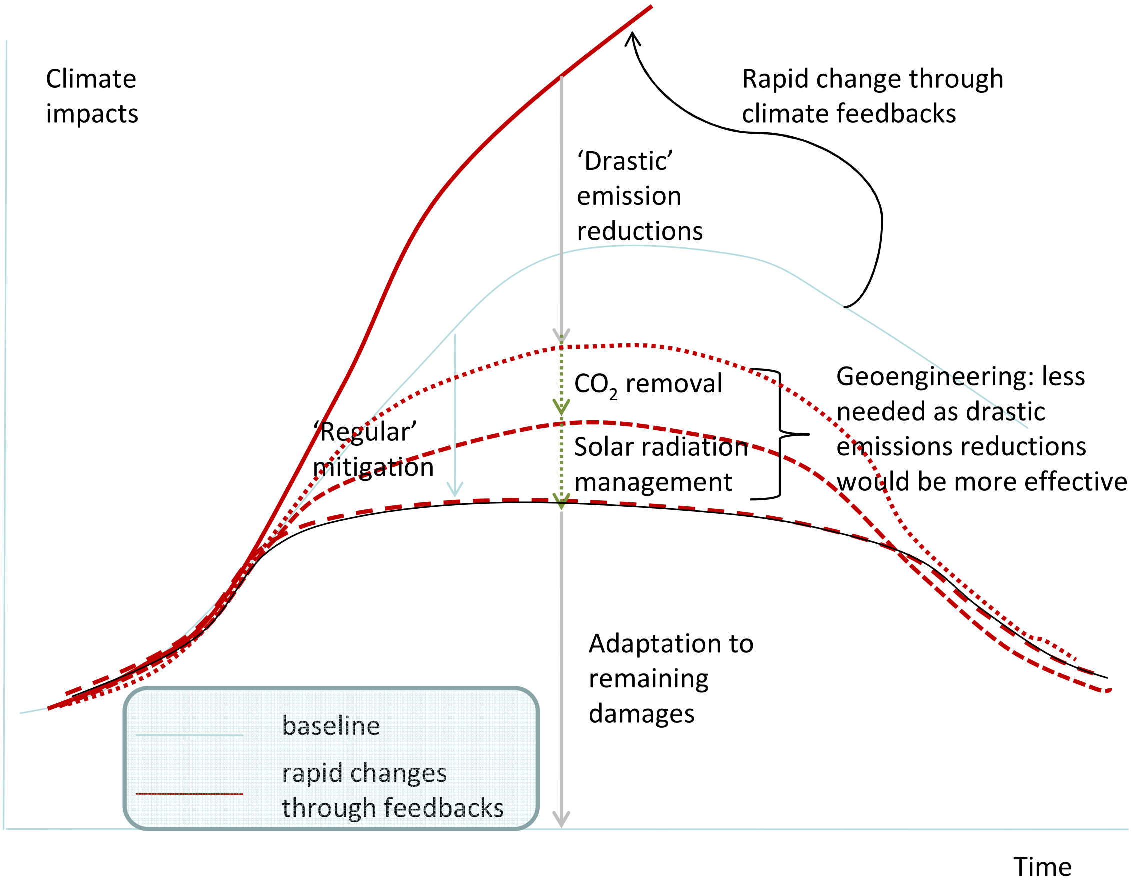

Figure 6. Four categories of options to respond to accelerating climate change: lowering impacts and buying time; see main text for explanation

Text box 4.1. Rapid climate change – rapid emission reductions?

A key question in the emission reductions–climate change relationship is how fast global emissions can be reduced and how fast the climate system would respond to such reductions. While in the past, maximum emission reductions were often estimated to be between 2 and 4% per year, recent model analysis suggests that in a theoretical case, analysed with the IMAGE/TIMER modelling framework, rates of up to 6% would be possible, if a combination of biofuels with carbon capture and storage is assumed (Van Vuuren and Stehfest, see Appendix D). This analysis assumes a relatively high climate sensitivity of 4.5 °C and does not take into account premature retirement of capital stock, behavioural changes, or maximum rates of carbon sequestration, which would lead to even higher reduction rates. Figure 7 shows the effects of radiative forcing, temperature change and sea level rise, for a scenario in which a 4%/yr GHG emission reduction after a global peak in 2020 is assumed, a scenario in which radiative forcing would be kept stable through geoengineering methods at the level of 2030 (3.6 W/m^2), and a scenario in which the radiative forcing would be brought back to levels equivalent to a 400 ppm CO_2 eq scenario (2 W/m^2).[12]

Preliminarily, we concluded from these analyses that a drastic emission reduction strategy, that would reduce GHG emissions by around 4% per year, may be able to effectively limit climate change to only a few tenths of a degree after the introduction of the policy. However, inertia implies that a peak in temperature would only occur around 30 years after the introduction of the policy – and after 70 years, the temperature still will not have returned to the level of the introduction year. Solar radiation management can lead to more rapid results, depending on the extent to which the measure is introduced. A modest strategy to limit radiative forcing would not do much better than the rapid mitigation strategy. However, an extreme strategy that would instantly bring radiative forcing back to a low level could have more immediate results. This would obviously also significantly increase the risks associated with such a strategy: should the measures that mask the radiative forcing be discontinued, global temperatures would soar, as a result of unabated GHGs from the radiative forcing. More rigorous work is required to corroborate our preliminary finding that solar radiation management options are only more effective than drastic emission reductions if applied globally and maintained over a long period of time.

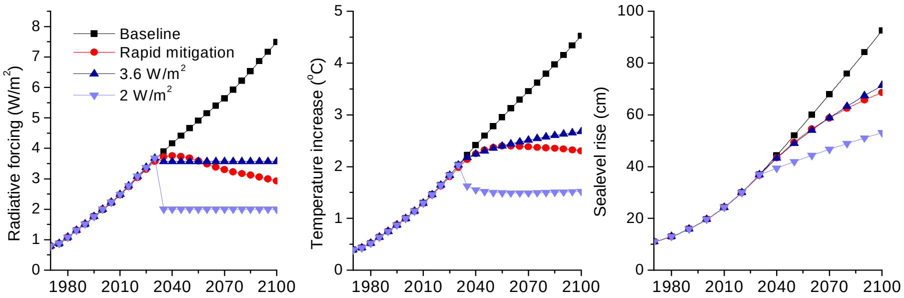

Figure 7. Radiative forcing, temperature change and sea level rise in the various scenarios

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[12] If greenhouse gas emissions would continue to increase, the efforts to counteract their radiative forcing would also have to increase in these scenarios (e.g., increasing the sulfur load), while these measures could not be discontinued without unmasking the warming associated with the greenhouse gases. Acid deposition and acidification of the ocean would be sustained collateral effects.

Scenarios for level of international collaboration and perceived urgency
The eventual response to accelerating climate change will depend on many different factors and there may be large differences in political priorities between countries. National governments in small countries, such as the Netherlands, will have to consider how other, larger countries may act, and design their own response accordingly. Next to the sense of urgency, a very important dimension in this context is the level of international coordination that will characterise tomorrow's world. The slowness of existing mechanisms, such as the UNFCCC, may cause countries to follow their own paths, individually or in coalitions. This may have advantages in terms of decisive responses, but would also add risks, should these actions have consequences for others. A second factor influencing the policy choice is the sense of urgency amongst the population and decision makers (see also Text box 4.2). With good climate monitoring systems in place, and clear attribution of observed changes to human-induced climate change, this sense of urgency may be high. However, in case of poor monitoring and continued controversy over attribution, political issues other than climate change may get priority.

Text box 4.2. Detection of extreme climate change and sense of urgency

In 'regular' climate change scenarios, as well as in more extreme (high or low) scenarios, climate change impacts are likely to be most apparent through changing intensity and frequency of extreme events. Because of the interdecadal variability, even very targeted monitoring programmes may only gradually reveal that climate change is indeed happening faster than was assessed by the IPCC. Therefore, it is possible that an accelerating climate change will reveal itself only through a gradually increasing series of observed changes and events that can be fully or partly attributed to climatic change, although abrupt climate change equivalents of 'the hole in the ozone layer' cannot be excluded. The targeted monitoring programmes would build an evidence base that would not convince everyone at the same time. Different stakeholders will react differently to the evolving evidence base, leading to different senses of urgency, similar to the climate change policy developments of the last decades. With good monitoring systems in place, and clear attribution of observed changes to climate change, this sense of urgency may be high. However, in case of poor monitoring and continued controversy over attribution, political issues other than climate change may get priority, because – parallel to climate change – other world tensions are also likely to occur.

Figure 8 suggests four scenarios along these dimensions, based on a background paper drawn up for an expert meeting in the Netherlands, in spring 2009 (Zoeteman and Kersten, 2009). The likelihood of effectively responding to accelerating climate change is highest in a world with a high risk perception and consensus about the need to respond, and the wish to do this in an internationally coordinated fashion (top right, scenario 1: 'global green endeavour'). In such a scenario, the success of a drastic emission reduction programme and coordinated responses to support those who are most vulnerable in adapting to the remaining changes, is most likely. If there is a high sense of urgency, internationally, but the political differences prevent an effective international coordination, all countries will try to find their own solutions through adaptation, but the application of geoengineering options also could be an attractive option in this scenario, for example, for large countries (top left, scenario 2: 'sauve qui peut'). In a third scenario, with effective international coordination, but a low sense of urgency to respond to climate change because there are too many other issues to address (bottom right, 'together through the other crises'), internationally coordinated programmes may be preferred to address problems that are exacerbated by climate change (such as management of climate refugees, food and water security). Finally, in a fourth scenario, in which there is no will for international coordination but also no great sense of urgency, protecting only one's own country appears to be the most attractive response (bottom left, 'survival of the fittest').

Extreme climate change is likely to change income and power distribution between nations and other public and private actors, and put tension on current political and social structures. Different possible futures with respect to international response to extreme climate change are characterised by very different constraints and opportunities, for the various options discussed in the report. The scenario analysis also raised the question of whether, in such a situation, current national and international decision-making structures are adequate to deal with climate emergency situations.

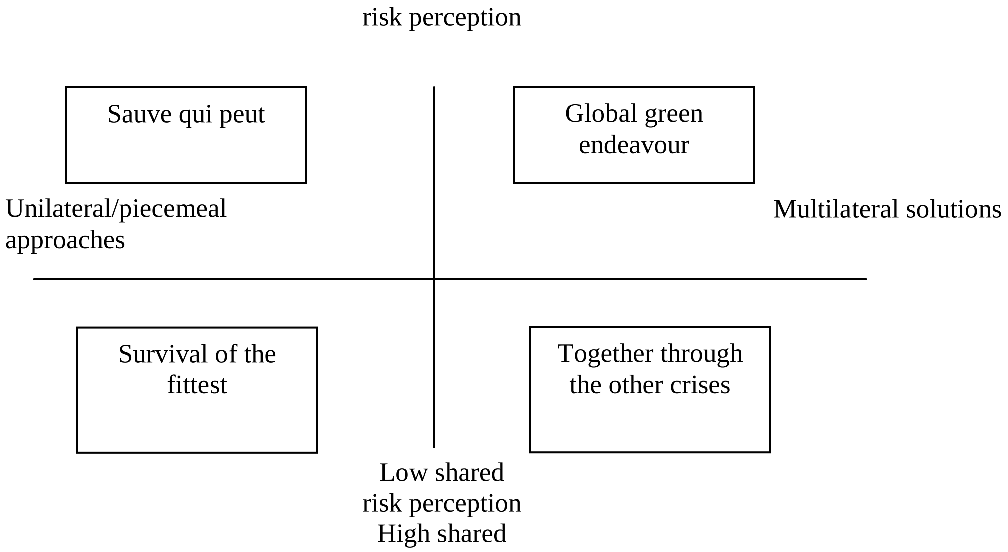

Figure 8. Four scenarios for global political responses to rapid climate change (Source: Zoeteman and Kersten, 2009)

There may be a tendency to shape a policy response to accelerating climate change, under the assumption that countries share a common perception of urgency, recognising the need for global cooperation. However, it would be prudent to anticipate a future in which this would not be the case. The expert meeting identified a number of options which would be robust, that is, useful in each of the four scenarios (Zoeteman and Kersten (2009):

- enhance climate resilience of water and food supplies;
- improve monitoring of climate change variables, notably of indicators of tipping points in the global climate system;
- develop and agree on rules for research and application of geoengineering options;
- enhance the flexibility of the infrastructure and constructions with regard to high sea level and flood levels;
- develop and export adaptation knowledge and technologies;
- improve international agreements on (legal status) of climate refugees;
- decrease dependence on unsustainable energy sources;
- increase public support for mitigation options, such as wind energy and CCS.

In reality, none of the above stylised scenarios will materialise exactly in the way described, and it will become only gradually clear in which direction the world will evolve. The actual future also depends on the way in which a possible rapid climate change will become ‘visible’, over time, through an evolving evidence base, and on the response of society and politicians to such evidence (Text box 4.2). From the perspective that a faster climate change than projected by the IPCC cannot be ruled out, policy choices and investment decisions should leave the door open for future course corrections. Important questions are not only about the specific additional policies that should be developed now, but also about which particular investments or development plans would likely be adequate for which level of climate change, and when that level may be reached. The next and final chapter presents possible policy strategies.

Priorities for policy development

- *A timely assessment of possible drastic policy measures to counter extreme climate change, allows for a balanced evaluation of the pros and cons of each of the options, in case an urgent situation would arise in the future.*
- *Geoengineering options are mostly considered a temporary solution, to win time, but in case emission reductions or carbon sequestering would fail, it may become a more permanent solution. Given the risks involved, development and implementation should be subject to international control, in both cases.*
- *Individual countries should acknowledge the possibility of international failure to address climate change, in which case even more attention to national adaptation will be required.*
- *A portfolio of policy options for small countries, such as the Netherlands, would include: the explicit inclusion of considerations of extreme climate change in various foreign (climate and non-climate) policy areas; integrating appropriate flexibility for long lifetime investment decisions; stepwise intensification of national mitigation and adaptation actions, as more information about rapid climate change would become available; accounting for the possibility that the country will be indirectly affected by climate impacts elsewhere; support for climate research and monitoring of potential tipping points; research targeting innovation and knowledge export; and a strategy to cope with climate refugees.*

What can we learn from the above for the possibilities to respond to extreme climate change? More specifically, what would be possible implications for Dutch policymakers, involved in both national climate and relevant sectoral policies, and international climate policy and other foreign policies? In any case, policymakers should take into account that the rest of the world may respond to an accelerating change in climate in very different and, as yet unpredictable, ways. Basically, all options would work best and with the least negative consequences if they would be developed and implemented in an internationally coordinated manner, not in the least because, in that way, costs and liabilities could be shared. However, examples of countries that have transferred national sovereignty to an international body in the area of resource management in the past, are scarce. The difficulty of developing an effective internationally coordinated climate change mitigation regime in the UNFCCC, is just one example.

In this context, it probably would be prudent not to exclude any of the non-optimal responses, at this stage, including controversial solutions, such as most of the geoengineering options. Indeed, countries and companies already have tested iron fertilisation of the ocean, and some countries are about to start substantive research programmes. It is also clear that different options have different characteristics, in terms of risks and feasibility. The best way of dealing with new options, such as geoengineering, may not be to treat them as one, but to distinguish between different variants. In our assessment, we concluded that the knowledge about most of the options is insufficient, at present, to perform a satisfactory comprehensive assessment, and it is too early to exclude any of them. A main dilemma concerns the fact that the option with the least risks (emission reduction) requires effective globally coordinated action that appears to be very difficult to realise, while some of the other options can be deployed by just a limited number of actors but can have large but uncertain impacts and risks. However, they could do this either on their own initiative or be sanctioned by the world community.

Our assessment has led to the following potential approaches, not in order of priority (see also Table 3 for a summary):

a. *International climate policy and other foreign policy*
   The Netherlands is only a relatively small player in the world economy, and, in case of a globally accelerating climate change, the country would be very dependent on international cooperation and action. Nevertheless, in the area of climate change, the country has played a sometimes defining role in international negotiations, which could be a basis for a future international role, in case of extreme climate change. Several areas for international policy interventions can be identified:
   - *Emergency climate change response negotiations.* If climate change would accelerate, and geoengineering options would remain politically controversial, enhanced efforts to reduce greenhouse gas emissions would be required, globally. The UNFCCC provides a framework for negotiating such increased emission reductions, but parallel efforts with coalitions of countries (including the EU) may be warranted. This includes efforts to mainstream climate change mitigation in relevant sectoral policies that are strongly dependent on international developments, such as those of energy and agriculture, but also the development of new financing mechanisms, building on CDM and similar experiences. Drastic emission reductions may include forced behavioural or structural economic changes, of which the political and ethical implications require careful evaluation. The International Energy Program (IEP), which forms the basis of the International Energy Agency, may inspire arrangements to address extreme climate change. The IEP is a legally binding treaty, addressing emergency oil stocking and sharing arrangements, to effectively respond to oil crises (IEA, 1973, amended 2008). Also, pressure on or sanctions for countries which refuse to participate cannot be excluded.
   - *Development of rules for research, testing and deployment of geoengineering options.* As discussed above, many of the geoengineering options have serious risks, and can be associated with many ethical and even security-related questions. International agreement on research and application can be pursued using the existing mechanisms (e.g., ocean fertilisation has been addressed in the context of LOS (Law Of the Sea) and CBD (Convention on Biological Diversity), and weather modification in the Environmental Modification (ENMOD) convention, but new mechanisms might be required. Proponents of geoengineering, such as the NOVIM group (Blackstone et al., 2009), and adversaries, such as Greenpeace, have proposed a number of rules for research (Santilo and Johnston, 2009). Greenpeace does not support any research into geoengineering, because it distracts from the real solutions, and

because large-scale manipulation of natural systems should be avoided. However, if research is proposed anyway, they say 'it must, at the very least, be scientifically justified, carefully and consistently assessed and regulated with precaution'. It should also be transparent, subject to international consultation and consent, non-commercial, and liability and redress should be clear (Santillo and Johnston, 2009).

The American Meteorological Society (AMS, 2009) recommends:

> 1) Enhanced research on the scientific and technological potential for geoengineering the climate system, including research on intended and unintended environmental responses.
> 2) Coordinated study of historical, ethical, legal, and social implications of geoengineering that integrates international, interdisciplinary, and intergenerational issues and perspectives, and includes lessons from past efforts to modify weather and climate.
> 3) Development and analysis of policy options to promote transparency and international cooperation in exploring geoengineering options, along with restrictions on reckless efforts to manipulate the climate system.

The Royal Society (2009) recommends to consider which types and scales of research require regulation, validation and monitoring; to establish de minimis standards for regulation of research; and to develop guidance on the evaluation of methods, including relevant criteria, and life cycle and carbon/climate accounting. In order to have a say in the development and application of controversial emergency response options, small countries, such as the Netherlands, could put the issue on the agenda and work towards international cooperation and control. Before doing so, a national view on these options would need to be developed.

- *Limitation and protection of climate refugees.* In parallel, increasing impacts of climate change in the most vulnerable parts of the world requires attention in the area of development collaboration, refugee management and international security. While there are legal mechanisms for environmentally displaced people, 'climate refugees' are not well-defined. Identifying hotpots and providing support to those areas, to limit vulnerability and enhance adaptive capacity, can limit the number of refugees, but those who cannot be avoided will have to be properly protected. Since one of the manifestations of rapid climate change will be increasing (frequency and/or magnitude of) extreme weather events, enhanced disaster prevention programmes also will be important. Particularly, innovative schemes to support the poor in coping with the economic impacts of disasters, such as risk transfer programmes, can be effective (Linnerooth-Bayer et al., 2005). In some cases, intentional migration as an adaptation mechanism may be considered.
- *International cooperation on knowledge and technology transfer.* International cooperation on knowledge and technology transfer should not be limited to developing countries, not in the least because the boundaries between developed and developing countries are increasingly fuzzy. Maximum support to large industrialising countries would be required to limit their emissions, because this is where most of the increases are expected.

Countries, such as China and India, are already rapidly catching up in developing new environmentally sound technologies, and countries, such as the Netherlands, can collaborate in these developments in priority niches. This also applies to adaptation methods and technologies, which could include enhanced technology transfer, targeted foreign investments, and novel instruments for knowledge and resource transfers.

- *Enhancing emission reductions in the Netherlands.* Limiting Dutch emissions can ultimately only make a marginal dent in global emissions. However, there are reasons to seriously consider preparing for drastic and innovative emission reductions. First, a serious reduction target may become part of an internationally agreed emergency response package. Knowledge of potential national policy options and impacts on economy and society is essential before entering into such an agreement. Second, drastic reduction targets, well beyond the current *Clean and Efficient* white paper, would need to seriously incorporate and integrate different policy areas – especially concerning the ministries of environment and spatial planning, economic affairs, agriculture and the treasury department. Third, there may be a first mover advantage, creating economic benefits. In the Netherlands, this may be particularly relevant for CCS, potentially a key technology to achieve drastic emission reductions. The Netherlands, with a large number of point sources, pipeline infrastructure and storage capacity, could be an international hub for CCS knowledge and experience. Policies and technology options for serious emission reduction are likely to affect consumers directly, maybe curtailing freedom. Moreover, some policies and options are outright controversial, including CCS and others, such as nuclear energy and various forms of renewable energy. Any preparation for drastic emission reduction, therefore, should include a strategy on handling public acceptance.

b. *Enhanced adaptation action in The Netherlands.* With the recent adoption of the National Adaptation Strategy 'Make Space for Climate', the recommendations of the Delta Commission to make The Netherlands safer and more climate-resilient and the National Water Plan, already major steps have been taken to prepare the country also for projected, but also for accelerating climate change. However, in parallel with the three above options it may be wise to start thinking more seriously than hitherto about alternative, or additional adaptation options.

- *Broadening the portfolio of adaptation options.* In a situation of 'recognised ignorance', enhancement of adaptive capacity with 'soft' measures, such as insurance and disaster planning, may prevent investments that later would be deemed unnecessary. Also, adaptation options that are more radical than the currently considered incremental options, may be required and deserve further exploration.
- *Flexibility and anticipation.* Another option is anticipating design, at little extra cost, taking into account the possibility that, at a later stage, constructions may have to be enlarged or changed to respond to the impacts of an accelerating climate change, at the same time minimising the risk that investments already made, may prove to have been unnecessary. In addition,

if different adaptation pathways appear possible, the strategy with the highest degree of flexibility may be preferable. Evidently, the optimal solution depends on the lifetime of the investment; ranging from decades for sewerage systems, to more than a century for urban and industrial areas.

Main knowledge gaps

Presently, the possibility of rapid climate change and sea level rise cannot be ruled out, but their probability cannot be established. For a timely response, it is crucial to monitor changes in the climate, atmosphere and ocean, as well as in marine and terrestrial systems, and to strengthen research into these systems and their interrelations.

Therefore, the bad news is that extreme climate change cannot be excluded. The good news is that there is still time to develop innovative responses by strengthening and possibly redirecting research priorities. Ongoing research aimed at increasing the understanding of the climate system, climate change impacts, and the economic, environmental and social dimensions of mitigation and adaptation options, remains valid and urgent. At the same time, a recognition of the possibility of extreme climate change suggests a number of specific areas where research can be strengthened or initiated:

- *Feedbacks and tipping points.* Because of the large risks involved, future climate change research could more explicitly include work on the feedbacks that may trigger more extreme climate changes than was assessed by the IPCC, focusing on those feedbacks that appear to lead to the highest risks. Several potential tipping points have been identified, often related to specific (positive) feedbacks in the climate-ocean-biosphere system.
- *Triggering points.* In addition to ‘tipping points’ that reflect elements of the coupled ocean-atmosphere-biosphere system, which are susceptible to threshold behaviour, one could also distinguish ‘triggering points’ in the social-political system. Triggering points are factors that raise the sense of urgency and generate sufficient social concern to move the political system to the adoption of measures. In the area of the environment, dying forests and the ‘ozone hole’ are examples of such triggering points in the past, for climate change, melting glaciers and ice caps appear to fulfil such a role, globally. For the Netherlands, an example is the unlikelihood of the popular, historic ‘Eleven Cities’ skating tour taking place in the future. Exploring the dynamics of such triggering points in the context of climate change would be an interesting topic for research, complementary to the tipping points.
- *Upgrade of monitoring and early warning systems.* Related to the above tipping points and triggering points, additional monitoring efforts may be needed, because the current monitoring systems may not be best equipped to identify signs of accelerating climate change, for example, related to the eventualities in the climate system discussed in Kattenberg and Verver (2009). The Netherlands could play an active role in stimulating such enhanced monitoring, and possibly by providing financial and organisational support.

- *Worst case climate impact research.* Most impact research focuses on the IPCC range. It would be useful to analyse the risks of low probability/high impact events for vulnerable sectors, not only within the boundaries of the Netherlands or Europe, but also including indirect risks through global impacts.
- *Modelling analysis of long-term effectiveness of emergency response options.* Scenario and modelling analyses of combinations of the four options discussed in this report, and their deployment, over time, is recommended. Research aimed at increasing the understanding of these issues may be more important than attempts to achieve higher resolution climate projections.
- *Environmental, technical and socio-economic assessment of innovative emergency response options.* Comprehensive multidisciplinary research into emergency response options would become increasingly important, including:
    - *System transitions.* Extreme climate change would require mitigation and adaptation responses that go beyond incremental improvements of current technologies. This suggests that (additional) research should focus on system changes, for instance, mobility rather than automobiles, energy security rather than power plants, global food security rather than crop yields.
    - *Geoengineering.* Geo-engineering, particularly 'solar radiation management' options that would quickly counteract warming by changing the earth's radiative balance, is increasingly proposed as a safety valve in case of an accelerating climate change, and research started in the United States and other countries. However, these options are still surrounded by very important questions about risks and ethics. Participation in internationally organised and controlled research might be preferable to non-participation and the associated lack of influence. Options which are currently assumed to have relatively low risks (such as cloud seeding, or methods to artificially capture carbon from the atmosphere) may be priority candidates.
    - *Policy instruments.* The current assessment focused on the physical characteristics and where possible economic and societal implications of emergency response options. Follow-up work is required on possible policy instruments that can be used to implement the options, and their consequences.
    - *Global crisis management.* A climate crisis may develop on top of food, water and financial crises. More fundamental transitions in consumption and production patterns that may be needed to respond to such crises are likely to require behavioural or structural economic changes, and may involve shifts in the international power balance, with associated international security implications. Here, the social sciences have an important role to play, and we may learn from the area of disaster management.

Table 4. Selected options for 'worst case' policies in the Netherlands (in italics: options often called 'geoengineering')

Worst case policy option		**Foreign policy**	**National mitigation policy**	**National adaptation policy**	**Monitoring and research**
Drastic emission reductions		• Intensify EU, UNFCCC action • Support international debate on emergency emission reductions (IEA+) • Bilateral agreements • Integrate in development collaboration, technology cooperation	• Stimulate pioneering low-carbon technology experiments • Maintain national policies at forefront of international initiatives	• Explore options for using synergies and avoiding trade-offs	• Research on system transitions and national niche areas • Stimulate knowledge and innovation for export
CO_2 sequestration	Terrestrial options	• Address in UNFCCC, CBD	• N/A for small countries	• Explore using synergies and avoiding trade-offs	• Continue ongoing research
	Marine options	• Address in IMO, CBD • Promote rules for research	• N/A	• N/A	• Follow/participate in international research
	Aquatic options	• Promote coordination international research	•	•	• Intensify ongoing research
	Air capture	• Promote coordination international research	• N/A	• N/A	• Follow/participate in international research
Albedo change	*Space/stratosphere*	• Promote rules for research • Avoid unilateral action	• N/A	• N/A	• Follow/participate in international research
	Surface options (cropland, desert, urban), cloud seeding (e.g., sea salt)	• Avoid unilateral action; develop international rules (ENMOD, other), coordination or moratorium	• N/A	• N/A	• Follow/participate in international research
Adaptation	Global impacts: refugees, security	• Enter issue in existing international mechanisms, explore need	• Explore options for using synergies and	• Broaden portfolio • Integrate flexibility and	• Contribute to international monitoring of potential tipping points, and their

		for new ones • Focus development collaboration on most vulnerable hotspots • Develop mechanism for extra support vulnerable regions/ compensation • Integrate in trade, food, security policies	avoiding trade-offs	anticipation in policy development • Prepare for unconventional emergency options	societal impacts • Scenario analyses emergency response options • Research on robust, flexible and innovative options • Stimulate knowledge and innovation for export

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Appendix 1 A. Drastic emission reduction

A.1. CO_2 capture and storage

1. Short description of options

CO_2 capture and storage (CCS) is a process whereby CO_2 is captured from a large point source, transporting it to a storage location and isolating it from the atmosphere, underground or in the lower regions of oceans. It can be applied most effectively to large CO_2 point sources in industry, power production and (fossil) fuel production (IPCC, 2005). CCS applied to biomass-fuelled plants would result in 'negative' CO_2 emissions.

On a global level, industrial and energy sectors emitted 22 $GtCO_2$ eq in 2004, or 45% of total GHG emissions including Land use and Land-Use Change and Forestry (LULUCF, IPCC, 2007). CCS is considered a promising option for reducing emissions from industry and energy supply (IPCC, 2007), and most modelling studies consider it to contribute around 20% to the total mitigation effort in a 450 ppm long-term policy scenario (IEA, 2008a). In the Netherlands, industry and power production account for 100 Mt or 57% of CO_2 emissions in 2002, and are projected to steadily increase to 125 Mt by 2020 (Van Dril et al., 2005).

2. Effectiveness

CCS is the only technology that allows for deep cuts in CO_2 emissions while allowing for the continued use of fossil fuels in industry and energy production (Bakker et al., 2008). The importance of CCS is particularly large in scenarios based on electricity, hydrogen and gas/coal-to-liquids without a full transition to renewable power generation or drastic reductions in energy demand.

The entire process chain of CCS, that is, capture, transportation and storage of CO_2, has not been demonstrated on a full scale. However, most of its components have been demonstrated individually, on smaller scales. As such, CCS is not expected to pose major technological challenges, but scaling up would take time, costs are still high, and questions of social acceptance remain. The geological storage capacity for CCS is also a source of uncertainty. Having commercial CCS up and running by 2020 (G8, 2008) is aimed for, but this requires far-reaching additional policies to incentivise CCS.

In several scenarios, CCS plays a large role from 2020 onwards. For example, several gigatonnes are projected to be stored in the Blue Map scenario of the IEA Energy Technology Perspectives to 2050 (IEA, 2008a). In the IEA ACT scenarios (IEA, 2006), CCS accounts for 20 to 30% of the total global GHG reduction by 2050, aiming for 550 ppmv CO_2 eq stabilisation levels. This is broken down into 12 to 18% for the power sector, 3 to 5% for coal-to-liquids and gas-to-liquids technology and hydrogen production, and 4 to 6% in industry. Projections by the IPCC (2005) assumed that, by 2050, 10 $GtCO_2$/yr can be stored, accounting for 15 to 55% of the total GHG reduction achieved in a range of scenarios.

Physical leakage of CO_2 from storage reservoirs back into the atmosphere is called seepage. Potential seepage pathways include faults in the cap rock, migration through the ground water, and in particular through injection wells. It is not straightforward to predict leakage of CCS as this would depend on the specific reservoir features. The IPCC (2005), however, considered that 'the fraction retained is likely to exceed 99% over 1000 years'. This number should be considered an educated guess, based on natural analogues, geological knowledge and modelling, but not on empirical data of long-term storage in geological reservoirs. In general, there is widespread faith in permanent storage of CO_2 in geological reservoirs, as long as the storage locations are well selected, maintained, monitored and, if necessary, repaired.

The CO_2 capturing process is rather energy-intensive and reduces the efficiency of a power plant or manufacturing facility. For a coal-fired power station, the decrease in conversion efficiency is around 10 %, for instance, from 45 to 35% (IPCC, 2005). This results in significantly higher power generation costs, and if these are the marginal cost of production, in higher prices. This may, at least in theory, shift production of energy-intensive products, such as aluminium and steel, to other regions where CCS is not applied. It has been difficult, however, to quantify this 'carbon leakage' effect. Reinaud (2008) concluded that there are currently no indications that increases in power prices due to the ETS, have resulted in a shift of production to outside the EU. Apart from driving up the costs, the energy penalty results in significant upstream emissions, as more coal mining needs to take place. Life-cycle emissions have been quantified by, for instance, Koornneef et al. (2008), and led to the conclusion that CCS could reduce emissions from a coal-fired power plant by some 70 to 80%, compared to a conventional plant. Its effectiveness can be enhanced by co-firing with sustainable biomass.

3. Feasibility

The immediate feasibility of CCS is limited because of the costs, the lead times for implementation and storage potential. It is estimated that a stable carbon price of at least 50 USD/tCO_2 eq (around 35 euros/tCO_2 eq) is needed for CCS to be commercially viable (IEA, 2008b). For some industrial sources of CO_2, including ammonia, some stacks in refineries, and natural gas processing, the costs are likely to be lower. For other industries, such as steel and cement, the costs are estimated to be higher, at some 100 euros/tCO_2 or more.

These costs are made up of investment cost and fuel costs in the capturing process and, to a small extent, costs for transportation and storage. As CCS is applied to large point sources, the investment costs are also high, for example, 0.5 to 1 billion USD for a large coal-fired power station.

The largest technical challenge is that of a full-scale demonstration of CCS on a range of CO_2 sources, and storage in different types of reservoirs in different countries. Once the technology has been proven on this scale, in technological terms, only a CO_2 pipeline network would be required. However, also important is the availability of suitable storage sites within reasonable distances. These can be in empty oil or gas fields, on-shore or off-shore, or in saline aquifers. Most estimates of global storage capacity are of the order of 1000 to 2000 $GtCO_2$ (IPCC, 2005), but this number is surrounded by uncertainty, and the large-scale and long-term feasibility of CCS would depend more on local geology than on global capacity. The Netherlands is estimated to have significant storage potential, but over half of this potential is located at the huge Slochteren gas field, which will not become available until after 2050.

Application of CCS requires a range of planning activities:

- Designing of the capture installation
- Planning and obtaining licences for a CO_2 pipeline (or ship network) and compression and injection facilities
- Selecting and characterising a suitable storage reservoir
- Implementing procedures for monitoring and safety
- Acquiring the required licenses
- Financing and liability arrangements

Subsequently, the capturing installation (possibly integrated in power or other industrial installations), the pipeline or other transport mode, and the storage injection facilities, need to be constructed. Assuming the technology has been demonstrated for a wide range of applications, and that policy frameworks for monitoring and licensing are in place, the minimum lead time for implementing CCS in industrial and power generation facilities would be around five years.

As CCS is an end-of-pipe solution to CO_2 emissions, it requires no structural changes in the economy. Apart from the abatement costs, no significant welfare effects from application of CCS are currently projected.

4. Political implications

Large-scale application of CCS could be achieved through economic incentives or command-and-control regulation. Carbon pricing, however, is only likely to be sufficient, if the required price level would be maintained and secured for a long period of time (the economic lifetime of the plant). There is much uncertainty about the costs, and estimates vary between 30 to over 80 euros/tCO_2 eq, which is higher than price levels attained by the EU ETS. Therefore, could be concluded that additional policies are necessary. These may include, for instance, a CCS mandate, emission portfolio standards at plant level, sectoral level or national level, and a variety of financial instruments, such as soft loans and grants, and various forms of public and private partnerships (Groenenberg & De Coninck 2008). Mandatory CCS or emission portfolio standards would come at a cost to plant operators and could be covered by a fund, or by increased electricity or product prices.

Because of the possible 'leakage effects'[13] in industrial sectors that operate in a global market, it is preferable to implement strong CCS incentives on a global scale. However, in the absence of an adequate global policy framework for GHG reductions, incentives for CCS on a global level are difficult to implement. Therefore,

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[13] In this context, leakage refers to the relocation of emission intensive activities to countries or regions that have more favourable policies. The net global emission reduction in such cases is nil.

implementing them regionally (EU) would be a suitable policy level. For power production, 'leakage effects' are limited, as electricity is not easily transported over long distances.

Application of CCS in industry and power production can be seen as an option that, given the need for substantial GHG emission reductions, protects the interest of the large players in the current economy, that is, the fossil-fuel industry and energy-intensive industries. This can be seen either as an advantage or a drawback: an often highlighted concern is that large-scale introduction of CCS may lead to a lock-in of a fossil-fuel based economy, and reduce the chances for renewables (or nuclear energy).

A significant social issue is related to the (perceived) risks of on-shore CO_2 storage. For the Netherlands, this became apparent through the amount of public resistance to a CO_2 storage project at Barendrecht (Dutch daily newspaper De Telegraaf, 2009). Local public resistance is expected to decrease with successful demonstration projects providing confidence in the feasibility of safe on-shore storage, as well as better public communication and community engagement methods.

5. Options and consequences for the Netherlands

In sum, CCS plays an important role in recently developed mitigation scenarios and could also be important in drastic mitigation. It can be applied to all large stationary CO_2 sources, which make up more than half of domestic CO_2 emissions in the Netherlands. Moreover, CCS could facilitate low-carbon transportation if used in electricity or hydrogen production, and in combination with biomass-fuelled plants, even in situations of negative emissions. The lead time is modest, around (at least) five years, particularly if a CO_2 pipeline network would be in place. The abatement costs are most, below 60 euros/tCO_2 avoided.

Wide application of CCS could be achieved by strong economic incentives, with certainty over the longer term, or by mandating it for new and existing large CO_2 point sources. When CCS policy is implemented at a national level only, this may cause relocation of economic activity (so-called *carbon leakage*), although this is not likely at a European level.

As a policy option for drastic emission reduction in the Netherlands, CCS has significant potential, as well as some major challenges. First, there is still substantial uncertainty surrounding full-scale implementation – in terms of both costs and feasibility. Second, even in a situation where the necessity of drastic emission reduction is widely shared, implementation of CCS can only be effective when there is sufficient public acceptance, and this is by no means a certainty. Third, CCS policy can potentially increase the attractiveness of fossil energy over renewable energy. This notion should be taken into account, to avoid policy competition and adverse effects. In the fourth place, geological storage capacity may not be available, immediately, and gas fields may need to be abandoned or depleted faster to allow for immediate storage of CO_2.

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A. 2. Power Supply – Nuclear Energy

1. **Short description of option**

Nuclear power plants use fission of radioactive material to produce heat, which is then transformed to power via steam. Theoretically, nuclear *fusion* can also be used, but this is currently still in an early experimental phase and not likely to become available before the middle of this century (Clery, 2009).

At present, 370 GW (436 reactors) in 30 countries provide 15% of the global power supply, with 39 GW under construction. Over the past decades, nuclear power has developed slowly. The IEA and IAEA expect that, under current economic growth expectations, global capacity may double by 2030, or possibly triple, under a stringent climate regime. Sixty per cent of the currently installed capacity is in France, the United States and Japan. Most new capacity will be realised in Asia, Russia and transition economies (IAEA, 2007; IEA, 2007; IEA, 2008).

Nuclear power provides base load electricity, typically, in large power plants with output of 500 to 1000 MW_e. Smaller units are being developed, allowing for regional power generation and use with desalination plants – but this concept is not yet widely available. Although proponents claim that it is technically feasible to create an inherently safe reactor (so-called type IV), the current generation of reactors is expected to stay mainstream for the coming decades (Van der Zwaan, 2008).

2. **Effectiveness**

The technical mitigation potential of nuclear energy is large (IPCC, 2007) and fuel is available in abundance for the coming decades. The speed needed for drastic measures, such as emergency response, cannot be met by nuclear plant construction. Building a new nuclear power plant takes up to eight years, permit procedures take around five year. The lead time until the mitigation effect occurs is instantaneous once the reactor starts operating.

Greenhouse gas emissions from nuclear energy, even with a LCA approach, is several percent, maximally (IAEA, 2008). The lifetime of a nuclear plant is long, so deciding on the expansion of nuclear energy now will, from an economic perspective, lead to decommissioning in 65+ years from now (lead time of at least 5 years, economic lifetime of 40 years, with two optional extension periods of 10 years).

The (negative) spillover effects of scaling up nuclear energy are significant and relate to three main problems that have not been solved, yet. First, nuclear waste will remain radioactive for 10,000 years, even if processed. Second, proliferation of nuclear technology for non-peaceful purposes is still a concern and the basis for several initiatives, such as the non-proliferation treaty (NPT). Besides state supported development of weapons, terrorist attacks on storage and transport facilities or reactors pose a real threat. Finally, the third problem that has not been addressed, yet, is reactor safety and accident risks, which pose a potential health hazard (Bruggink and Van der Zwaan, 2001). Substitution and rebound effects of nuclear energy consumption are non-existent, since it is only the production process that is different – the resulting energy is physically the same.

3. Feasibility

The production costs of nuclear energy vary somewhat per location, but are typically similar to costs of coal or on-shore wind energy (IEA, 2008). As a result, the abatement costs in euros/tCO_2 are (very) low. Fuel, operation and maintenance costs are small, compared to capital costs (Scheepers et al., 2007). The private sector, however, is hesitant to invest in nuclear energy, since (1) the regulatory risk over the lifetime of the reactor is high, and (2) the capital intensity leads to the requirement of large initial investments.

Although a nuclear power plant can be easily integrated in the power grid of most countries, technology for construction and fuel production is not globally available. Concern about the use of nuclear technology for non-peaceful purposes prevents free transfer of technology, severely limiting possibilities for global deployment.

4. Political implications

The costs of nuclear power are comparable to those of coal, even under a very modest carbon price. The main obstacle to scaling up nuclear capacity is public acceptance and associated permit restrictions. In the light of the significant risks involved, national governments take a certain amount of control over the question of whether or not new installations should be built – even if the energy sector is market-based and deregulated. Policy instruments to effectively increase nuclear capacity are mainly guaranteeing long-term stability with respect to regulation (i.e. minimise the regulatory risk). Addressing proliferation concerns in a world that increasingly relies on nuclear power, would be a major challenge.

5. Options and consequences for the Netherlands

In the Netherlands, a single nuclear power plant is in operation for energy production at Borssele, which produces around 3% of the total demand. Technically, there is no reason why the current coal-fired plants cannot be replaced by nuclear plants, especially if the main aim is to further decarbonise the energy sector.

As a policy option for drastic emission reduction in the Netherlands, nuclear energy is not useful in the short term, since the lead time is too long. Nuclear energy, however, can play a role in the medium term, to help phase out fossil-fuelled power plants until a full-scale renewable energy alternative is available.

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A. 3. Energy Supply – Renewable Electricity

1. **Short description**

Renewable energy is derived from natural processes that are replenished constantly. In its various forms, it derives directly from the sun, or from heat generated deep within the earth. It includes electricity and heat generated from solar, wind, ocean, hydropower, biomass, geothermal resources, and biofuels and hydrogen derived from renewable resources (IEA, 2002). In short, in developing countries, of the 15% in renewable energy, 7 to 8% is traditional and potentially unsustainable biomass, and 5.3% is large hydropower, which leaves only 2.5% in 'new' renewables (IPCC, 2007). Typically, a distinction is made between renewable energy sources for heat (RES-H), power (RES-E) and transport fuel (RES-F).

- **Heating and cooling** from renewable sources consists of geothermal, solar thermal and biomass combustion, and takes on 6% of total heat demand worldwide (IEA, 2008). There is a substantial potential for solar water heating which can be implemented in urban areas at low cost.
- **Electricity** from renewable sources amounted to 18%, in 2006, of which 16% hydropower (IEA, 2008: 162-165). Wind power installed capacity has been growing very fast in some countries, but still only accounts for less than 1% of global power production (IEA, 2008). Contributions of Solar PV and Concentrated Solar Power are only marginal, but have huge potential (IEA, 2008). Biomass accounts for only 1.3% of power production.
- **Transport fuel** from renewable sources is limited to 1.5% of all road transport fuel demand. Most is bioethanol, replacing petrol, with major producers in Brazil and North America. Biodiesel replaces a small fraction of the total fossil-diesel market for transport, and is currently mainly used in Europe.

This fact sheet mainly deals with renewable power production. Transport fuels are discussed in the fact sheet on transport, whereas heating and cooling is typically related to the building sector. IEA projections show that renewable energy, excluding traditional biomass, will grow from 7% in 2006, to 10% by 2030, under influence of high fossil-fuel prices and what they refer to as strong policy support. In the climate policy scenario that targets 450 ppm, the amount nearly doubles by 2030 (IEA, 2008).

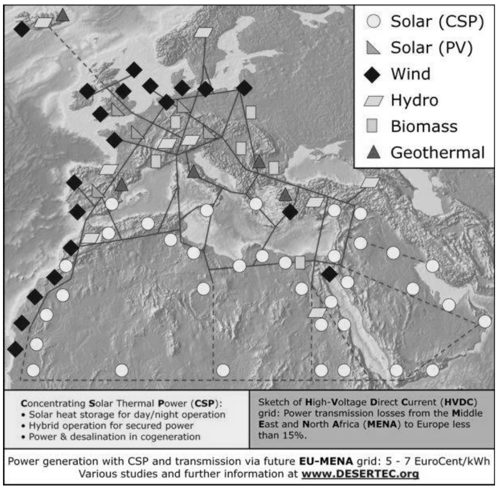
Intermittency

Renewable energy supply is mostly intermittent, following natural fluxes of sun light, wind and water. Energy demand is dictated by human behaviour, and does not necessarily coincide with supply.

Technological maturity

Renewable energy technologies vary widely in their stages of technological maturity. A number of technologies are considered 'mature', such as bioethanol production, biomass combustion, on-shore wind energy and hydropower. Technologies, such as off-shore wind energy, solar-PV and concentrated solar power, are in the deployment phase, but still gain much from ongoing research. In addition, a number of new concepts are in the (very) early stages of development, such as artificial photosynthesis and nanotechnology photocells (IPCC, 2007).

In the absence of efficient means to store energy on a large scale, a large share of renewable energy in the total energy mix can cause problems. Moving towards renewable energy shares of over 50% requires increasing decentralised production, more sophisticated demand management and enhancing battery storage or pump storage capacity. Various innovative ideas have been launched to address the intermittency problems: linking grids across the North Sea to absorb large shares of off-shore wind energy, creating energy hubs with pump storage capacity, and even creating a huge new infrastructure linking the Middle East and North Africa (MENA) to Western Europe, to link solar abundance areas with high energy consumption areas .



Concentrating **S**olar Thermal **P**ower (**CSP**):
- Solar heat storage for day/night operation
- Hybrid operation for secured power
- Power & desalination in cogeneration

Sketch of **H**igh-**V**oltage **D**irect **C**urrent (**HVDC**) grid: Power transmission losses from the **M**iddle **E**ast and **N**orth **A**frica (**MENA**) to Europe less than 15%.

Power generation with CSP and transmission via future **EU-MENA** grid: 5 - 7 EuroCent/kWh
Various studies and further information at **www.DESERTEC.org**

Figure A.4.1. DESERTEC, a German Industry Initiative, aims at connecting Europe (high energy demand) to the Middle East and North Africa (high renewable energy potential) by means of an advanced high voltage direct current network.

2. Effectiveness

Although, currently, there is not one technology that can replace all carbon-intensive uses of energy, the technical potential for renewable energy is substantial. Geothermal and solar PV represent the largest share with 6600 EJ/y, followed by wind and biomass combined at 850 EJ/y, and hydro and ocean at around 80 EJ/y (IPCC, 2007). The greenhouse gas abatement potential is substantial at reasonable costs if pursued aggressively – McKinsey, for example, projected a combined share of CCS, nuclear and renewables at 70%, by 2030 (McKinsey, 2008).

Coal-based and renewables-based power productions are complementary: coal runs in baseloads and does not easily react to fluctuations in demand, whereas renewables typically run either in baseloads or intermittently. A combination of intermittent/baseload renewable power and a variable source, such as natural gas, makes more sense than completely replacing all fossil capacity with renewable energy. The luxury of choosing or prioritising between different types of renewables is not available with drastic mitigation, since all available and achievable options are needed to reach a significant share of renewable power.

Implementation and lead time
Most renewable technologies can be implemented quickly, with construction times from six months to two years. Lead times cover environmental assessments and permit procedures, and currently take anywhere between 1 and 7 years. The typical economic lifetime of a plant is anywhere between 12 and 20 years. Once installed, the effect on emission reduction is direct.

Indirect effects
Positive spillover effects from renewable energy include enhanced energy security, potential access to energy in developing countries and increased employment. Negative spillover effects include local environmental pollution (e.g., through biomass combustion or pv-panel production). Substitution and rebound effects of renewable energy consumption are non existent, since it is only the production process that is different – the resulting energy is physically the same.

3. Feasibility
In terms of feasibility, renewable energy is one of the most promising solutions for mitigation of greenhouse gases. The implementation speed is limited by a number of factors: cost and local potential, intermittency, and environmental and sustainability concerns. In a drastic mitigation scenario, the local availability of renewable sources and problems concerning intermittency are most prominent. Costs of renewable energy depend on the technology and the availability of resources, varying from 0-20 euros/tCO_2 for biomass waste combustion to 750 euros/tCO_2 for small-scale grid-connected solar PV. As many technologies are in their early stages of technological maturity, the costs are expected to decline rapidly (IEA, 2007).

Welfare and equity considerations
As most renewable energy technologies are more costly than the non-renewable alternative, this will increase the price of energy, either through the increased market prices or through government policy intervention. Renewable energy resources are not spread evenly[14] across the globe, so increasing the share of renewables will place an unequal burden on different countries. Note that countries closer to the equator, typically, have more solar and biomass potential than those further removed from the equator.

Structural change and technological availability
Renewable energy requires relatively limited changes to the energy infrastructure, even at high levels of penetration, since the energy itself is not significantly different from the high-carbon alternative. The main challenge for increased shares of RES-E is dealing with intermittency (matching demand and supply).

4. Political implications
To increase the share of renewable energy, possibly by actively displacing existing carbon-intensive production, two types of instruments are available. The first type is market-based, either price based (direct subsidies, feed-in tariffs) or quantity-based

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[14] The EU, for example, reflects this in the specification of the 20% goal for 2020: countries have a national target according to potential and GDP.

(tradable obligation, portfolio standard). The second type is command and control, using minimum standards and requirements to direct production away from carbon-intensive energy and towards renewables. In case of extreme mitigation, a mix of command and control (to displace coal) and market-based instruments (to create a balanced mix) are most likely to be effective. Price-based mechanisms are slightly less efficient, but much more effective and flexible than quantity-based instruments.

Pro-renewable energy policy can be implemented at all policy levels, but in practice it is most effective on national government level. Support schemes on regional levels (e.g. EU) can improve efficiency, but involve burden-sharing agreements between nations.

Renewable energy consumption is not distinguishable from 'grey' energy consumption and, as such, consumers are neutral towards renewable energy. Therefore, there is no change in behaviour required, although the price of energy will increase substantially, in most situations. Wind parks in populated areas are typically met with resistance; biomass is accepted only if the production sufficiently addresses sustainability issues.

5. Options and consequences for the Netherlands

As a policy option for drastic emission reduction in the Netherlands, moving to renewable energy is paramount. However, being a densely populated country, the natural resource base in the Netherlands is limited. The main resources available are imported biomass for power, heat and transport, and (off-shore) wind power. Solar energy use in urban environments is an option, but still costly for large-scale application in the Netherlands and, therefore, a less likely candidate for drastic mitigation.

The technical potential for off-shore wind energy production in the North Sea is at least 10 GW, 20 to 25% of total demand. The potential for on-shore wind energy production in the Netherlands is limited; 5 GW, 6% of total demand[15]. Current coal-fired plants representing over 4 GW in production capacity, of which 30% can be replaced by direct co-firing of biomass with minor plant modifications – and with major modifications and gasification plants this can increase to over 80%. Current gas-fired capacity of 8 GW can almost entirely replace natural gas by synthetic natural gas (SNG). Note that the biomass required to displace coal and gas is all import-based, and requires an increase in the market size by about one or two orders of magnitude.

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A. 4. Transport and its infrastructure

1. Short description of option

In this fact sheet, the transport sector covers road, rail, water, air and non-motorised transport, based on full chain emissions (i.e., including emissions from fuel and power production, although not all emission figures cover these).

Globally, the transport sector accounted for 6 $GtCO_2$ eq[16], or 13% of 2004 emissions (Kahn Ribeiro et al., 2007) and is projected to double by 2050, with the bulk of the increase taking place in non-Annex I countries. In 2005, CO_2 emissions[17] from the transport sector in the Netherlands were 39 Mt, almost 20% of the national emissions (Hanschke, 2009), which also includes non-road transport. Road traffic (responsible for about 85% of GHG emissions in the sector) is projected to increase by about 10% in the period up to 2040, assuming continuation of current policy (Hanschke et al., 2009). It is generally accepted to be a crucial but difficult sector to address, when it comes to GHG reduction.

GHG emissions in the transport sector can be reduced by (after Grütter, 2007; VROM-council (VROM-raad), the Dutch Council for Housing, Spatial Planning and the Environment, 2008):

1. Limiting the demand for transport
2. Improving efficiency in transport on a person/tonne-km basis (i.e., modal shift)
3. Reducing the carbon intensity of vehicles on a km basis (energy efficiency, low-carbon fuels and reduction in CH_4, N_2O and F gases)

2. Effectiveness

The first two mitigation categories mainly relate to behavioural changes, while the third contains measures of a more technical nature. Examples of mitigation policies and measures include:

1) Limit (private) vehicle use or amount of air travel allowed, possibly broken down by subsector, such as ‘for leisure’, or ‘commodity air travel’;
2) Promoting or mandating more use of non-motorised transport, mass-transit public transport and shipping;
3) More efficient driving and improving energy efficiency and setting standards for emission factors for vehicles, ships and aircraft and /or mandating biofuel/electrical/hydrogen-based transportation (with appropriate measures for upstream emissions, notably CCS); and reduction in emissions from air conditioners.

The measures mentioned above can add up to a large technical mitigation potential, that is, transport emissions can be reduced by over 90% (given a decarbonised power and hydrogen production). Generally, bunker fuels for aviation and shipping are more difficult to decarbonise than those for road transport (Hoen et al., 2009;

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[16] Including bunker fuels; excluding indirect emissions

[17] Conform IPCC definition, excluding bunker fuels

Hileman et al., 2009). The report *Saving oil in a hurry* (OECD/IEA, 2005) provides an overview of a number of oil demand reducing measures that could be used during an extended oil crisis. Most of these also reduce GHG emissions, and may also be 'acceptable' in case of an extreme mitigation scenario.

Hanschke et al. (2009), in a scenario analysis for the road transport sector in the Netherlands, estimated that a 30 to 35% reduction in CO_2 emissions by 2040, compared to the business-as-usual scenario (BAU) (including current policy), is possible, assuming gradual introduction of power or hydrogen. However, because of the projected growth, the emissions in 2040 will be around 1990 levels, on a well-to-wheel basis[18]. Hoen et al. (2009) estimated a 65 to 95% reduction in emissions from private vehicles, in the long term, by a combination of low-carbon fuels and advanced vehicle technology. The freight transport sector appears more difficult to address.

It is likely that a mix of both the behaviour/demand side (options 1 and 2) and supply side (3) are necessary, in order to achieve deep emission reductions, as the technical measures are not likely to be sufficient (Hoen et al., 2009; Johansson, 2009; CE Delft, 2007).

Options 1 and 2 mainly require behavioural changes, and to some extent infrastructure (e.g., improved public transport or ports, and system changes in the economy related to freight transport). Under strong policies, these measures could be implemented within 5 to 10 years. As energy efficiency improvement of the internal combustion engine has a limited potential (Hoen et al., 2009), decarbonisation of the transport sector (option 3) requires large-scale infrastructural changes (hydrogen production and distribution, CCS, or large-scale renewable power), and would require more than 10 years to take effect. In addition, a change in the vehicle stock is generally slow, as the average economic lifetime of vehicles is more than 10 years. Large-scale biofuel use would not require such infrastructural changes but the potential for emission reduction could be much smaller. The main limiting factor is on the supply side, that is, the amount of agricultural land available to produce biofuels[19]. In addition, second-generation biofuel production facilities need to be built. On the end-user side, there are no major issues, but in order to use more than 20% ethanol, flex-fuel vehicles need to be introduced.

With regard to substitution effects and carbon leakage, we note that freight transport might be sensitive to policy changes and shift to other world regions, leading to carbon leakage. A limit on travel demand may shift economic activities to other sectors. Changing to 'zero-emission' fuel carriers may increase emissions in other sectors, such and power production or agriculture, if these are not covered by ambitious climate policy.

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[18] Given substantial share of biofuels and hydrogen/electricity, this provides a better indication than the IPCC methodology, where the emissions for the production of these energy carriers are included mainly in other sectors.

[19] If dietary changes towards less animal protein are achieved, this will increase the potential substantially.

3. Feasibility

To limit the demand for transport (option 1), both the investment and abatement costs are generally low. The OECD (2005) estimated the cost of driving bans, telecommuting and a compressed work week, below 1 USD/tCO_2 eq. Modal shift (option 2) may imply high investment cost (e.g. infrastructure for public transportation) but abatement costs are generally low (carpooling) to medium (>50 USD/tCO_2). No data were found on modal shift in the freight transport sector. For decarbonisation (option 3) of the road transport sector, the investment costs are often high, while abatement costs, in the short term, are 200 to 300 euros/tonne, and in the longer term, <100 euros/tCO_2 eq. Biofuel abatement costs are of the order of 100 to 200 euros/tCO_2 eq (Hanschke et al., 2009). When oil prices are around 150 USD/barrel, abatement costs may come down by 200 euros/tonne (Bakker et al., 2009). Ecodriving and speed limits have low investment and abatement costs (OECD, 2005).

Welfare effects, in terms of constraints on the choices of the individual, and productivity, could be significant for several options. Limiting transport demand implies reduced opportunities for travel and trade and availability of goods, assuming options such as telecommuting/teleworking and urban planning yield only a small emission reduction. Modal shift implies reduced use of private vehicles and, thus, less freedom of choice. For the decarbonisation options the impacts are much smaller, although smaller vehicles and carpooling could also lead to loss in welfare (OECD, 2005). Therefore, the public acceptance is likely to be higher for option 3 than for options 1 and 2. For those options, the required change in behaviour is also larger than for option 3.

However, for large-scale decarbonisation, the technological options are not fully market ready (Hoen et al., 2009). More research and demonstration is required for hydrogen/electric vehicles, CCS and second-generation biofuels. A large-scale shift to public transport is likely to require a long lead time. For all options, the structural changes in technological and economic organisation are large.

On the positive side, we should note that there are large co-benefits associated with GHG reduction in the transport sector, in terms of reduction in air pollution, noise and congestion, and improved security of supply and biodiversity (EEA, 2009). These are important drivers for transport policy and enhance feasibility and acceptability.

4. Political implications

For the different types of options, a broad range of policy instruments is available:

- Limiting demand (1): Travel or fuel budgets for personal and commercial purposes, such as for air and private vehicle travel (possibly with the element of trading allowances); road-pricing or other taxes; driving bans, for instance, car-free Sundays.
- Modal shift (2): Very strong financial incentives (taxing and subsidising), combined with implementation of excellent mass transit infrastructure.

- Decarbonisation (3): Emission standards in gCO_2 eq/km for vehicles, ships and aircraft, possibly applied to the manufacturers; an emission trading system for the same; mandatory diffusion of hydrogen/electric vehicles, and CCS for fossil-fuel-based production; scrapping of existing cars; banning of (particular types of) cars from the market; and implementation of speed limits.

Command-and-control measures are likely to be most effective, but may imply more public resistance. Financial instruments may be effective, but changing system dynamics (car-pooling, car-sharing, compressed work weeks) could work, as well. Therefore, a combination may be preferable.

Options 1 and 2 can be implemented on a national level; option 3 would be best implemented on regional or global levels as manufacturers are not located in the Netherlands, and an emissions trading scheme is very difficult to implement in a small country. Mandatory diffusion, however, could be implemented on a national level.

Implications for the political economy and vested interested may be large:

1) Limiting transport demand may have substantial impacts on the sector itself (e.g., airlines/airports or freight transport), particularly, for the Netherlands as a freight transport country, but also for tourism.
2) By a modal shift, equity may be enhanced (more bicycles and trains) but there will be an impact on the automobile sector.
3) For large-scale decarbonisation, very substantial changes in the fuel chain are required, which implies an impact on oil production and conversion and the automobile sector. There can be positive impacts on equity, due to reduced air pollution (though limited for biofuels), particularly, for regions where Euro V norms are not implemented.

5. Options and consequences for the Netherlands

For drastic GHG reduction, it is essential to address the transport sector. Although emission reductions are not achieved easily, there are significant opportunities in the Netherlands, which reduce air pollution and congestion and improve energy supply security as co-benefits. Policy options, first of all, need to look at limiting the demand for transport, as much as possible, for example, by people teleworking, driving or flying bans and a reduction in freight transport demand. Secondly, a modal shift away from private vehicles can be achieved through large investments in excellent public transport systems alongside strong financial incentives, together with incentives for non-motorised transport. For a shift from road to rail and ships, in freight transport financial incentives can be used, as well.

In the longer term, the largest reductions may be achieved by decarbonisation of transport. For private vehicles, this should be done internationally through binding agreements with car manufacturers. The Netherlands, however, has an advantage when it comes to providing decarbonised fuels (electricity or hydrogen), due its high population density, and potential and infrastructure for CCS. GHG reduction in the freight transport sector can be achieved through large-scale application of biofuels, while for rail decarbonisation of power supply is sufficient.

The implications of such large GHG emission reductions in the transport sector are diverse. In general, it can be stated that the transport sector would be moving towards sustainability, reducing negative impacts on the environment and society. However, the options require significant investments in infrastructure, and the limiting of transport demand may have negative implications for the economy and society.

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A. 5. Industry

1. Short description of option

With 12 Gt CO_2 eq, industrial activity is responsible for 19% of global GHG emissions (IPCC, 2007). Given the great diversity of industrial activities, several approaches to mitigation can be distinguished (IPCC, 2007). Sector-wide options (e.g., efficient motors, boilers, heaters), process specific options (highly tailored, process integration and optimisation) and operating procedure enhancement (insulation, use of steam, etc.). Since 85% of emissions from industrial activity are directly related to energy use, mitigation options in industry tend to be energy-related with a useful distinction between increasing energy efficiency, switching to environmentally friendly fuel types and using better energy recovery and waste management techniques.

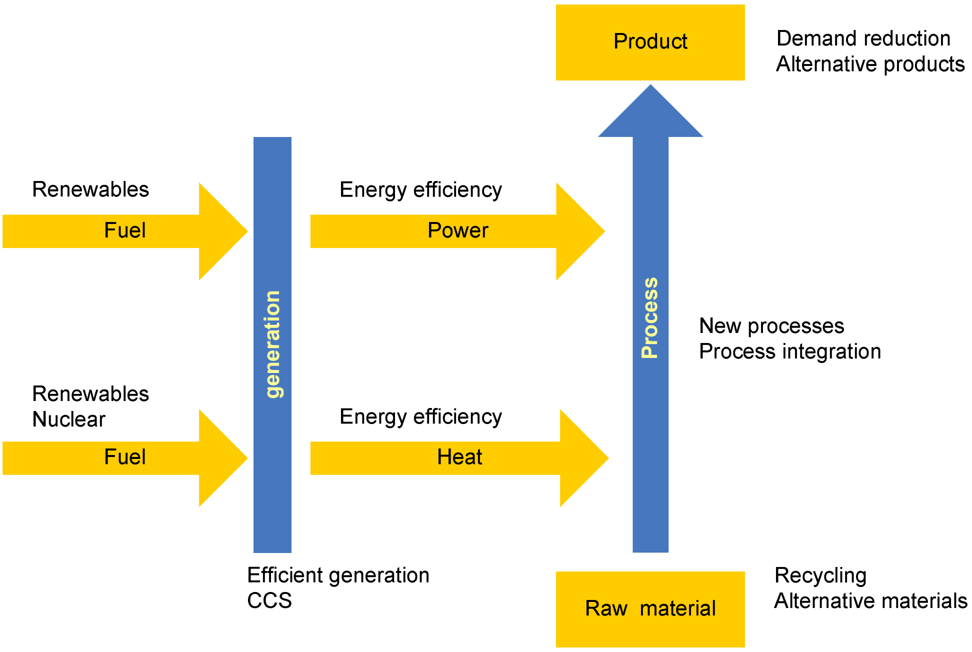

Figure A.5.1. schematic representation of mitigation options (Source: ECN, Bert Daniels)

Characteristics of the main sectors within industry

The most significant industrial sectors in terms of emissions and mitigation potential are basic metal (steel), cement, paper and pulp, and chemicals.

- *Iron and steel* has limited opportunities for increasing process efficiency, switching fuel or recovering power, since most CO_2 comes from the *chemical* process of turning iron ore into metal, rather than from energy production[20]. For the metal industry, the most promising directions for drastic mitigation are drastic demand reduction and introduction of end-of-pipe solutions, such as CCS.

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[20] The amount of CO2 that results is determined by a chemical formula. For processing two units of Fe (iron), one unit of CO2 is produced. New processes are able to work with a four-to-three ratio.

- *Paper (and pulp)* production is energy intensive, and the key to mitigation lies mainly in increasing energy efficiency.
- *Cement* production is around 10% of industrial emissions and responsible for 4 to 5% of all anthropogenic emissions worldwide (McKinsey, 2008). It is energy intensive by its very nature (Worrell et al., 2001). CO_2 is emitted from the calcination and mineralisation of limestone (around half) and from heat and power production needed in the production process (also around half). Demand for cement and concrete is directly related to economic development, since concrete is used for buildings and infrastructure. Production emissions can be reduced by substituting the main ingredient clinker with alternatives, such as fly ash or slag (McKinsey, 2008). Alternatively, demand can be reduced by adopting less concrete intensive construction methods. Switching to wood-frame construction would greatly reduce demand for cement, but can be problematic with the construction of high-rise buildings.
- *Chemicals* are responsible for around 15% of industrial emissions. The sector is energy intensive, but there is ample potential for process integration and design optimisation. Reductions in fossil energy use of 50 to 80% are technically achievable, although this would require process innovation – short-term actions are mainly end-of-pipe, better use of heat and management of waste materials.

2. Effectiveness

Industrial plants and processes are capital intensive, typically have a long lifetime (10 years and longer) and a significant lead time for construction (up to 5 years). Replacement is costly as it does not coincide with a 'natural moment', such as the end of the economic lifetime or large planned maintenance. In a situation of drastic mitigation, there is no time to wait for 'natural' replacement moments. With drastic mitigation, replacing active plants and developing end-of-pipe[21] solutions are two likely paths. With end-of-pipe solutions, such as carbon capture and storage, the original installation is allowed to remain more or less unchanged. Note that adjusting the actual process from raw material to end product generally requires innovation and time, as it cannot rely on techniques that are readily available.

Drivers behind development of environmentally friendly ways of industrial production are mainly economic and based on increasing demand and lowering costs. Policy efforts that take into account requirements for economic viability are likely to be effective, as the social and behavioural aspects to policy effectiveness are limited. Industrial activity is very energy- and resource intensive. For a concerted, global action to lower the environmental impact of industry, the bottleneck is likely to be the huge demand for, and mobilisation of capital goods and labour. Substitution and rebound effects as a result of lowering industrial emissions, are not likely to occur. As with any change in economic activity, spillover effects are likely –

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[21] End-of-pipe solutions take the original installation emissions, and make sure that these emissions do not end up in the atmosphere. One of the most promising end-of-pipe solutions for large installations is carbon capture and storage.

but it is not clear beforehand which sectors and activities will benefit and to what extent.

3. Feasibility

Industrial production has traditionally been confronted with (very) low and often subsidised energy costs, in the interest of national employment and international competitiveness. As a result, cutting back energy use has never been a priority, and there was little or no incentive to invest in emission reduction innovation and R&D. As a peculiar result, medium term extreme mitigation is more feasible than short-term moderate mitigation – because mitigation options need time to develop. Currently, not all necessary mitigation options are available[22].

The costs of mitigation options for industrial activities range from negative costs to moderately high costs. The capital intensity of the mitigation options is far less than with transport or building-related mitigation (McKinsey, 2008). In a situation where global emission reduction is taken seriously, it makes sense to invest in mitigation in industry (and energy supply): a significant number of low cost mitigation options exist and acceptance and behavioural barriers are limited. With extreme targets, however, marginal costs rise steeply – especially in the absence of off-the-shelf mitigation technologies (as mentioned above).

Note that the cost of energy (and hence of emissions) is often a relatively small part of the price of the end product. Price-based policies targeting end products are, therefore, unlikely to be very effective. Focus should be on introducing minimum standards and on facilitating, and suitable options should be found in decreasing emissions from energy rather than trying to decrease demand by price incentives.

4. Political implications

Curbing emissions from industrial activity makes sense only when pursued internationally, as it is relatively easy for a company to move its resource- and emission-intensive activities abroad. Consequently, unilateral national policy efforts may lead to emission 'leakage', limiting the effect on overall emissions. A notable exception is the situation where countries consciously present themselves as front-runners, showcasing that it is possible to develop low-carbon industry (and gaining a competitive advantage from it).

Several instruments are available to induce far-reaching mitigation in industry.

- A cap-and-trade system, such as the current EU ETS, is likely to be effective only when it is strict enough. In a fast reduction scenario, it is worth considering refinements, such as *benchmark-based emission trading*, which provides an even stronger incentive to move towards a low-emission sector.
- Subsidies and taxes are very effective for targeting specific sectors and developments, and help innovation, demonstration and deployment.

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[22] Industry representatives in the Netherlands state that 30% by 2020 is much harder than 80% by 2050.

- Sectoral agreements may have a coordinating role, but in cases of extreme mitigation, this instrument is not expected to be very effective. Note that some industries may be suited to international sector-wide agreements because of their medium to high international exposure, the high concentration of actors, and uniformity of production processes (IEA, 2008).
- Technology standards are usually a good incentive for those technologies that stay behind, regardless of stimulus. In a drastic mitigation scenario, such standards may be used more seriously.

For drastic mitigation in industry, the likely core elements of an international policy package are technology standards and a strict cap-and-trade system. To overcome specific barriers, align efforts and support specific developments, a combination of taxes/subsidies and sectoral agreements are useful as supporting policy, creating an environment in which the core cap-and-trade and technology standards are most effective. Ideally, the focus of the incentive is on the marginal abatement and not on the entire production costs – this increases the incentive and the acceptance (e.g., tax/subsidy that starts only from a certain benchmark value).

Most of the mitigation options in industry take place within the facilities, so members of the public are not confronted with it directly. Notable exception is carbon capture and storage, for which public acceptance is a very important issue.

Industrial mitigation potential is large and relatively low cost. Extending or replacing production facilities requires extensive permit and local (spatial) planning procedures with ample room for societal involvement. Given that typical industrial plants have a building period of up to five years, in a drastic mitigation scenario it is worth considering the situation in which new plants are built in parallel to existing plants, which are decommissioned only when the new one comes online. This approach, however, requires flexibility and possibly limitations to public interference.

5. Options and consequences for the Netherlands

In the most developed economies, industrial output grows less fast than overall output, since these economies tend to focus more on goods and services. Developing economies, however, usually have greatly expanding industrial sectors. In the past decades, Europe has profited from the booming industrial sector in Southeast Asia. The Netherlands is somewhat of an exception, as the energy-intensive industry is quite progressed. Three drivers behind this are the exploration of coal in the south of the Netherlands, up until the 1960s, the discovery of natural gas, in the 1950s, and the large Rotterdam sea port providing opportunities for industrial activity.

The Netherlands has no industrial activity for which it has a natural competitive advantage, except for the activities that benefit from Rotterdam as gateway to north-western Europe. Adjusting infrastructure to facilitate new industry takes up too much time and resources, so initially, it is reasonable to start with extending existing locations.

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A. 7. Building sector

1. Short description of option

Energy use in residential and commercial buildings is responsible for about 18% of global greenhouse gas emissions, of which 38% is from commercial buildings and 62% is from residential buildings (McKinsey, 2009) . Apart from construction, the emissions come from space heating, ventilation and cooling, provision of hot tap water, lighting, and the use of appliances. For accounting clarity, emissions from electricity production are attributed to the power supply sector.

There is a logical distinction between emissions directly related to the buildings and those from the use of appliances. Building-related emissions depend strongly on choices made in the design and construction of the building – changing this is so costly that it is practically limited to 'natural' moments when houses are built, being renovated or change owner. Appliances, however, have a lifetime of only several years and do not represent as much 'stored' capital as buildings do.

Building-related emissions

Technically, building-related emissions can be reduced, substantially, and in most cases it is possible to create energy-neutral buildings[23]. It is, however, not possible to make existing buildings energy-neutral, since this would require design and specific features, such as physical orientation to the sun and the use of specific materials. In existing buildings, insulation and energy supply can be optimised, but it is near impossible to achieve this without consent of the owner, since most countries prescribe that the government cannot impose new rules on existing property. Addressing time restrictions is one of the main challenges in designing policy for reducing building-related emissions.

For space heating and cooling, and warm tap water, the order in which curbing emissions is most effective is first to reduce demand, for example, by insulation or by the use of passive solar heating. Next, as much of the remaining energy demand as possible should be supplied by renewable energy sources, such as solar boilers and heat pumps[24]. Finally, use of fossil fuels can be optimised, by using micro CHP or highly efficient conversion technologies. The energy sources used to provide buildings with heating, cooling and warm water differ greatly; most developing countries use wood and coal, but natural gas, oil and electricity from hydro or nuclear facilities is also used.

Non-building-related emissions

Long lifetimes and limited windows of opportunity for reduction measures do not apply to non-building-related emissions, coming from operating appliances with lifetimes between a few year to 10 years maximum.

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[23] Or buildings that need external energy supply only under periodic extreme weather conditions in mid-summer or mid-winter.

[24] Heat pumps use energy for pumping, but are able to recover four units of energy for every unit used to operate them.

Note that the absolute number of appliances still increases. Economic development almost everywhere translates to an increase in demand for comfort and electric appliances. This is true for the developing world, but, in affluent countries, the number of appliances per household also still increases. Note that the observed trend is that people work toward an imaginary budget for energy use: when the building they live or work in is very energy-conscious, people tend to be less careful with the number of appliances they use. The number of computers and external devices, and the demand for space cooling still increase rapidly in commercial (office) buildings.

2. Effectiveness

The technical mitigation potential for building-related emissions is substantial, but time is a serious limitation. Drastic mitigation policy should, therefore, not be limited to programmes for new buildings, but also target optimising existing buildings. The lifespan of existing buildings is 35 to 70 years, with averages in developed countries of around 65 to 70 years (i.e., 2% of existing buildings will be replaced annually).

Average appliances for kitchen use, entertainment and work (i.e., computers) can generally be made 50 to 60% more energy efficient. Switching lighting from traditional bulbs to energy saving or LED based lighting can save up to 90% in use and emissions. Producers are capable of quickly making the appliances energy efficient, if technology standards are introduced. Unlike buildings, appliances have short lifetimes, with new product lines every 2 to 3 years and maximum economic lifetimes of near 10 years. Any policy aimed at improving energy use (i.e., emissions characteristics) of appliances is potentially very effective. Traditionally, buildings are not very thoroughly isolated, which has the advantage of ventilation – with tighter construction specifications, the ventilation also needs to be improved consciously.

There are several potential indirect effects in greenhouse gas mitigation in the building sector. When buying an energy-efficient appliance, the existing appliance often stays in the house – imagine for example TVs in bedrooms or in children's rooms. In the building sector, taking half measures will create a lock-in situation for the decades afterwards.

3. Feasibility

Costs of mitigation of direct building-related emissions are low, compared to the long lifetime of the buildings, but require rather high upfront costs. For appliances, the initial costs will increase somewhat for more energy efficient alternatives.

Building in an energy neutral fashion requires very good communication between the different contractors in a building project and a keen eye for detail. Also, building methods will need to change to more tight-fitting pre-fabricated units, instead of making extensive use of concrete and cement on site. Note that many large building companies own concrete factories and are quite conservative in their operating habits; vested interests are barriers to swift implementation of structural changes in the building sector.

For non-building-related emissions, implementation is feasible in a relatively short time, even without lack of functionality.

4. Political implications

Policies for reducing building-related emissions can be implemented on a local level, since the choice of moving to a certain location is not likely to be affected by emission constraints. Limiting measures can be imposed directly on the users of buildings, but it may be more effective to involve the energy supplier[25] (e.g., using white certificates) or the owner of the building, rather than the end user. Imposing standards is the preferable policy option. For new buildings this is likely to be successful, but for existing buildings this will pose legal implementation difficulties in most countries. Since the upfront capital costs for most building-related improvements are high, financial incentives addressing this barrier may be effective.

For appliances, the most promising policy instrument is imposing strict technology standards on producers in an international setting. Restricting end use of appliances is much more difficult to implement.

The acceptance of imposing tight standards for building-related emissions is likely to be low, since it involves interference with choices 'behind the front door'. Most individuals are very keen on keeping full control over their private lives.

The acceptance of energy efficiency standards for non-building-related emissions in the building sector (i.e., appliances) is likely to meet with little or no resistance, as long as the same functionalities are offered. If the consequence of technology standards is that certain appliances are no longer available (e.g., saunas, terrace heaters, leaf blowers) then resistance can be expected, although it is culturally dependent to what extent individuals tend to accept government interference in their individual choices.

5. Options and consequences for the Netherlands

The building sector in the Netherlands is quite conservative and the process of building is not yet equipped to the communication and detailed standards required for very low-energy building. Changing workers knowledge and project infrastructure to meet the required standards takes time and is a potential barrier to drastic implementation of tight regulation for new buildings. Wood frame building, which requires less concrete, is only being used sporadically, and vested interest around use of concrete and on site construction may prove to be a barrier to quick introduction. Potential for improved insulation and energy efficiency in existing buildings is quite large, but hard to implement, for reasons of high upfront costs, timing and lack of information and skilled implementation.

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[25] Whether this will work with extreme mitigation efforts such as 80% reduction is questionable.

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Appendix 2 B. Removing greenhouse gases from the atmosphere

B.1. Agriculture, Forestry and other Land Use (AFOLU)

1. Short description of option

AFOLU is an important sector and source of emissions, badly covered by the Kyoto Protocol (Trines et al., 2006). AFOLU options include, reduction of agricultural emissions of methane and nitrous oxide, and sequestration in soils, forests, or the type of land cover. The former two formally fit under the category in Appendix A, but we have included the latter two in this Appendix B, and biofuels under renewable energy in Appendix A. Agricultural emissions accounted for approximately 10 to 12% of global GHG emissions in 2005, mainly methane (CH_4) and nitrous oxide (N_2O) (Smith et al., 2007). Emissions in non-Annex I countries are about three quarters of the total and rising, while, in Annex I, they are declining. AFOLU-related CH_4 is emitted mostly by ruminant livestock, and from stored manures and rice cultivation, while N_2O mainly comes from the transformation of nitrogen in soils and manures. In a situation of accelerating climate change, especially methane emission reductions can be effective, because of the relatively limited lifetime in the atmosphere.

The rate of deforestation between 2000 and 2005 was 13 million ha/yr, mainly due to the conversion of forests to agricultural land, but also expansion of settlements, infrastructure and unsustainable logging (Nabuurs et al., 2007). Compensated by afforestation, natural forest expansion and land restoration, on balance, the net deforestation rate is approximately seven million ha/yr. Deforestation and forest degradation contributes about 20% to global GHGs (Pirard, 2008). Most studies project the rate of deforestation, mainly in the tropics, to continue in the coming decades, though there are great differences, and in some regions it is likely to increase (e.g., Congo Basin) and decrease (e.g., Malaysia) (Nabuurs et al., 2007).

The AFOLU sector can be characterised by a high number of relevant actors (farmers, loggers), dispersed sources of emissions (livestock, soils, forests) and large uncertainty with respect to monitoring emissions and establishing baselines. There are important links with human diet (Stehfest et al., 2009), bio-energy and sustainable development (Nabuurs et al., 2007).

2. Effectiveness

Given the large share of AFOLU in global emissions, the abatement potential is very substantial. Agricultural emission reduction options include improved crop and grazing land management, restoration of drained organic soils and degraded lands, improved livestock and manure management, water and rice management, land-use change and agroforestry. The technical abatement potential is estimated to be 5.5 to 6.0 $GtCO_2$ eq/yr, by 2030, with the economic potential up to 100 USD/tCO_2 eq, approximately 4 $GtCO_2$/yr (i.e., 8% of global emissions of 2004). About 70% of this potential is in non-OECD countries (Smith et al., 2007).

Thomson et al. (2008) estimated that the highest rate of 1.8 to 2.6 $GtCO_2$/yr of terrestrial sequestration will be reached by mid-century. The contributions from agricultural soils, reforestation and pasture will be about 0.77 $GtCO_2$/yr, 1.14 $GtCO_2$/yr and 0.55 $GtCO_2$/yr, respectively. They calculated that the total contribution of terrestrial sequestration over the next century will be between 84 to 150 $GtCO_2$/yr, depending on the used scenario.

The realistic potential in agriculture, however, may be much lower, because of several barriers (see below) and uncertainty with respect to the effectiveness and persistence of CO_2 soil sequestration and CH_4 and N_2O mitigation. Van Minnen et al. (2008) suggested that social, economic and institutional barriers could decrease by more than 75 to 80% of the physical potential of forest carbon sequestration, by preventing carbon plantations in natural vegetation areas.

In the forestry sector, REDD[26] is the single most important mitigation option (Trines et al., 2007). Forest management and afforestation also contribute to the potential. The estimates on abatement potential vary widely: from 2 to 4 Gt/yr by 2030 according to bottom-up models, to over 13 Gt/yr by top-down models, if options with a cost up to 100 \$/tCO_2-eq are included(Trines et al., 2006; Nabuurs et al., 2007). An important part of this is located in South and Central America, with significant shares also for non-Annex I countries in Asia, Africa and North America. Van Minnen et al. (2008) estimated that, even in the most conservative scenario, carbon plantation could compensates for 5 to 7% of the total CO_2 emissions by 2100. This would consist of large-scale afforestation and reforestation programmes, soil carbon management, and forest management. Very recently, Ornstein et al. (2009) suggested large forestation programmes for the world's deserts, using desalinated seawater for irrigation. While such a scheme would not be cheap, and would have uncertain side effects (e.g., on weather and Saharan dust transport), the proposal illustrates that innovative options can still be explored.

Biochar – injecting charcoal in soils – could be a method for long-term (centuries/millennia) storage of carbon. However, the dynamics in the soil are not well understood, and leakage effects may also occur, yielding significant uncertainty regarding the overall GHG balance (Reijnders, 2009, see also Appendix B5).

In addition to the technical options mentioned above, changing the human diet could also be a very important mitigation option, as the livestock sector (i.e., meat and dairy) accounts for 18% of global GHG emissions and 80% of land-use emissions, including the emissions from the production of fodder. Changing from our current and projected consumption practices to a 'Healthy diet'[27] (consisting of 52% of beef, 35% of pork and 44% of poultry/eggs, compared to the 2050 baseline diet) would reduce 4.4 $GtCO_2$ eq by 2050. This would reduce the total abatement cost of

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[26] UN Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries.

[27] Based on dietary recommendations by the Harvard Medical School (Willet, 2001, cited in Stehfest et al., 2009)

reaching a 450 ppm CO_2 eq stabilisation target, by more than 50% (Stehfest et al., 2009).

All options can be implemented directly, as they rely on changing current practices (although setting up monitoring systems may take time). Construction time for technical options, such as manure management, is short, in the order of years. The abatement effect will be immediate (although with afforestation it stops when the forest is fully grown). One of the key issues is successful implementation, however, this may be difficult (see below). Leakage is a key issue when it comes to forestry: shifting of activities may lead to land-use change elsewhere, and a leakage rate of 50% has been associated with forestry projects (Reijnders, 2009). National programmes could reduce the leakage rates (Nabuurs et al., 2007). An important positive effect of most of these abatement options is the increased potential for bio-energy from dedicated lands, due to more efficient use of agricultural land (Nabuurs et al., 2007).

3. Feasibility

The economic costs of the main part of the technical potential for the AFOLU emission mitigation options are below 100 USD/tCO_2. The potential is more or less equally divided into the cost classes of 0 to 20, 20 to 50 and 50 to 100 USD/tCO_2 eq (Smith et al., 2007; Nabuurs et al., 2007). Most of the forestry options require significant financing upfront. The options generally rely on current technologies, but, in the agricultural sector, technological advancement is a key driver for future mitigation (Smith et al., 2007).

Harnessing the total economic potential, however, might be challenging, because of several reasons; it requires institutional capacity, investment capital, technology R&D and transfer, as well as appropriate policies and incentives, and international cooperation. Broadly, there are three major barriers to enacting effective policies to reduce forest loss: (i) profitability incentives often run counter to forest conservation and sustainable forest management; (ii) many direct and indirect drivers of deforestation lie outside of the forest sector, especially in agricultural policies and markets; and (iii) limited regulatory and institutional capacity and insufficient resources constrain the ability of many governments to implement forest and related sectoral policies on the ground (Nabuurs et al., 2007). Pirard (2008), therefore, noted that ‘readiness is a major and necessary component for any REDD strategy to counter deforestation and forest degradation in the tropics. This encompasses institutional, technical and political measures.’ Also social and economic implications need to be considered (see below). Environmental impacts of virtually all AFOLU options are positive (Smith et al., 2007; Nabuurs et al., 2007).

4. Political implications

In general, many of the AFOLU options have to be considered from a much wider perspective, which includes issues around the production of food, fodder and fuel, biodiversity protection, water management, and other issues. Considering the barriers mentioned above, designing proper policy is crucial. Historically, AFOLU climate policies have had little impact (Smith et al., 2007). Designing international and national policies, including financing for REDD, is currently a priority. Pirard (2008) argued that, broadly, two options are available for providing the necessary finance: 1) rewards based on demonstrated emission reductions, and 2) sponsoring of relevant policies and measures, that is, providing financing upfront. The former is compatible with carbon markets, but the latter may provide better incentives and could be more effective as GHG impacts are hardly measurable in a quantitative manner, particularly, in the short term. Hybrid forms of these options can also be designed.

Trines et al. (2006) highlighted the importance of capacity building for emission inventories and monitoring technologies. The Brazilian Government (2008) highlighted the following actions in order to achieve zero deforestation: protection, preservation and management of public forests; territorial and land organisation, including incentives for sustainable production; high precision monitoring; strengthen capabilities for enforcement; raise financial resources for the Amazon Fund and the Climate Fund; and setting minimum prices for non-timber forestry products.

The multiplicity of actors, land sovereignty issues, and ingrained cultural and behavioural practices make the adequacy of AFOLU options in an emergency situation questionable. Nevertheless, drastic mitigation policy options, such as meat and dairy consumption policies, or a ban on deforestation, can be considered, and at least in theory, can be introduced quickly, if properly enforced. A complication is that most of the emissions and sequestration potential is in non-Annex I countries, and equity and sovereignty considerations, therefore, have to be taken into account. Effective reduction of smoking in several industrialised countries suggests that policies and awareness campaigns can in fact change behaviour, which may set an example for changing diets in climate-friendly directions.

For some of the options, the societal impacts could be significant, notably the necessary change of livelihoods or reduced income, as a result of REDD. Afforestation may have positive or negative impacts, while sustainable forest management has positive social and economic consequences (Nabuurs et al., 2007). Dietary changes may also encounter substantial social barriers, even though desirable from a health perspective. Most of the agricultural options have a limited or positive impact, though there is also some uncertainty (Smith et al., 2007).

5. Options and consequences for the Netherlands

The largest share of the potential is outside the EU, and most of the options above pertain predominantly to the developing/EIT countries. For a densely populated country with a relatively large agricultural sector, such as the Netherlands, there is a set of specific options:

- Reduce emissions from greenhouse horticulture, either by turning it into a zero-emission sector, abolish lighting practices, or abandon energy consuming greenhouses altogether. The last option, however, would obviously have substantial impacts.

- Technologies, such as CHP, biodigesters, improved feeding practices for livestock, manure management, and bio-energy, have a significant potential, against costs of up to 200 USD/tCO_2 eq (Daniels and Farla, 2005) and limited societal impacts.
- If there is an acceptable way of substantially reducing meat and dairy consumption, preferably in international context, this would also be highly effective.

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B.2. Enhanced ocean sequestration

1. Short description of option

Because the availability of nutrients in the oceans exhibits considerable regional variations, many authors suggested to increase the efficiency of the oceanic 'biological pump' (see Text box 1), via addition of nutrients in areas with nutrient deficiency, in order to stimulate the net primary production in the top layer. While a fraction of this additional biomass will be recycled in the upper zone, another part will sink and will be incorporated into the ocean sediments, and thus be drawn from the global carbon cycle (e. g. Martin and Gordon, 1988; Hutchins and Bruland, 1998). Two types of macronutrients are proposed as 'ocean fertilisers':, those that are required in relatively high concentrations, such as nitrogen (N) and phosphorus (P), and those of which much smaller quantities would suffice, such as iron (Fe) and zinc (Zn). The role of the micronutrients is to facilitate more efficient usage of existing macronutrients (Lampitt et al., 2008).

Enhanced phytoplankton productivity affects the climate through one feedback process, that may have even greater effect than the direct sequestration of CO_2 - that of increased emissions of dimethyl sulphide (DMS) (e.g., Charlson et al., 1987; Ayers and Gillet, 2000; Wingenter et al., 2007). DMS emissions play an important role as cloud condensation nuclei, especially in the Southern Hemisphere, where anthropogenic sulphate emission is low (Gondwe et al., 2003). Gondwe et al. calculated that DMS accounts for 43% of the atmospheric nss-sulphate[28] burden in the Southern Hemisphere, with a regional peak of more than 80% in the Southern Ocean during the summer. For a comparison, DMS contribution to the global nss-sulphate burden is only 19%.

In addition to the biological options, also chemical uptake of CO_2 by the ocean, theoretically, can be enhanced. In total, three different schemes to enhance oceanic carbon uptake can be distinguished:

A) *Adding macro- and micronutrients.* In the experiments carried out so far, macro and micronutrients were just dumped from ships into the ocean. For large-scale implementation, however, it is proposed that fertiliser cocktails of macro- and micronutrients should be manufactured on land and transported by submarine pipe to a region significantly beyond the edge of the continental shelf. The nutrient ratios and the temporal supply rates could be controlled so that biological populations that optimise sequestration can develop. Such environmental manipulation is carried out, today, in a sophisticated manner in terrestrial glasshouses (Lampitt et al., 2008).

B) *Bringing up nutrient-rich deep water.* Lovelock and Rapley (2007) suggested to enhance the production and sequestration of organic carbon, by bringing up to the surface

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[28] Dimethyl sulphide (DMS) is a semi-volatile organic sulphur compound, which is oxidised to sulphur dioxide (SO2) and other products in the atmosphere. From SO2, non-sea-salt (nss) sulphate is produced, which, in turn, can form sulphate (SO 4 2−) particles, that act as condensation nuclei for water vapour (Stefels et al., 2007)

layer nutrient-rich deep ocean water by the means of pipes, using kinetic wave energy.

Text box 1: The Biological and Solubility pumps

The oceans are a huge CO_2 sink – containing 50 times more CO_2 than the atmosphere, and having absorbed almost 30% of the anthropogenic CO_2, emitted since the beginning of the industrial revolution (Raven and Falkowski, 1999). The oceans are involved in the carbon cycle through two mechanisms: the first one, called 'solubility pump', is driven by ocean circulation and by the solubility of CO_2 in seawater; the other one is called 'biological pump'. The latter is determined by two counteracting processes, namely primary production and calcification, and the rate with which organic matter is transferred to the deep sea (Figure B.2.1). The two pumps create a vertical carbon gradient, because they tend to increase carbon concentration of the deep water. Only carbon from the zone below the depth of winter mixing can be considered as sequestered. The depth of winter mixing demonstrates high regional variability in the range of 200 to 1000 metres (Lampitt et al., 2008).

Solar radiation warms and illuminates much more surface ocean water than nutrient-rich deep ocean water, thus, giving rise to a thermal gradient. The upper layer is well-mixed, with higher CO_2 concentration and abundance of phytoplankton. While the thermal gradient isolates phytoplankton in the upper layer, seasonal heating and cooling, storms, eddies, high frequency internal waves and coastal upwelling driven by winds, improve the mixing and, hence, accelerate the transfer of nutrients from deeper waters to the surface. (Raven and Falkowski, 1999). Moreover, the mixing brings cold water to the surface and, thereby. enhances the ability of the ocean to sequester CO_2, as the solubility of CO_2 increases in cold water.

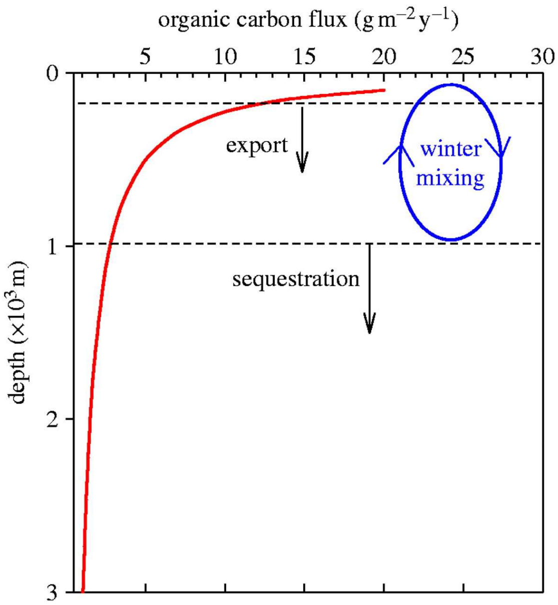


Figure B.2.1. Schematic of the decrease in downward flux of organic carbon as a function of depth in the water column (Source: Lampitt, 2008)

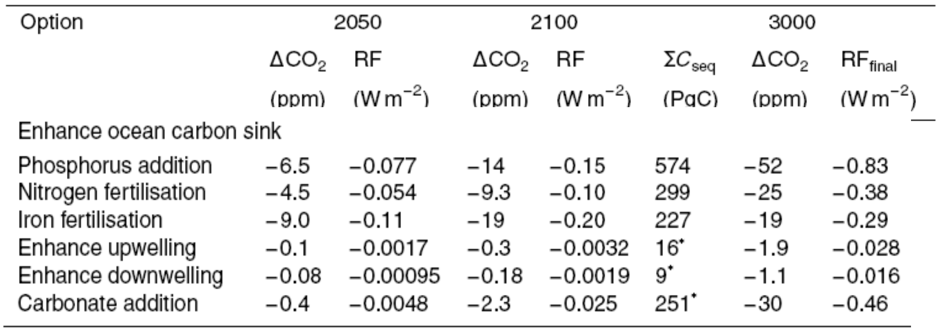
C) *Enhancing oceanic uptake of CO_2 by addition of limestone.* The idea to enhance the absorption of CO_2 by adding alkaline minerals to the ocean was first explored by Kheshgi (1995) and further developed by Rau and Caldeira (1999). Kheshgi (1995) proposed to heat limestone ($CaCO_3$) to about 850 °C, in order to split it into CO_2 and CaO. CO_2 could be sequestered directly, for instance, and the soluble CaO could be added to the surface layer. Rau and Caldeira (1999) also considered reaction of

CO_2 with limestone in chambers on land prior to releasing them into the ocean. Appropriate locations would be in regions that have a combination of low-cost 'stranded' energy, considered too remote to be economically viable to exploit – such as flared natural gas or solar energy in deserts – and regions that are rich in limestone, making it feasible for calcination to take place on site. Seawater would be able to take in more CO_2 than is generated by the lime creation process (quote Tim Kruger of Cquestrate, http://www.scienceblog.com/cms/dash-lime-new-twist-may-cut-co2-levels-back-pre-industrial-levels-16931.html). However, Harvey found that the process could be performed without this first step – his idea was to sprinkle crushed limestone directly over the ocean surface (Harvey, 2008).

2. Effectiveness

Lenton and Vaughan (2007) assessed the potential effect on radiative forcing of various fertilisation options, using a climate model (Table 1). As can be seen from this table, some options, such as ocean upwelling and downwelling have very small mitigation potential and, therefore, their deployment would have very tiny impact on the GHG emission reduction. Moreover, this assessment was based on the assumption that the proposed schemes are effective in drawing down CO_2, while the question of whether ocean fertilisation is effective is not persuasively answered yet (Boyd et al., 2007; Lampitt et al., 2008). Lutz et al. (2007) discovered, for instance, that the transport of organic matter to deep water is less in the summer during algal blooms than during the rest of the year, because, instead of sinking, the organic matter is recycled within the food web and stays in the upper ocean layer. The enhancement of oceanic uptake of CO_2 by addition of limestone is also questioned. Shepherd et al. (2007) argued that, as deep waters contain high concentrations of CO_2, when this CO_2 is brought to the ocean surface and consequently released, it may offset the CO_2 sequestration, because of higher primary production and cooling the upper layer. Karl and Letelier (2008) identified a new mechanism of CO_2 sequestration via secondary blooms, however, pointing out that higher sequestration rates are plausible. Further research is needed in order to assess the real sequestration potential of this method, too.

Table B.2.1. Effectiveness of fertilisation options (Source: Lenton and Vaughan, 2009)



Option	2050		2100		3000		
	ΔCO_2 (ppm)	RF ($W m^{-2}$)	ΔCO_2 (ppm)	RF ($W m^{-2}$)	ΣC_{seq} (PgC)	ΔCO_2 (ppm)	RF_{final} ($W m^{-2}$)
Enhance ocean carbon sink							
Phosphorus addition	−6.5	−0.077	−14	−0.15	574	−52	−0.83
Nitrogen fertilisation	−4.5	−0.054	−9.3	−0.10	299	−25	−0.38
Iron fertilisation	−9.0	−0.11	−19	−0.20	227	−19	−0.29
Enhance upwelling	−0.1	−0.0017	−0.3	−0.0032	16^{*}	−1.9	−0.028
Enhance downwelling	−0.08	−0.00095	−0.18	−0.0019	9^{*}	−1.1	−0.016
Carbonate addition	−0.4	−0.0048	−2.3	−0.025	251^{*}	−30	−0.46

Effectiveness also depends on the speed with which the option can be deployed. Ocean fertilisation through the addition of macro- and micronutrients and limestone could be implemented immediately, if proved efficient. The enhancement of CO_2

sequestration by bringing up nutrient-rich deep water could be employed within a decade. How quickly the climate system responds, will depend on the removal rate of CO_2. Harvey (2008) argued that the full effect of adding limestone powder on the eventual change in radiative forcing may be delayed by up to 100 years. The process should be continued until the desired atmospheric CO_2 concentration levels are reached.

Major questions exist with respect to the ratio between the energy required and the greenhouse gas emissions associated with that energy consumption, and the carbon removed. Lampitt et al. (2008) suggested that 'the energy costs of producing the cocktail (of macronutrients) and piping it from the land to regions of nutrient limitation, are likely to be large with a carbon footprint that may be greater than the carbon sequestered'. In general, this is also the conclusion about the energy efficiency of heating limestone on land in order to split it into lime and CO_2 (Harvey, 2008). An open source project, studying the practicality of limestone addition (http://www.cquestrate.com/) has calculated that 'to offset current emissions (in the region of 7GtC per year) would consume 10.5 km^3 per year, and require some 80 billion GJ in heat energy – equivalent to a power output of 2500 GW. At double that power output, the amount of carbon dioxide in the atmosphere could be reduced back to pre-industrial levels in about forty years.'

3. Feasibility

A number of tests for adding nutrients to the ocean have already been performed, including ship-based experiments (e.g., Boyd et al., 2007). The US Department of Energy is carrying out laboratory tests on limestone addition (Golomb et al., 2005). The company Atmocean carried out the first experiment, bringing up nutrient-rich cold water from 300 metres depth using 'wave pumps'. (http://www.atmocean.com/sequestration.htm).

Although there are global biogeochemical models available, gaps in knowledge and insufficient data hinder the accurate prediction of ecosystem response, upper ocean production and the transport of organic carbon to deep waters (Lampitt et al., 2008). For some possible fertilisers, such as phosphorus, resource limitations may be an issue.

As to the economic feasibility, many of the published calculations of the costs of different ocean fertilisation options are very rough and incomplete and, therefore, often very low. In addition, the lack of understanding of key processes and, thus, the effectiveness of different options, make such estimation even less reliable. In the case of macronutrient addition, Lampitt et al. (2008) estimated the costs of phosphorus and nitrogen fertilisation at about 45 and 25 USD (12 and 7 USD per tonne CO_2 avoided) per tonne sequestered carbon, respectively, excluding the costs of purification and injection. For iron fertilisation, Barber (2001) estimated a price of 4 to 8 USD per tonne C sequestered (1 to 2 USD per tonne CO_2 avoided). In much more detailed calculations, where the costs for fisheries, such as downstream losses of productivity, delivery systems (multiple vessels or aircraft), monitoring and verification, and research and development, are taken into account, the cost of C sequestered using ocean iron fertilisation would be between 30 and 300 USD (8 to 80

USD per tonne CO_2 avoided)(Boyd, 2008). Rau et al.(2007) estimated the cost for limestone addition and concluded that costs of 11 to 15 USD per tonne C (3 to 4 USD per tonne CO_2 avoided) are plausible for certain locations with most favourable conditions.

4. Earth system risks and co-benefits

Direct and indirect climate effects other than radiative forcing, such as effects on GHG concentrations and other positive and negative environmental and ecological side effects include:

- *Changes in the structure and function of the ecosystems and biogeochemical cycles.* Ocean fertilisation most probably will lead to changes in the structure and function of marine ecosystems. As a result, lowering of biological diversity, decreasing ecosystem services, eutrophication and anoxia due to algal blooms, and alteration of ocean chemistry, can be expected with both positive and negative effects on fisheries (Lampitt et al., 2008). Our current level of knowledge does not yet allow us to estimate the potential magnitude of these side effects.
- *Dimethyl sulphide production.* Nutrient abundance plays a secondary role in DMS production. Other factors, such as species composition, light and temperature have much higher impact, but we cannot control them. Therefore, our ability to stimulate DMS production via ocean fertilisation is very limited. (Stefels et al., 2007). Moreover, ocean fertilisation is not always accompanied by an increase in DMS – the experiments show that fertilisation could makes the Southern Ocean a DMS source and the subarctic Pacific a DMS sink (e.g., Wingenter et al., 2004; Levasseur et al., 2006).
- *Increase in trace and greenhouse gas emissions.* In addition to DMS, marine microorganisms produce and consume many other trace gases (e.g., Jin and Gruber 2003; Wingenter et al., 2004). While increase in DMS is considered a valuable side effect of ocean fertilisation, increase in emissions of other gases, such as halocarbons, methane, and nitrous oxide, raises concerns, as the first gas contributes to ozone destruction and the last two have high global warming potential.
- *Increase of ocean pH.* Ocean fertilisation probably counteracts the current trend of increasing ocean acidification, caused by decreasing pH in the surface zone (Harvey, 2008; Lampitt et al., 2008) . Therefore, addition of alkaline substances, such as limestone, is proposed as an approach to mitigate ocean acidification. This approach has its own drawbacks, however, because adding high amounts of alkalinity could potentially also lead to ecosystem changes. Moreover, mining of huge amounts of limestone will have adverse environmental effect, too. (Raven et al., 2005).
- *Unknown effects.* Finally, the possibility of unforeseen, cumulative, and long-term adverse consequences cannot be ruled out (see Sulfur injections).

As to irreversibility, ocean fertilisation can be stopped at any moment and, hence, could be considered as a reversible option, but some side effects may have irreversible results. The option does not have a rebound effect.

5. Political implications

Ocean fertilisation can relatively easily be implemented by individual (or groups of) nations or private companies. To date, a few companies have already been established, hoping to acquire future carbon credits. However, because of the above risks and uncertainties, international control is required, and some existing mechanisms provide a basis for such control. The United Nations Convention on the Law of the Sea (LOSC, 1982) regulates the protection and preservation of the marine environment, stipulating that all states, including those which are not party to the LOSC, are obliged to take individually and jointly all measures necessary to prevent, reduce and control pollution of the marine environment. It also prohibits dumping, defined as 'any deliberate disposal of wastes or other matter from vessels, aircraft, platforms or other man-made structures at sea' (Article 1(5)).

A number of other global and regional treaties, among which the London Dumping Convention (1972) and its London Protocol (1996), regulate further dumping of wastes in the ocean. The London Convention lists wastes and other matter, of which dumping is prohibited or requires a special prior permit, while for all non-listed substances a general prior permit is required. The London Protocol introduces the precautionary principle in regulating disposal activities in the ocean, requiring a total prohibition on all dumping unless it is shown there are no alternatives and it can be proven harmless to the environment.

There is ongoing debate over whether or not ocean fertilisation practices is exempt from this ban on dumping. However, given the lack of scientific consensus on its efficacy, and the apprehension about its potentially serious side effects, the contracting parties to the London Convention and London Protocol agreed in November 2007 to ban large-scale fertilisation activities and to allow only scientific research (Freestone and Rayfuse, 2008; Rayfuse et al., 2008). This was followed by a moratorium on large-scale commercial ocean fertilisation schemes, adopted by 191 nations on 30 May 2008, at a meeting of the United Nations Convention on Biological Diversity (1992), in Bonn, Germany. The moratorium will remain in force until 'scientists better understand the potential risks and benefits of manipulating the oceanic food chain' (Tollefson, 2008).

6. Options and consequences for the Netherlands

The Netherlands could take part in research and development and monitoring of large-scale tests.

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B.3. Aquatic carbon sequestration (algae)

1. Short description of option

Principle

CO_2 cannot only be removed from the atmosphere or from flue gases through terrestrial systems, but also through algae in aquatic systems. After sequestration, the algae can be used as a renewable energy source and further contribute to mitigation. From this perspective, this option could also have been included in Appendix A. The name algae is given to a large group (more than 100,000) of organisms with very different cell morphologies. These organisms are photoautotrophic, converting sunlight via a photosynthetic process into biochemical energy, fixing carbon dioxide and producing oxygen. Algae can be found in any habitat on the planet where water or at least moisture might be present for some time; from hot springs and deserts to snow; in fresh and saline water and in the sea. Some of them are free-floating in large water bodies in the form of phytoplankton, forming the base of food webs, while others live attached to the bottom and are called benthic algae. Photosynthesis of the algae is oxygenic and involves a set of chemical reactions where solar energy is used to split water into electrons, hydrogen ions, oxygen and carbohydrates, storing carbon dioxide as chemical energy in the form of organic compounds. This can be summarised by the following stylised equation (different algae have different compositions and different molecular weights):

$$6CO_2 + 12H_2O \longrightarrow C_6H_{12}O_6 + 6O_2 + 6\,H_2O$$

Cultivation of algae is of interest, because of their fast growing rates, production of valuable components, such as proteins and fats, their ability to fix CO_2 and to be grown on marginal lands with utilisation of waste or brackish water (Chaumont, 1993). The extreme diversity in their preferred habitats and physiology has led to many different technical solutions for mass cultivation (Pulz, 2001). These could be divided into two big groups: open systems and systems providing an artificial environment to grow, called photobioreactors, each having its advantages and disadvantages.

Open systems

Open systems comprise of natural waters, artificial shallow ponds, tanks, circulation ponds and raceway ponds (Ugwu et al., 2007). They are relatively cheap and easy to construct and maintain, but do not allow controlling key factors, such as temperature, pH and light conditions, and are vulnerable to invasive species and plagues. In dry, hot conditions evaporation could be significant, while dilution due to rainfall may decrease salinity much below the requirement of some strains. Open ponds have to be shallow, in order to prevent mutual shading of the cells and this increases their land requirements. Paddle wheels are often used to mix the air, in order to increase the CO_2 levels in the water and to improve the light conditions for the average cell, impeding the development of a thin dense upper layer (Pulz 2001; Chaumont 1993; Ugwu et al., 2007).

Photobioreactors

Most of the problems that plague open systems are solved by the use of photobioreactors, as these offer much greater control of most parameters and, hence, offer higher productivity. Theoretically, when all factors are optimised, they can provide an up to 10 times higher productivity than current open ponds. There are many designs: horizontal, vertical and inclined; tubular, plate-type (Pulz, 2001; Janssen et al., 2003), triangular (Vunjak-Novakovic et al., 2005), ultrathin immobilised configurations with inclined lanes (Doucha et al., 2005), and membrane technology using solar collectors (Byless et al., 2001). Algae reactors could be directly fed by the flue gases from coal-fired power plants. Companies in the United States and Israel are currently testing this technology.

Figure B.3.1. Left: GreenFuels photobioreactors, source: GreenFuels Inc. Right: Pilot plant in Hawaii, source: Nakamura et al.,2005

2. Effectiveness

For the production of 1 MT of algae, up to 1.83 MT CO_2 can be fixed. The technology is available, but requires optimisation and upscaling to play a role on a global level, to be able to respond to accelerating climate change. Contamination with other algae, bacteria, yeast, and fungi, is one of the mayor problems for the algal cultivation systems, especially for the open ones. It could reduce the yield or even completely destroy the culture (Chaumont, 1993).

Our knowledge about algae photosynthesis having direct influence on the productivity of the algae, is still limit, especially the enzyme processes and feedback mechanisms. The number of well-known algae species is very low, approximately 400. A comprehensive inventory of species in all regions and sufficient knowledge of their metabolites, which will allow strains with desired features to be obtained, are still lacking.

One of the Dutch producers of algae oil reaches a ratio of approximately 3:1 for fossil oil as input: algae oil as output, using photobioreactors, but the technology of this company is not highly energy optimised. The companies, researching production of algae for biofuels, claim that their energy efficiency is much better, but we could find no reliable numbers in the literature. If the system would work well with adequate efficiency, it could be continuously used as a renewable energy source, for as long as it is needed.

3. Feasibility

There are already small commercial units for algae production, but they produce only limited quantities of high-value products and, hence, the volume of CO_2 that they sequester is not of great importance. The number of pilot projects for production of algae biofuels is growing, but none of them is at a commercial scale, yet. If they would succeed, they could produce large volumes of algae. The algae technology is relative new and, therefore, far from optimised. There are many remaining technical challenges, for example, the multitude of different algae species. The first difficulty is to choose the right species, for instance, for specific climate conditions, production design, and productivity. Routine agricultural techniques, such as breeding, have not been employed, so far. In addition to the species selection, there are many parameters which can hinder the system performance, such as the duration of the light–dark cycle, utilisation of the light without photo-inhibition, temperature, pH, and removal of O_2. The methods for wall cleaning and effective sterilisation of the reactor's interior need improvement, too. Availability and impacts of fertilisers may be another issue, unless the nutrients can be recycled in closed systems. It is estimated that it would take about 10 to 15 years before large-scale application of algae for bioenergy could be realised (AER , 2008)

System integration is also in the initial phase and the scale-up poses significant engineering challenges. One class of problems is directly associated with the size of reactors. The requirements for maintenance of optimal mixing, light conditions and temperature, oxygen concentration and stability, impose limits on the diameter, width and height of reactors. The distance between bioreactors has to be optimised, too, because there is an obvious trade-off between the requirement of minimised shading, thus, setting the reactors wide apart, and the economical considerations for more compact configurations, in order to minimise expenses on infrastructure and land (Janssen et al., 2003; Ugwu, 2007; Vunjak-Novakovic et al., 2005). Other types of problems emerge when more units have to be put together, because each unit needs separate equipment for maintaining and controlling the optimal conditions within photobioreactors (Janssen et al., 2003). As there is still so little experience with scaling up, obviously, much could be achieved, not only through improving of each element of the system, but also through system integration. Unfortunately, the existence of many designs and many algae strains does not allow for uniform solutions, therefore, it is expected that each case has to be optimised separately.

One of the most expensive processes in the algal production is the harvesting. Further developments have to make it more economically feasible. Grobbelaar et al. (2000) calculated that for the fixation of 50% of CO_2, emitted from 300 MW coal-fired power plant, approximately 100 km^2 of algal culture would be needed. In this case, the investment costs would be 2.8 billion USD, and operational costs would be more than 0.6 billion USD, per year. These costs are highly speculative, however, as there is no such big unit operational, yet. (It should be noted that the efficiency of open pond systems is much lower than that of bioreactors). The AER (2008) estimated that current prices of 50 to 100 euros/kg can be reduced through upscaling and optimisation to less than 1 euro/kg, provided that sufficient capital will be invested.

4. Earth system risks and co-benefits

Algal systems are able not only to fix CO_2, but also other GHG emissions (CH_4 and NO_x) from flue gases, and during waste-water treatment, to recycle nutrients from agricultural wastes. Algae can be used, among other things, for the production of animal feed, for aquaculture, and fertilisers, and, therefore, their production can contribute to the reduction in energy use and GHG emissions, indirectly.

Some of the biggest advantages of the algae-based systems, however, is that they do not need arable land, and that algae are able to grow in brackish water, and, hence, do not compete with food production. Algae were found to be tolerant to a wide range of salinity. Salinity changes, due to evaporation and rainfall in open cultivation systems, and could be controlled by adding either fresh water or NaCl. High oil content in some algae and their high-rate growth make these organisms one of the best candidates for biofuel production. Producing algae-based bio-diesel, for instance, will require from 5 to 70 times less space than that based on rapeseed. The production of bio-diesel is not the only algae-based fuel; ethanol, methane, gas from gasification processes, and methanol (as a by-product), are other possibilities. Another direction of research is hydrogen production. Algae are able to produce H_2 photosynthetically. At the moment, however, the production of O_2 hampers the production of H_2. If scientists are able to overcome this problem, genuine clean fuel would become available. At present, algae biofuels cannot yet compete economically with fossil fuels.

Algae can also be used in waste-water treatment. Sijtsma and Reith (2006) estimated that 500 million m^2 of water could be cleaned in the Netherlands with algae systems, by 2030, fixing 1 Mton (1,000,000 MT) CO_2. These systems have some drawbacks, however:

- they are expensive;
- they are relatively slow (hours to days), compared to chemical systems;
- the algal biomass concentration is rather low, what makes harvesting difficult and costly;
- for the optimal result, light and specific temperatures are required, which makes these systems quite often unstable and very dependable on weather conditions, while waste water has to be cleaned all year round.

High protein content in some of the algae species, availability of unsaturated ω3 and ω6 fatty acids, pigments, and almost all essential vitamins, make algae very attractive for commercial production. The current market for algae products is 5000 t/year, with a turnover of approximately 1.25 billion USD/year and is expected to grow (Pulz and Gross, 2004). Algal products are CO_2 neutral, and because of the high price of some of them, they can offset the high costs for CO_2 fixation and biofuel production. The present market is only a niche market, however, and development of new markets would be needed if algae are to play a role in global GHG emissions reductions.

5. Political implications

Compared to other options discussed in this report, the political implications appear to be limited. When applied unilaterally as a source of energy, or as a way of removing CO_2 from flue gases, it can be a local way of reducing CO_2 emissions without significant risks to other countries. In these cases, but also if the method would be used to draw CO_2 from the atmosphere, such as sequestration in forestry, reliable methods to quantify the net effect on national emissions would have to be developed.

6. Options and consequences for the Netherlands

The Netherlands is already involved in research and development and in the production of algae-based products. As this could be one of the most sustainable options, if implemented properly, still more efforts has to be made in selecting new algae strains and in scaling-up the production facilities, which at the moment are very small.

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B.4. Carbon storage through industrial mineral carbonation

1. Short description of option

The atmosphere and the lithosphere exchange carbon naturally, via mineral weathering. This part of the carbon cycle works on a million-year time scale. Industrial carbonation tries to mimic it and to return the carbon to the lithosphere, but at a much shorter time scale (Dunsmore, 1992). We discuss the option here (category B), because, theoretically, enhanced weathering can be implemented by spreading out powdered minerals over large surface areas (e.g., see Schuiling and Krijgsman, 2006). The effectiveness would be greater if applied with concentrated flue gases, and could then be listed under our category A. Calcium (Ca) and magnesium (Mg) are the most common elements to form stable carbonates and they are also the most extensively studied. Another big advantage of using Ca and Mg silicate minerals is their abundance – Ca and Mg each are found at about 2% in the Earth's continental crust (in molar per cent). Industrial solid residues, containing large amounts of Mg, Ca and Fe can be carbonated, too, and can be an interesting option for CO_2 reduction in the regions lacking underground carbon storage reservoirs (Stephens and Keith, 2008).

Mineral carbonation can be expressed by the following exothermic reaction:

$MO + CO_2 \leftrightarrow MCO_3 + \text{heat}$

In which M presents an element, such as calcium, magnesium or iron (Sipilä et al., 2008). As the weathering is an extremely slow process, the efforts by industrial carbonation are directed toward its acceleration. Experiments with different mechanical and thermal pre-treatments, high temperatures, and pressure, reveal that carbonation reaction rates of olivine can be accelerated ten times by an increase in temperature from 25 °C to 100 °C, and four to five times if the pressure increases from 25 to 150 atmospheres. Pre-treatment, activating the mineral surface, could decrease the required quantity of ore by 75 % (O'Connor et al., 2004).

Most of the research efforts are focused on Mg silicates (primarily the most abundant serpentine [$Mg_3Si_2O_5(OH)_4$] and olivine [Mg_2SiO_4]), which are more easily accessible and are found in deposits more concentrated than Ca silicate. The former is more abundant and accessible, while the latter has higher molar concentration of Mg and reacts more rapidly
(Stephens and Keith, 2008).

Olivine is a magnesium iron silicate with formula $(Mg,Fe)_2SiO_4$, that forms a solid solution series between the two end members forsterite (Mg end member) and fayalite (Fe end member), with the ratio of magnesium and iron varying between these two end members. The crystal structure of olivine makes it very susceptible to weathering, because it is easily dissolvable by acidic groundwater or rainwater. The dissolution accelerates the weathering considerably, but it is a very slow process and a number of approaches are proposed to speed it up: reduction of grain size, changes in pH of the solution, preferences to fayalite (Fe end member) as a feedstock, as it roughly has a 50 times higher rate of dissolution than Mg end member forsterite, application of high temperature, and CO_2 pressure. However, most of these approaches involve energy penalties, reducing the overall mitigation potential of olivine carbonation. In addition, the deposits of serpentine in the Earth's crust are an order of magnitude larger than those of olivine, making serpentine a better candidate for mineral carbonation (Veld et al., 2008).

According to the location, mineral carbonation could be divided in:

- *in situ*. This involves the injection of CO_2 into underground reservoirs. If the injections are in thin (ultra)basic rocks at depths of 500 to 3000 metres, where the Earth's high temperature will assist the carbonation to start with, the process can even become energy neutral, would the heat released be used as geothermal energy. It is worth noting, however, that most of current in situ studies are oriented mainly on deepening the general understanding of mineral carbonation.
- *ex situ*. This involves processing in a dedicated plant. The most simple industrial mineral carbonation is a direct gas–solid carbonation, a process, where particulate metal oxides are brought into contact with gaseous CO_2. However, the process is very slow, even at high temperatures and pressures, and, therefore, is considered not very promising. Instead, research currently focuses mainly on a two-step process, involving extraction of magnesium followed by a carbonation at high temperature and under high pressure (above 500 °C and 20 bar) (Sipilä et al., 2008). The extraction of magnesium or calcium could be further accelerated by using some solvent, for instance, acetic acid. This approach is called aqueous carbonation, and its outcomes depend on multiple factors, such as temperature, pressure, liquid to solid ratio, and additives. Research on the optimal conditions is ongoing, but Sipilä et al. (2008) noted that 'despite partial successes and promising process ideas, so far, the keys to success have not been found.'

2. Effectiveness

Zevenhoven et al. (2006) estimated that there are large quantities of calcium and magnesium containing minerals around the world, of which theoretical capacity for carbon sequestration on a millennium time scale is comparable with the sequestration capacity of biomass and atmosphere (see Figure B.4.1).

If the 15 EU Member States, which were EU member at the time that the Kyoto Protocol was agreed, would decide to sequester the CO_2 required by the Kyoto protocol for the 2008-2012 period, by olivine carbonation, the world production of olivine would need to increase 55 times. It is possible to increase the world olivine production, which was four million tonnes, per year, in 2003. While olivine is found on all continents, it is known that its dissolution is faster in warm than in cold climates, making mineral carbonation in the Caribbean, Indonesia, Philippines and the Arabian peninsula especially attractive (Veld et al., 2008). The olivine could be spread in the vicinity of the mines in these countries, where the wet tropical climate stimulates weathering, wages are low, transport costs limited, and new jobs can be created (Schuiling, 2009).

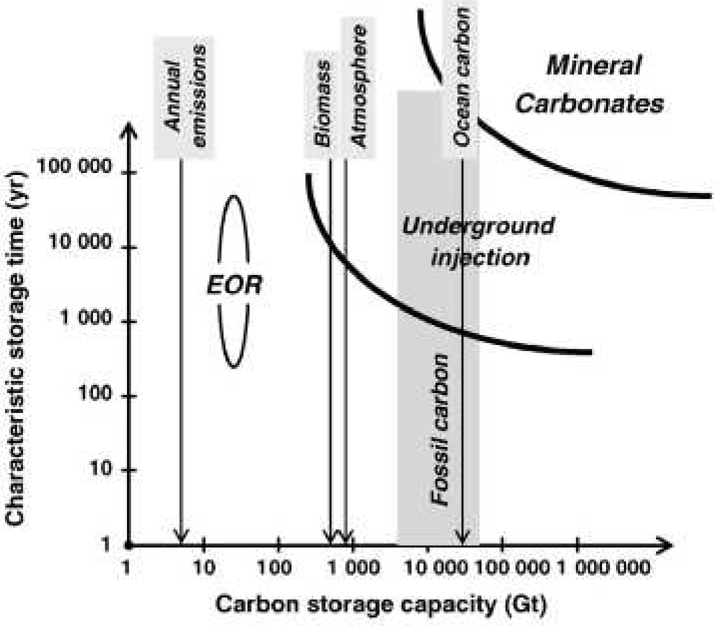
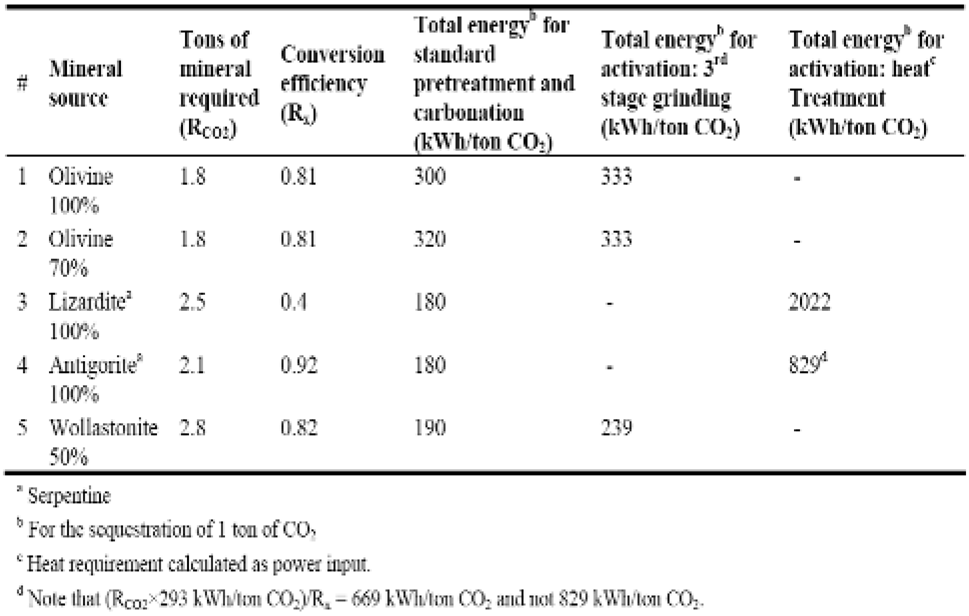


Figure B.4.1. Estimated storage times and capacities for various CO_2 *sequestration methods (Source: Zevenhoven et al., 2006)*

The effectiveness of this option is also determined by the amount of energy required to run the process. Khoo and Tan (2006) calculated the energy requirements for five methods and found that CO_2 capture by chemical absorption and wollastonite carbonation have the best energy performance, followed by chemical absorption and olivine carbonation. In these calculations, transporting CO_2 from the power plant is not taken into account (see Table 1). Sipilä et al. (2008) recalculated some early published analyses of energy use, making a distinction between power and heat, as it is possible, sometimes, to use already existing waste heat streams instead of heat from electricity. They concluded that the energy input requirements are overestimated by approximately 30%, if it is assumed that heat can be used for the thermal pre-treatment instead of electricity. Earlier full life cycle analysis implies that the deployment of mineral carbonation, in combination with carbon capture, would increase the energy consumption of power plants by 60 to 180%, reducing their average 35% efficiency to between 25 and 18% (IPCC, 2005). As the analysis of Sipilä et al. (2008) was not based on full life cycle analysis, it is not clear what the total energy reduction will be, when their methodology is applied.

Table B.4.1. Energy requirements per tonne CO_2 for the five processes investigated (Source: Khoo and Tan, 2006)



#	Mineral source	Tons of mineral required (R_{CO2})	Conversion efficiency (R_x)	Total energy[b] for standard pretreatment and carbonation (kWh/ton CO_2)	Total energy[b] for activation: 3rd stage grinding (kWh/ton CO_2)	Total energy[b] for activation: heat[c] Treatment (kWh/ton CO_2)
1	Olivine 100%	1.8	0.81	300	333	-
2	Olivine 70%	1.8	0.81	320	333	-
3	Lizardite[a] 100%	2.5	0.4	180	-	2022
4	Antigorite[a] 100%	2.1	0.92	180	-	829[d]
5	Wollastonite 50%	2.8	0.82	190	239	-

[a] Serpentine

[b] For the sequestration of 1 ton of CO_2

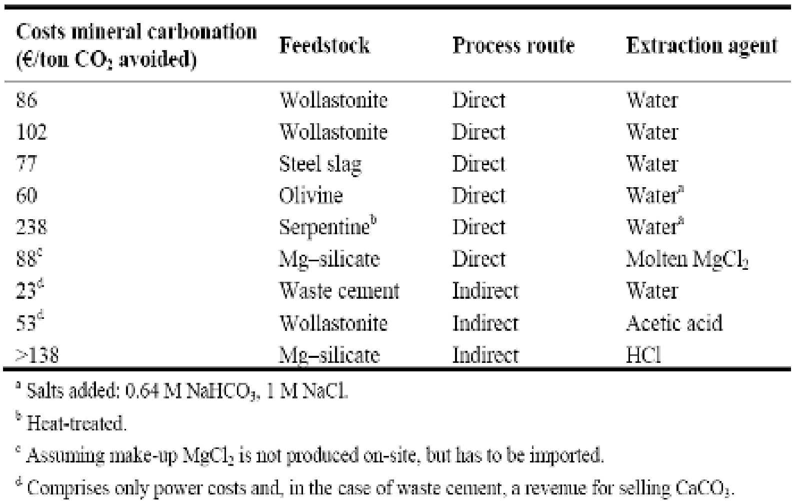
[c] Heat requirement calculated as power input.

[d] Note that (R_{CO2}×293 kWh/ton CO_2)/R_x = 669 kWh/ton CO_2 and not 829 kWh/ton CO_2.

3. Feasibility

Different reactions are being tested. However, research around mineral carbonation requires completely new approaches or significant improvements of old ideas and process routes (Sipilä et al., 2008). As previously outlined, industrial mineral carbonation is a very slow process and, therefore, pretreatment, such as crushing, elevated temperatures and pressures, are applied to accelerate the reactions, but there are significant trade-offs between the costs, the required energy and the rate of reactions, which have not been resolved, yet (Stephens and Keith, 2008). Questions related to effective recycling of the extraction agents and additives remain unanswered (Sipilä et al., 2008).

Table B.4.2. Costs of mineral carbonation (Source: Huijgen et al., 2007)



Costs mineral carbonation (€/ton CO_2 avoided)	Feedstock	Process route	Extraction agent
86	Wollastonite	Direct	Water
102	Wollastonite	Direct	Water
77	Steel slag	Direct	Water
60	Olivine	Direct	Water[a]
238	Serpentine[b]	Direct	Water[a]
88[c]	Mg–silicate	Direct	Molten $MgCl_2$
23[d]	Waste cement	Indirect	Water
53[d]	Wollastonite	Indirect	Acetic acid
>138	Mg–silicate	Indirect	HCl

[a] Salts added: 0.64 M $NaHCO_3$, 1 M NaCl.

[b] Heat-treated.

[c] Assuming make-up $MgCl_2$ is not produced on-site, but has to be imported.

[d] Comprises only power costs and, in the case of waste cement, a revenue for selling $CaCO_3$.

The production of valuable end products could offset high operational costs for carbonation, but even though many options have been proposed, none of them has resulted in large-scale production, yet (Sipilä et al., 2008). The amount of carbonates produced in a large-scale mineral carbonation would be huge and, hence, their disposal would be a challenging task (Sipilä et al. 2008). The current costs of mineral carbonation are in the range of 23 to 238 euros/tCO_2, or 84 to 872 euros/tC. The price of olivine is 60 euros/tCO_2 and 220 euros/tC (Huijgen et al., 2007; see also Table 2). If powdered olivine simultaneously would be used for liming and C sequestration, the net costs would be lower (Schuiling and Krijgsman, 2006). A recent TNO report (Veld et al., 2008) estimated the cost of CO_2 avoided by olivine carbonation to be between 12 and 60 euros. Laboratory experiments demonstrated that, in tropical conditions, 80% carbonation of olivine could be accomplished, in 6 years, if olivine is spread on agricultural land, and in 28 years, if spread alongside the coast. The report notes, however, that in real settings, this rate could be 100 to 1000 times slower. In temperate climates, the rate is also a few times slower than in tropical ones . Based on the findings of this report, Environment Minister J. M. Cramer (VROM) advised the Dutch parliament to consider olivine a less promising option than others, and to not dedicate funding to it, at present (Cramer, 2009).

4. Political implications

The option can be implemented at levels varying from local to international. It does not seem to have any special policy implications, compared to other emission reduction options considered here.

5. Earth system risks and co-benefits

Mineral carbonation allows immobilisation of CO_2 for millennia. Unlike carbon storage in the ocean or underground, it does not suffer from leakage[29] or uneven distribution of storage reservoirs, and has minimal requirements for integrating with existing infrastructure (Stephens and Keith, 2008). It also does not require long monitoring (Sipilä et al. 2008). There are huge quantities of mineral material required for large-scale mineral carbonation: for instance, CO_2 sequestration from a coal-fired power plant via mineral carbonation requires five to ten times more mineral material than the amount of coal that is used by the plant. The associated mineral mining and processing activities will have similar negative environmental impacts on the typical ore mining: increasing the potential for soil erosion, sedimentation, landslides, habitat loss, air pollution, and landform modification. Serpentine mining needs extra attention, because chrysotile, which is a natural form of asbestos, is found very often in serpentine. Mineral carbonation destroys chrysotile, however, and the products of the process are asbestos free. The carbonation is also an effective way to demobilise some toxic wastes (IPCC, 2005). Theoretically, in situ mineral carbonation can be energy neutral, if the heat produced by the carbonation could be recovered. This could prove impossible, however, because the minerals and CO_2 could reach thermal equilibrium with the surrounding rocks if the kinetics are very slow.

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[29] IPCC (2005) suggest, however, that the potential leaching of metals could be excluded only after conducting tests.

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B.5. Biochar

1. Short description of option

Biochar is a black carbon, produced by pyrolisis of biomass. Charcoal is one of its varieties, produced from wood. The production of biochar allows for carbon sequestration and long-term storage, for many centuries and even millennia, and, therefore, was proposed as one of the possible options for CO_2 mitigation, by Prof. Wim Sombroek from Wageningen University, who was a pioneer in studying the Amazonian charcoal rich deep black soils *terra preta*. It can be produced from wastes, which otherwise would release carbon dioxide.

Feedstock for its production could consist of wood and crop residue and organic wastes, including manure and sewage sludge. Carbon recovery, on average, is 50%, but varies for different types of feedstock from 39 to 64% (Lehmann, 2007a). Lehmann et al. (2006) also emphasized that biochar production enables unambiguous verification of sequestration. Moreover, it has additional positive environmental and economical effects, because it is a by-product of energy production, and can be used as soil additive to improve soil quality and fertility. Evidently, the biomass used for biochar could also directly and fully be used as a renewable fuel. In addition, producing biochar as a means to sequester carbon also can have advantages in terms of enhancing soil fertility and crop yields, improve water quality, and reduce pressure on forests. Modern techniques allow for a combination of biofuel production and biochar sequestration.

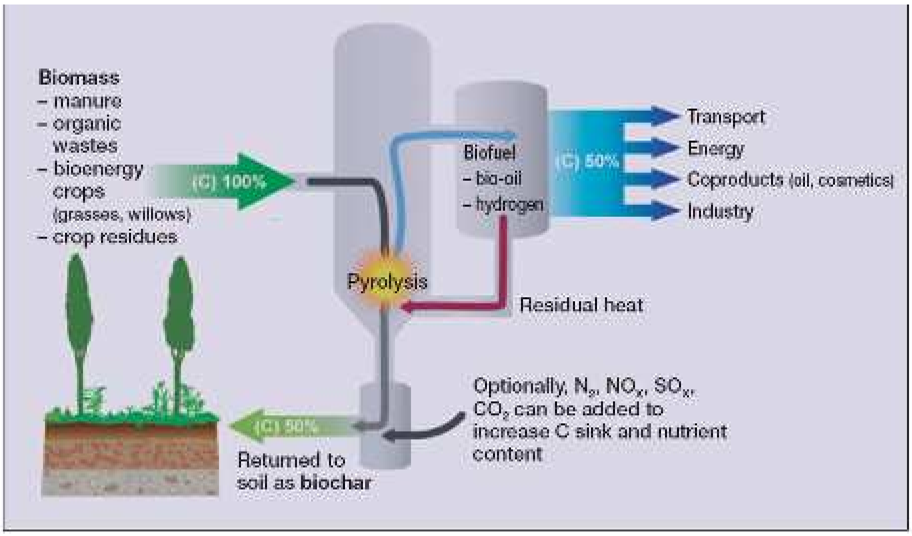

Figure B.5.1. Concept of low-temperature pyrolysis of bio-energy with biochar sequestratio (Source: Lehmann 2007a)

2. Effectiveness

Lenton and Vaughan (2009) proposed a mitigation potential of 0.12 Wm^2 (10 ppm CO_2), by 2050, and 0.37 Wm^2 (40 ppm CO_2), by 2100. The technology exists and Lehmann et al. (2006) estimated that the current global potential for biochar production is 0.6 ± 0.1 PgC/y , but could reach 5.5 to 9.5 PgC/y, by 2100. As to the effect on the energy balance (and thus mitigation requirements), the production of biochar is associated with some 'energy penalties': production and transportation of biomass, the process of pyrolysis and the application of biochar to the soil. Lehmann (2007a) stated that 'pyrolysis produces 3 to 9 times more energy than is invested in generating the energy', but there has not been a full assessment of the whole chain and different possible scenarios, yet. It should be continued for as long as there are excessive CO_2 emissions. The climate system responds to it, instantaneously.

3. Feasibility

Charcoal is produced today. Biochar as soil fertiliser is implemented on a small scale (e.g., Rondon et al., 2005), but there are natural analogs, for instance, the Amazonian charcoal rich deep black soils *terra preta* (Sohi et al., 2009). Nevertheless, there are several technical challenges that would have to be addressed:

- In the process of co-production of biochar and energy there is a conflict between simultaneously maximising them, while increasing one leads a decrease in the other. Wolf (2008) estimated that from a 45% yield of char, 32% of energy could be recovered, while a 20% yield of char will allow a maximum energy recovery of 72%.
- There is no suitable technology for incorporation of biochar in soil, yet. (Lehmann, 2007a).
- Different combinations of feedstock and production conditions will result in different amount and composition of toxic and potentially carcinogenic organic materials, produced during pyrolysis (Lima et al., 2005), and will give as output a different type of biochar with different stability (longevity) and effectiveness of retaining soil nutrients. (Lehmann, 2007a).

As to the costs and economic challenges, Lehmann (2007b) estimated that 'biochar sequestration in conjunction with bio-energy from pyrolysis becomes economically attractive under one specific scenario, when the value of avoided carbon dioxide emissions reaches 37 USD per tonne. According to Sohi et al. (2009), application of biochar may be attractive, even today, for producers of high value crops, because of its water storage ability. They emphasise, however, that 'the feasibility of optimising its multiple useful characteristics is not known'.

4. Earth system side effects

As a soil addition, biochar may further decrease the emissions of nitrous oxide and methane, substantially (Rondon et al., 2005; Lehmann, 2007a), in greenhouse experiments has been observed that the addition the addition of 20 g biochar to 1 kg forage grass reduced the N_2O and methane emissions by 80 and 100%, respectively. This effect, therefore, needs further research. Addition of black biochar will decrease soil albedo, if tillage is practised. Biochar particles, which reach ice caps and ice sheets as soot, will affect their albedo, too, thus contributing to global warming (Woolf, 2008).

Biochar can increase crop yield and, hence, can contribute to sustainability. It can restore soil fertility very effectively, and this characteristic is of particular interest for degraded soils. In additions, it needs to be applied only once to a certain location, unlike current fertilisers, which have to be reapplied, annually (Lehmann et al., 2006). As biochar improves nutrient retention in the topsoil, it might reduce pollution caused by nutrient leaching. Biochar also directly reduces pollution caused by fertilisers, since it has fertilising properties. If sludge, manure or poultry litter are used as feedstock, pollution, caused by their leaching, is also avoided (Lehmann et al., 2007a). However, there is a limit to the amount of biochar that can be added to soil, both in terms of soil capacity and in beneficial effect as fertiliser. Lehmann et al. (2007a) suggested that additions of up to 50MgC/ha biochar have positive effects and only very high quantities might hamper crop growth. For instance, Amazonian *terra preta* soils contain up to 250 Mg of soil organic carbon per hectare, in the top 30 centimetres. More positive effects could be expected when biochar is applied to degraded soils, than in when it is applied to fertile soils.

In addition to its usage as soil fertiliser, biochar can be used as material for the terracing of sloping agricultural land or for raising ground level in flood zones (Woolf, 2008). Radlein (2007) proposed also to fill valleys with biochar and to cover it with soil. If biochar particles can find their way into air and water, they will cause environmental pollution. Such contaminated air, food and water will threaten human health and ecosystems (Sohi et al., 2009). There is growing evidence that biochar increases moisture retention (Sohi, 2009). Woolf (2008), however, stressed the need for further research on the impact of biochar on water repellency in soils. He quotes a study of Doerr et al. (2000), according to which organic coatings are a common cause of water repellency in soils, and suggesting that there is a possibility that hydrophobic compounds may occur in biochar.

This option is also quite irreversible because, once applied, it cannot easily be removed from the soil. It does not have a rebound effect.

5. Political implications

Because of its irreversibility and the potential health and environmental side effects, large-scale biochar implementation would require an international assessment and regulation. As is the case for all other large-scale applications for which gaps in knowledge exist, responsibility and liability are moral and political issues (Sohi, 2009). There seem to be less risks involved in unilateral actions.

6. Options and consequences for the Netherlands

The Netherlands has expertise in biochar research and, thus, the goal could be to maintain its good position, continuing this research. Further study is necessary on the possible side effects of large-scale implementation of biochar as soil fertiliser, particularly, in the (sub)tropics. Another field needing further research is the optimisation of the ratio of energy–biochar production.

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B.6. Air capture

1. Short description of option

Air capture systems remove CO_2 from the air and deliver a pure CO_2 stream for sequestration (Keith et al., 2006). A number of technologies to capture CO_2 directly from the air have been proposed over the last decade (e. g. Lackner et al., 2001; Keith et al., 2006; Nikulshina, 2007). They have a potential to remove already emitted CO_2 from the atmosphere and, hence, might play an important role in averting dangerous climate change, if applied on a huge scale. However, the CO_2 concentration in the air is only about 0.04 per cent, and, therefore, air capture should not be confused with CO_2 capture from flue gas at big sources, such as electric power generation plants, where the CO_2 concentration is more than 10%, making it thermodynamically much more favourable to separate the CO_2 gas. Assuming that carbon capture and storage can be directly applied to those large sources, air capture aims instead at capturing the emissions coming from remaining small and mobile sources (such as those in the transport sector), which account for approximately half of the total in emissions. Small-scale analogues of air capture already are used on board in submarines and spacecraft, to remove CO_2 from the air (Economist, 2009). Photosynthesis in plants could be considered to be a natural analogue of the engineering systems which could, therefore, be called 'artificial trees' (Kunzig and Broecker, 2009). Pure gases other than $CO_{2,}$ are commercially produced from air, but the costs and energy inputs for applying this to GHG reduction are prohibitive (Keith et al,, 2005).

Different schemes have been proposed for air capture and CO_2 disposition (e. g. Lackner et al., 2001; Zeman and Lackner, 2004; Keith et al., 2005; Baciocchi et al., 2006; Nikulshina et al., 2008). This fact sheet only discusses capture – for disposal and storage of the captured CO_2 we refer to IPCC (2005), because the issues involved are similar to CO_2 captured from power plants and other point sources. These schemes all use some 'sorbent' material (mostly a sodium hydroxide (NaOH) or calcium hydroxide (Ca(OH)2) solution), which reacts with CO_2 and binds it. Subsequently, CO_2 is removed from the sorbent using, for instance, a chemical reaction, heating or vacuum. In this document, we discuss the designs of Lackner, Keith and Stainfeld, the only ones who constructed prototypes, so far. Keith and Steinfeld published their results in scientific journals, while the information on the designs of Lackner, who is developing his technology commercially, was taken mainly from the mass media.

The design of Lackner and colleagues

Lackner's company Global Research Technologies (GRT) demonstrated one prototype in 2007, which uses membranes to capture CO_2, which are then rinsed off with liquid sodium carbonate and separated from the fluid, using electricity (Figure B.6.1). However, Lackner obtained a patent for another technology which, according to the author, reduces the energy required to repeat the process tenfold. Currently, his team is working on a prototype that will capture CO_2 from air on absorbent polymer sheets (ion exchange resins, used in water softening). Captured CO_2 will be consequently released (or exhaled, as Lackner describes it) by means of changes in humidity. This usage of warm water vapour is one of the core inventions of Lackner, allowing the process to be carried out at only about 40 ^{0}C , saving energy (Chemistry world, 2008; Adam, 2008; Economist, 2009; Kunzig and Broecker, 2009).

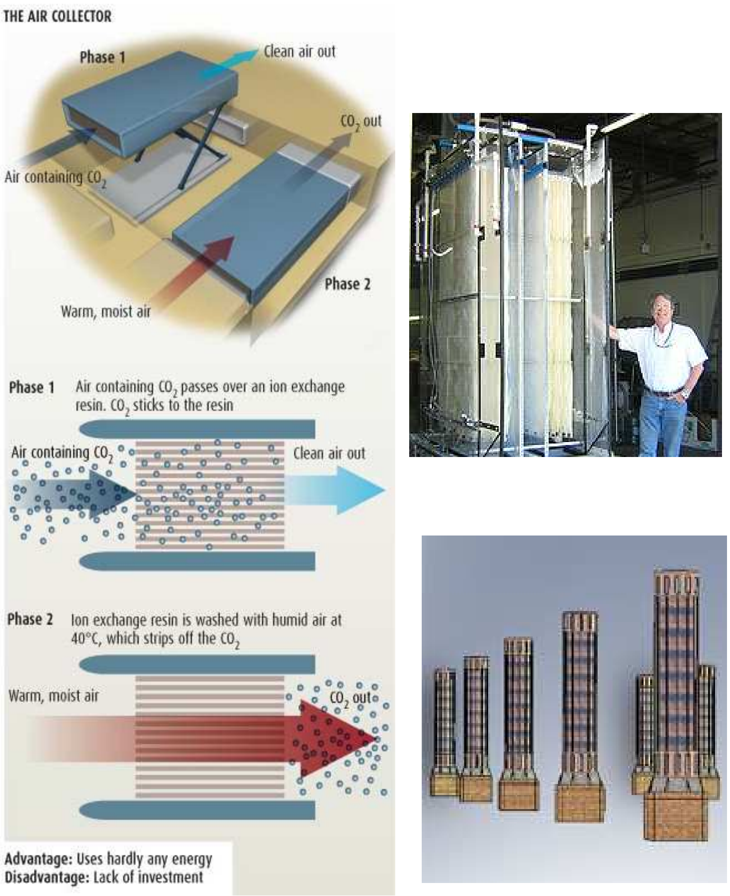

Figure B.6.1. Left – principle of Lackner's design (Source: Kunzig and Broecker, 2009), upper right – Lackner with his first prototype, bottom right - artist vision (Source: Borns, 2008)

The design of D. Keith and colleagues

The technology employed by D. Keith et al. uses a spray of liquid sorbent to capture the incoming CO_2 (Figure B.6.2). The liquid is subsequently led to a kiln, where it is heated to about 900 ^{o}C, in order to extract CO_2. The sorbent is recycled in this process. The use of droplets instead of wet surfaces or sheets distinguishes this technology from other proposals for air capture. It increases the surface area of the sorbent and, hence, the efficiency of CO_2 capture (Keith et al., 2005; Stolaroff, 2006; Stolaroff et al., 2008; Zeman and Keith, 2008; Keith, 2009).The choice of the sorbent is crucial for the feasibility of this design. Stolaroff (2006) described the ideal sorbent as 'having a binding energy with CO_2 just larger than the 20 kJ/mol required to pull it from the atmosphere, inexpensive, abundant, and non-hazardous'. There is ongoing research done on new sorbents. Current proposals use aqueous solutions of calcium hydroxide ($Ca(OH)_2$) and sodium hydroxide (NaOH), which conform with the last three requirements, but require relatively much energy and hence could increase GHG emissions if the energy supply would involve fossil sources. Keith et al., however, are concentrating at this stage on achieving low capital costs instead of looking for new absorbent that may reduce the energy costs. At the cost-optimal flow rate, a structural area of about 760 x 760 m^2 would be required to capture 1 Mt/yr of CO_2 (Stolaroff et al., 2008).

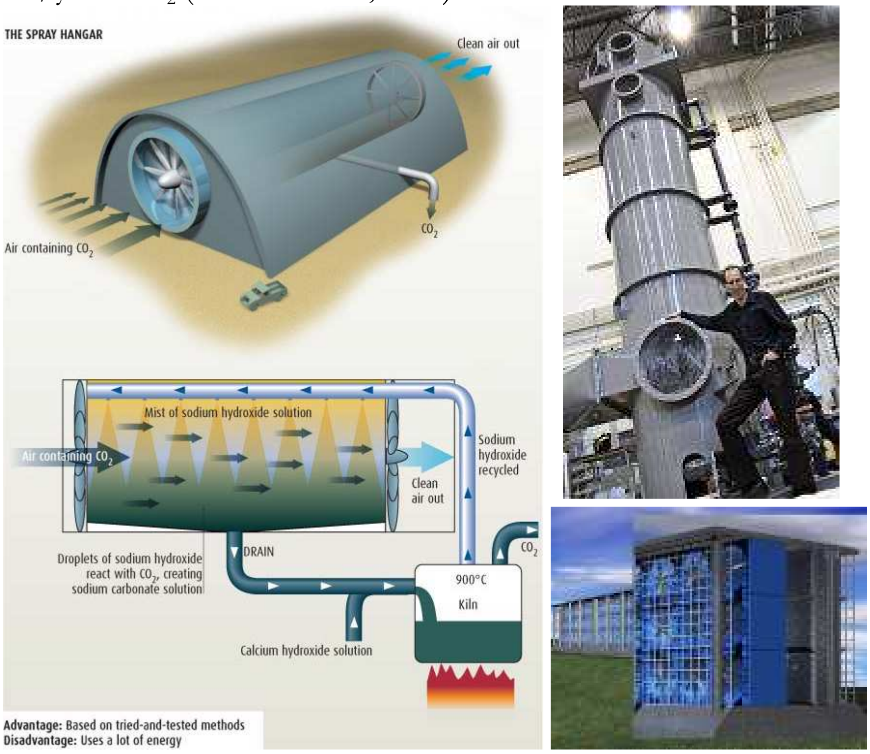

Figure B.6.2. Left – principle of Keith et al. design (source: Kunzig and Broecker, 2009), top right – Keith with the prototype from 2008 (photo: Ken Bendiksten), bottom right - artist vision (Source: University of Calgary, 2008)

The design of Steinfeld and colleagues

In two consecutive steps, the Steinfeld et al. fluidised bed first captures CO_2 from air and then releases and then removes the pure CO_2 gas (Figure B.6.3). During the first phase, calcium oxide (CaO) reacts with the CO_2 from ambient air when heated at about 400 °C, forming calcium carbonate ($CaCO_3$). In the next phase, the chamber is heated to above 800 °C and under these conditions particles of $CaCO_3$ are transformed to CaO and pure CO_2. In both phases, solar energy is used for heating, generated with parabolic mirrors. Changes in the position of the mirrors allow for adjusting to the required temperatures (Nikulshina et al., 2007; Nikulshina et al., 2008; Nikulshina et al., 2009). In this design, CaO is recycled and this recyclability is of great importance. It drops to 60% after five cycles, but can be reactivated with H_2O, pure CO_2 , Na_2CO_3 or NaCl (Nikulshina et al., 2009).

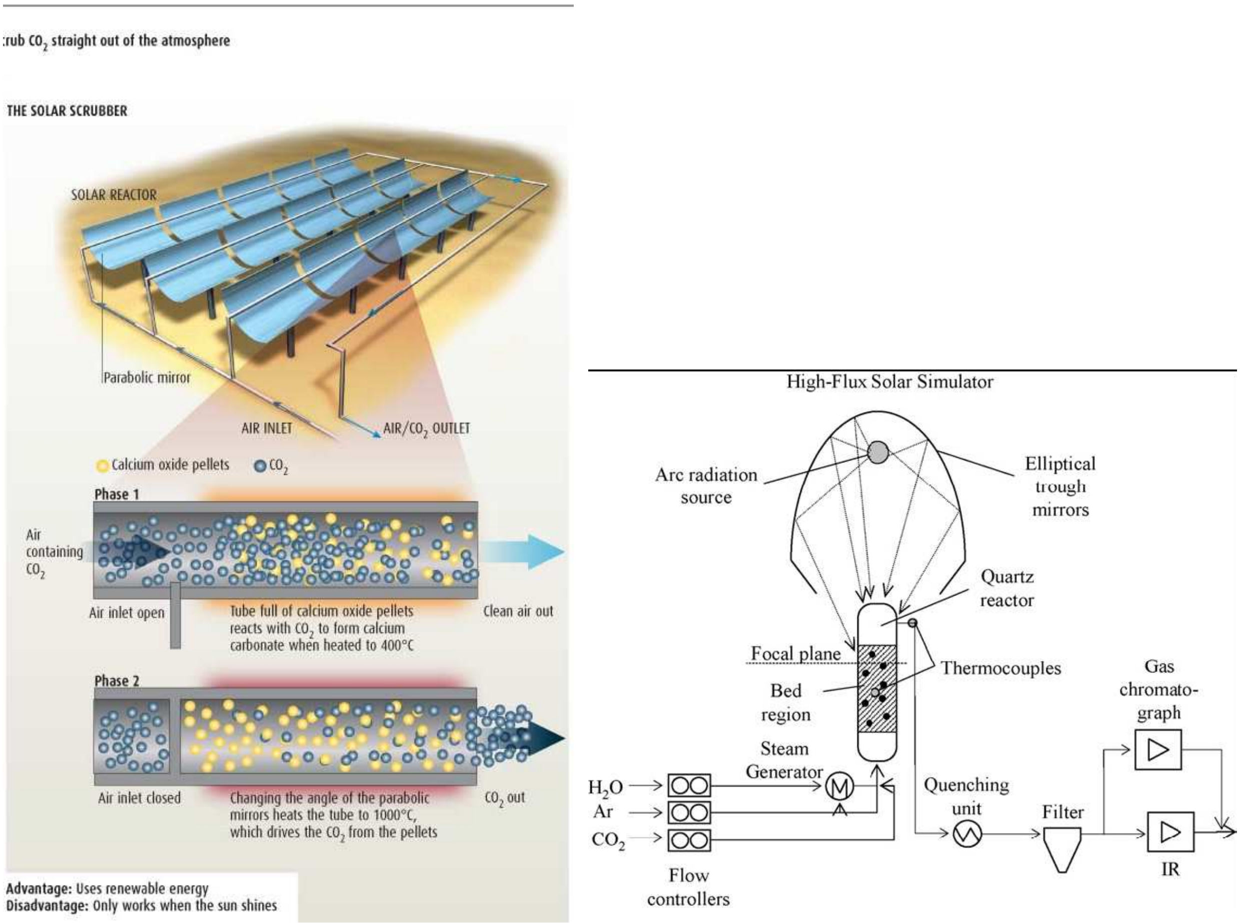

Figure B.6.3. Left - principle of Steinfeld et al. design (Source: Kunzig and Broecker, 2009), right - experimental set-up (Source: Nikulishina, 2009)

2. Effectiveness

Air capture could potentially generate any size of carbon sink societies would be willing to pay for. In the long term, it might have the potential to sequester more than 1000 PgC and cancel the total emissions from a strong mitigation scenario, or −1.43Wm−2 and more (Lenton and Vaughan, 2009). The option could possibly be implemented within a few decades (Keith, 2006). Main questions relate to the net effect on the energy balance, and, thus, to mitigation requirements. Lackner's team claim that their new technology massively reduces the amount of required energy, but does not reveal any details (Guardian, 2008). The team of Keith et al. concentrated on lowering the costs of the process instead of the electricity consumption. A lower price for air capture of 96 USD/tonne CO_2 could be achieved at energy consumption of about 94 kJ/mol (Figure B.6.4). This energy consumption can be brought down to 53 kJ/mol, if the total cost increases by 10% (this is compared to the heat of combustion of gasoline, which is about 660 kJ/mol CO_2). The team assumed further that the energy will come from carbon-neutral sources, such as nuclear or bio-energy. (Stolaroff et al., 2008). Keith (2009) has made another comparison: he calculated the energy needed to produce a bar of CO_2 from flew gas (starting from 14% concentration and assuming 100% capture) and from ambient air, and concluded that their ratio is 1.4.

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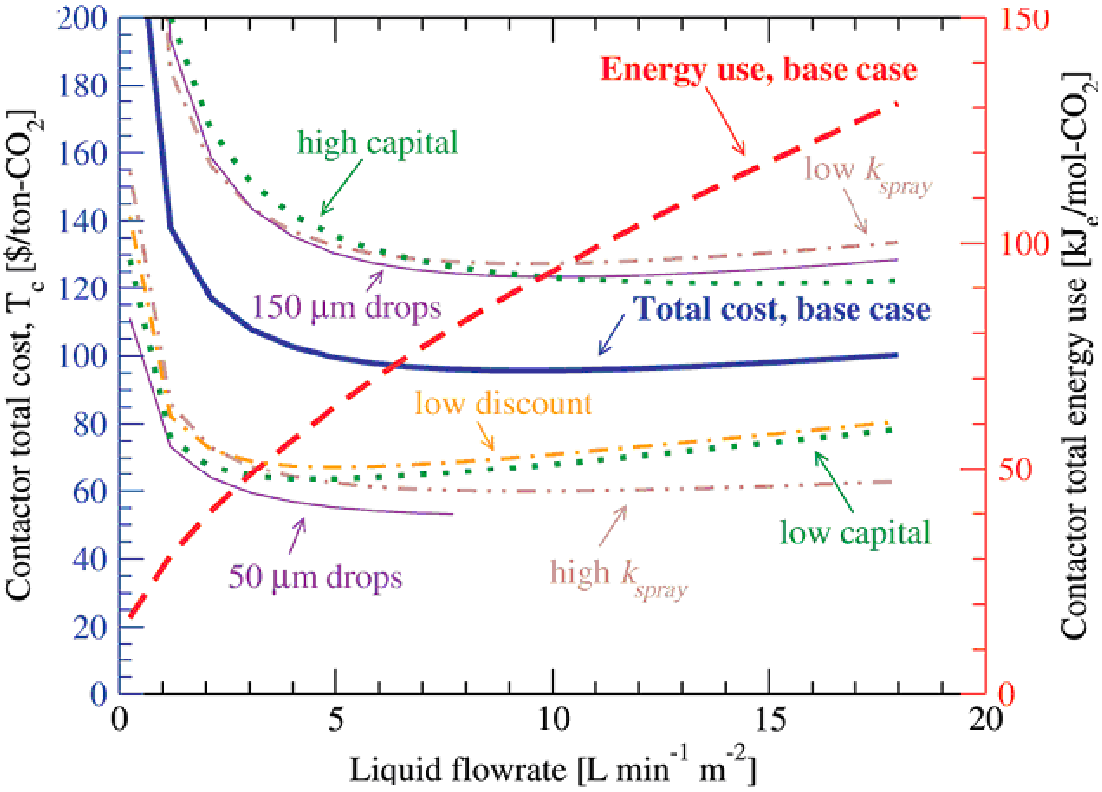

Figure B.6.4. The relation between energy consumption and total costs (Source: Stolaroff et al., 2008)

The total solar thermal energy requirement for the scaled-up reactor of Steinfeld et al. would be 2.5MW. This energy requirement is calculated for a rate of CO_2 capture of 1 mol/s CO_2, corresponding with air mass flow rate of 58 kg/s for a CO_2 concentration of 500 ppm (Nikulishina et al., 2007). If the same units are used, the design of Keith et al. (2006) will need a minimum of 4 GJ/tC (1 GJ/tCO_2) and the design of Steinfeld et al. would need 208 to 250 GJ/tC energy for capture and sequestration .

An important question is whether the renewable energy required to apply the air capture techniques in a carbon-neutreal way could not better be used directly for replacing the energy sources that cause CO_2 emissions in the first place.

The air capture should be maintained until desired concentration is achieved. In principle, the climate system responds immediately and proportionally to the devices used.

3. Feasibility

The various teams that are working with prototypes suggest that their solution can be scaled up quickly, if required. The team of Lackner claims that they can construct a prototype within two years, if the required funding of 20 million USD would become available. The design of Keith et al. already has a prototype, and the design of Steiner et al. also has a small laboratory-scale prototype. Technical challenges are those of making a soundly working prototype, to scale it up to engineering size, to reduce the energy consumption, and to recycle the materials.

As to costs, Lackner estimated that the price of capturing the CO_2 will be several hundred dollars per tonne of CO_2, when commercially available, but the prices will drop to 30 USD per tonne (110 USD per tonne C) (Borns, 2008). He suggested that if the technology could be deployed for small-scale commercial uses, such as in greenhouses, water treatment and enhanced oil recovery, it will be economically feasible, even at prices of 200 USD/t CO_2 (733 USD/tC) . This will give the technology the chance to be improved and scaled up. Keith et al. (2006) believed that the realistic price range, when only existing technologies and materials would be used, would be 200 to 500 USD (733 to 1833 USD/tC). These prices may fall to between 20 and 40 USD (73 to 147 USD/tC), in a long run (Keith, 2009). The design of Steinfeld, so far, has not been accompanied by economical analysis. Unlike the capture from power plant flue gases, where the costs of removing the last 10% of CO_2 are much higher than removing the first 10, 50 or even 90%, the costs of air capture from ambient air increase linearly , thus, the costs of removing the last 10% equals the costs of removing the first 10% of CO_2 (Lackner, 2001).

4. Earth system risks and co-benefits

CO_2 emissions can be captured from diffuse sources, such as automobiles, aeroplanes, agriculture and home heating. In addition, also historical CO_2 emissions can be removed (Keith et al., 2006). The process can be implemented independent of the location of CO_2 sources, because atmosphere is relatively well-mixed with respect to CO_2 (Stolaroff, 2006). The risks of air capture for the earth system appear to be limited, compared to other geoengineering options (e.g., no problems with irreversibility or rebound effect), but they are certainly not negligible. First, there are questions related to the energy required. Second, risks are involved in the disposal and storage of CO_2. Third, some of the options have huge water requirements in addition to high energy use. For example, if the design of Keith et al. is used, $2 \times 10^{10} m^3/yr$ of water will be needed to capture the emissions of the US transport sector alone. This equals half of all non-power industrial water use in the United States (Stolaroff et al., 2008). Finally, the technology could meet with opposition, because of aesthetic reasons, as is the case with wind energy parks.

The air scrubbing devices can be placed at the most convenient places, where it is cheapest to produce and maintain them, where there is enough available land or where concentrated CO_2 can be used or stored (Lackner, 2001; Keith et al., 2006) The land requirements are small: an area of about 530 x 530 km^2 would be enough to offset world energy consumption, would it reach the current US *per capita* consumption, while the technology does not require abandonment of existing infrastructure (Lackner, 2001).

A suggested co-benefit is that synthetic hydrocarbon fuels or 'carbon-neutral hydrocarbons' can be produced, if the extracted CO_2 is combined with hydrogen. This process, however, is still very energy intensive (Zeman and Keith, 2008). It can also be combined with renewable energy production; Lackner proposed to combine air capture devices with wind parks. Air capture devices could use the wind energy during the night, when electricity demand is low and some producers turn off their utilities. (Economist, 2009)

5. Political implications

Air capture can be implemented, unilaterally. If disposal and storage problems would be resolved locally, the international implications and, hence, the need for international management and control, may be limited. The main questions seem to be related to costs and resource requirements (energy, water, solvents), which could have international spill-over effects.

6. Options and consequences for the Netherlands

At this stage, the Netherlands could join the research and development of energy efficient, economically viable air capture systems.

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Appendix 3 C. Solar radiation management

C.1. Injections of aerosol or aerosol precursors *into the stratosphere*

1. Short description of option

Large volcanic eruptions cause global-scale cooling of the planet, by changing the Earth's albedo. They inject sulphur dioxide particles into the stratosphere, which consequently reacts with OH and water to form sulphuric acid aerosol droplets, and the latter reflect a fraction of the sunlight back into space. The eruption of Mount Pinatubo in 1991, for example, reduced the global temperature by about 0.5 °C (Soden et al., 2002). Budyko (1977) was the first who proposed the use of 'artificial volcanoes' or injections of sulphur dioxide into the stratosphere to cool the planet. In 2006, Nobel laureate Paul Crutzen revived the debate (Crutzen, 2006). Rasch et al. (2008) presented an overview of the latest developments at the time.

In order to make this option effective, aerosol precursors would have to be injected at the level of the stratosphere, because the residence time of the resulting particles there is relatively long, approximately 2 years (Brovkin et al., 2008). The aerosols could be carried to the stratosphere by balloons, rockets and aeroplanes, or by artillery guns (NAS, 1992). Robock et al. (2009) proposed to use nine KC-10 aeroplanes or fifteen KC-135 aeroplanes, each aeroplane making three runs a day.

2. Effectiveness

The sulphate climate cooling efficiency is 0.75 W/m^2 per Tg S in the stratosphere (Crutzen, 2006). Govindasamy and Caldeira (2000) found that a 1.8 per cent reduction in incoming solar forcing would compensate the global warming produced by a CO_2 doubling. Injection of 7MtS/year could fully compensate global warming induced by 5000Gt CO2 emissions[30], 90% of which may be released between 2000 and 2300 (Borovkin et al., 2009).

The effectiveness also depends on the speed with which the option could be introduced. The potential logistical problems of geoengineering, such as sulphur injections, are described by Tuck et al. (2008). It is suggested that the available technology could be used to inject sulphur into the stratosphere, although it has never been tested and would have to be optimized, over time. The climate system responds within months to this option (Matthews and Caldeira, 2007). For instance, the eruption of Mount Pinatubo in 1991 injected 10 Tg S into the tropical stratosphere (Wilson et al., 1993). One year later, the Earth's surface was cooled by 0.5 °C. Therefore, deployment could wait until the problem aggravates and political agreement about its necessity is reached.

Where effectiveness is considered, it should be noted that in order to continuously counteract the warming effects of greenhouse gases, sulphur injections have to be

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[30] But the actual mitigation effect will depend on the timing and the form of the sulphur (A. Robock, personal communications)

sustained for millennia (Wigley, 2006). Boucher et al. (2009) indicated that overshoot of CO_2 for decades has to be offset for centuries.

A final aspect of the effectiveness is the effect of the option on the energy system balance and, thus, onmitigation requirements. For this option, it will depend on the energy needed to produce the sulphur aerosols and bring them up into the stratosphere, and their impact on the energy balance probably will not be very significant (Robock et al. , 2009).

3. Technical and economic feasibility

Sulphur injections have not been tested. The scientists, involved in geoengineering research, assume that the current technology could be used for this option.
Tuck et al. (2008) warned that severe logistic problems with the delivery of sulphate aerosols may arise. They point out that 'the uncertainties, associated with the meteorological dynamics, the residence times of aerosols at 20 km, the physical and chemical properties of the natural and injected aerosol, and with the photo-dissociation of sulphuric acid in the stratosphere' have not been resolved, yet.

Feasibility is also determined by the costs. NAS (1992) estimated the cost of aerosol injection at 0.03 to 1.0 USD/tCO_2 (0.1 to 3.6 USD/tC) mitigated, based on the usage of hydrogen balloons or 16-inch naval rifles that could inject 1 t aerosol at an altitude of 20 kilometres. The cost would be five times larger, if rockets were used. Teller et al. (2003) calculated the total amount, needed for offsetting of all CO_2 emissions by 2100, and concluded that it would be even cheaper – 1 billion USD per year (3.6 USD/tC). Robock et al. (2009) roughly estimated the operational cost of lofting 1 Tg of sulphuric gas, per year, into the stratosphere, for three methods of doing this (aeroplanes, artillery shells, and stratospheric balloons), at between 4.175 billion and 225 million USD for the aeroplanes, depending on the aeroplanes used, 30 billion USD for the artillery shells, and between 21 and 30 billion USD for the stratospheric balloons. The purchase price of the aeroplanes has been calculated to be in the range of 784 million and 6.613 billion USD.

These are only initial, oversimplictic operational costs for the aeroplanes, however. There is no assessment of the full costs, so far, because purchase costs, the expenses for control and observations, and compensations for negative side effects (on human health and livelihoods, ecosystems and on the whole Earth system) have not been included. The biggest unknowns are the side effects, and Boyd (2008) insisted that, unless these are assessed, based at the least on current limited knowledge, the above mentioned numbers can not be presented as the real costs.

4. Earth system side effects

Scientists are not able to predict all possible impacts of geoengineering options, such as sulphur injections. However, a significant number of side effects has been identified:

- *Uneven spatial response.* A geoengineered climate is unlikely to reproduce the climate from the pre-industrial era, because of changed vertical and latitudinal distributions of atmospheric heating. Model studies suggest that the extra stratospheric aerosol could lead to warming in high latitudes in winter and, hence, increasing rates of polar ice melting (Robock, 2000; Stenchikov et al., 2006; Brovkin et al., 2009). Observations and modelling of the impacts of past volcano eruptions have shown that eruptions at high latitudes weakened the African (Oman et al. , 2006) and Asian monsoons (Oman et al. , 2005) and caused droughts in Africa and Asia and vice versa – eruptions in the tropics produced winter warming over the Northern Hemisphere (Trenberth and Dai, 2007; Brovkin et al., 2009). In a model study, Robock et al. (2008) demonstrated that by regular injections of SO_2 the changes in precipitation patterns became permanent.
- *Ozone depletion.* Aerosol particles in the stratosphere incite chemical reactions that destroy ozone (Solomon et al. 1996). They may cause between 30 and 70 years delay in the recovery of the Antarctic ozone hole, and considerable Arctic ozone depletion, if sulphur injection, compensating for doubling of atmospheric CO_2, would be implemented (Tilmes et al., 2008).
- *Acid rain and deposition.* Injected sulphates which reach the troposphere, will produce acid rain, snow and fog and may cause damage to ecological systems and human health (Crutzen, 2006). One model study (Kravitz et. Al., 2009), however, showed that the additional acid deposition from sulphur injections will not affect most ecosystems to a large extent – water bodies that are very sensitive to acid being probably the only exception.
- *Negative health effects.* Doubling of atmospheric CO_2 increases surface ozone levels by between 2 and 8 ppb, in all seasons, and this will have negative health effects (Sanderson et al., 2007). Robock (2008) pointed out, quoting the World Health Organization, that if sulphur injections deplete ozone by 3 per cent (the depletion caused by Mount Pinatubo), about 100,000 non-melanoma, 1500 melanoma skin cancers and more than half a million cases of cataracts can be expected.
- *Effects on Net Primary Production (NPP).* Geoengineering does not remove CO_2 , it only compensates its warming effect. CO_2 fertilisation will counteract the reduction in solar forcing and the result might be higher terrestrial NPP in a geoengineered world (Govindasamy, 2002). In addition, clouds and aerosols increase diffuse radiation, in turn, leading to more efficient canopy photosynthesis (Gu et al., 2002). It is still not known how the new combination (high CO_2 concentration/lower temperatures) can affect ecosystem composition and distribution, and biodiversity (Govindasamy, 2002).
- *Reduction in the efficiency of power-generating solar plants, using concentrating solar systems.* Murphy (2009) found that sulphur injections will have a negative impact on the power-generating solar plants that use concentrating solar systems, reducing their efficiency by as much as one-fifth, because they depend on direct sunlight. Murphy pointed out that the eruption of Mt Pinatubo in 1991, that reduced total sunlight by about 3 per cent, caused a

> 20% drop in peak power output of Solar Electric Generating Stations in California, the largest collective of solar power plants in the world, at that time. The effectiveness of other energy-saving measures, such as south-facing windows for winter heat and overhangs for summer shade, would be reduced, too. The output of household flat photovoltaic and hot water panels would decline much less, because they use both diffuse and direct sunlight.

In addition to the above possible side effects, under this criterion also the level of reversibility and the possible rebound effects of discontinuation are relevant. If a serious adverse effect is discovered after years of implementation of sulphur injections, there is no way back (Robock, 2008), because, while theoretically the injections could be stopped immediately, the rapid warming that would follow would be more dangerous than the gradual warming we are having now. That is why their effects could be considered as near irreversible: if CO_2 emissions continue to increase, interruption of sulphur injections might lead to extremely rapid warming, with rates of up to 20 times faster than today (Matthews and Caldeira, 2007).

All solar radiation management options for albedo change will only effect the temperature; they do not address ocean acidification. Increasing atmospheric CO_2 reduces ocean pH and carbonate ion concentrations (Cao et al., 2007), threatening the calcifying ability of key marine organisms, such as corals and plankton (Brovkin et al., 2009). Orr et al. (2005) found that, by 2050, in the Southern Ocean and, by 2100, in the Pacific Ocean, marine organisms will be threatened, even under a 'business-as-usual' scenario (IS92a scenario). These damages to high-latitude ecosystem conditions could develop very rapidly, on a decadal time scale.

5. Political implications

Finally, we look at the political implications of sulphur injections, that is, the international governance requirements; who decides and who controls the system? Governments will have a role to play, but private companies holding patents on proprietary technology can be expected to have a powerful position, which raises questions of procedural justice and responsibilities (Robock, 2008). Furthermore, weather modification and attempts at climate control have a history of more than half a century: military leaders in the United States and other countries have pondered the possibilities of weaponised weather manipulation for decades (Fleming, 2008). Reacting to the attempts at weather modification during the Vietnam War, the nations of the world agreed in 1978 to the UN *Convention on the Prohibition of Military or any Other Hostile Use of Environmental Modification Techniques* (ENMOD, Fleming, 2004), which essentially prohibits weather modification that any nation would consider hostile or environmentally damaging. The terms of ENMOD explicitly prohibit 'military or any other hostile use of environmental modification techniques having widespread, long-lasting, or severe effects, as the means of destruction, damage, or injury to any other State Party.'

This treaty may also apply to the use of geoengineering to address the effects of rapid global warming. This possibility for uneven distribution of the effects, both positive and negative, will most probably lead to huge international debates. It will be very difficult to determine what would be the optimal climate. As there will be winners and losers, reaching agreement may be impossible. This can easily provoke unilateral actions, with uncertain effects; it is impossible to modify the climate of each region, independently (Barrett, 2008).

An often used, final ethical argument is that the incentive for mitigation may be decreased by the prospect of being able to either capture the CO_2 or cancel (part of) the consequences (Robock, 2008). As Parson (2005) put it: 'In a dynamic optimisation framework, improving future options usually reduces the desirability of near-term mitigation efforts.' And knowing that these options (may) exist (in the future) will 'reduce the political pressure for near-term efforts, by providing well-founded supporting arguments for those who oppose near-term efforts to any degree and for any reason.'

6. Implications for the Netherlands

The Netherlands could take part in research and development, in modelling of the effects on the Earth system, and in monitoring. As this option is vulnerable to intentional harmful usage, the Netherlands could play a role in the creation of a proper legal framework and international institutions, in order to prevent it.

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C.2. Reflectors in space

1. Short description of option

Early (1989) and Seifritz (1989) proposed the implementation of a space-based 'sunshade' shield, situated at the Lagrange point between the Earth and the Sun at a distance of about 1.5 million kilometres from our planet. Such a shield, or shields, would avert the incoming solar radiation from the Earth.

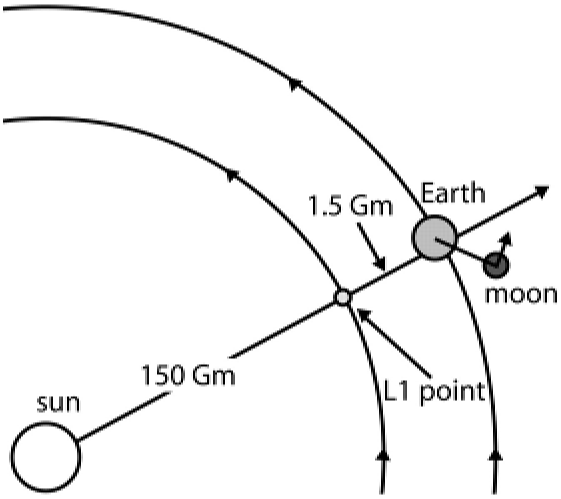

Figure C 2.1. Shadowing geometry. The L1 point and the common Earth–moon barycentre remain in-line, as they both orbit the sun with a one-year period (not to scale) (Source: Angel, 2006)

Two different types of designs have been proposed:

- *Large shields.* A single 2000 km diameter shield from thin aluminium folio, weighing 10 g/m-2 and weighting at least 45 million tonnes (Seifritz, 1989; Early, 1989; Keith, 2000).

- *Small reflectors.* A cloud of many transparent metre-sized spacecraft ('flyers'), weighing a gram each, assembled completely before launch and launched in stacks of 800,000. For 1.8% flux reduction they have to form an 6 million km^2 cloud and would weigh about 20 million tonnes (including the structural and control elements) (Angel, 2006).

2. Effectiveness

If in the right position, the option could fully compensate any increase in temperature caused by an increase in CO_2. Angel (2006) estimated that development and deployment could be realised in about 25 years. As to the net effect on the energy balance (and thus mitigation requirements), Seifritz (1989) proposed that for his scheme the energy required would be equal to the output of 30 nuclear stations, each of them producing 20GW over 20 years. One tonne of carbon from power production for the space shield would mitigate the effect of 1000 tonnes of atmospheric carbon, for the design proposed by Angel (Science daily, 2006). As for the sulphur injections, also the space reflectors would have to be sustained for millennia (Wigley, 2006) and according to a model study by Boucher et al. (2009) overshoot of CO_2 for decades would have to be offset for centuries. Advantage is that the earth system would respond instantaneously by cooling. A full assessment would need to compare the effectiveness of launching shields or small spacecrafts with large total surface areas to prevent the sun's power to reach the earth, with the harnessing of that power in a similar area of solar power stations at the earth's surface, for example, in desert areas.

3. Technical and economic feasibility

Although according to (Angel, 2006) some analogues in space engineering exist, this option is not beyond the stage of a creative idea. There are many technical challenges. The Lagrange position is unstable and, thus, the shield(s) would have to be stabilised actively. This requires permanent observation and control. The production of lightweight material with optimal reflectivity, able to withstand mechanical forces and solar wind is as yet a challenge, too (Seifritz, 1989). Old screens would have to be replaced probably every 20 to 50 years. The not functioning ones which would remain in orbit may threaten other Earth-orbiting spacecraft. (Angel, 2006)

As to the economic feasibility, the total cost, including development and operations is estimated to be about 5 trillion USD, with an average of 100 billion USD per year, if considered over a fifty-year lifetime. These costs will decrease thereafter, when only flyer and energy storage renewal is needed (Angel, 2006). In his calculations, Angel used a transportation cost of 50 USD/kg of payload, considering economy of scale (with present cost for multistage rocket transportation to high orbit being about 20,000 USD/kg). Seifritz (1989) estimated that his design could cost about 6% of world gross domestic product (in 1989), while the design of Angel (2006) was estimated at about 0.2% of the world gross domestic product.

4. Earth system risks and co-benefits

For space reflectors, many potential side effects also have been identified, many of which are similar to those for sulphur injections (see above), such as uneven spatial distribution of climate effects. Lunt et al. (2008) argued, however, that this change may be relatively small, compared with the changes in an unmitigated world (0.8 °C warmer at high latitudes in the 'shaded' case, compared with 8.8 °C in the unmitigated case). Also, ocean acidification would not be avoided. In addition, there may be yet unknown effects.

Different from sulphur injections, however, the controls employed to stabilise the shields could be used to stop the cooling at any time, by slightly changing the orbit. The space reflectors could have relatively long lifetimes and do not change the composition of the atmosphere. Steerable shields could be used to direct radiation at specific areas (Keith, 2000) – this has advantages, but could have the disadvantage of being used in weather warfare.

The level of irreversibility is similar to sulphur injections because of the rebound effect.

5. Political implications

The political implications related to governance questions and military use are similar to those of sulphur injections, as discussed above. The risks of unilateral action may be smaller, because costs appear to be higher. Different from the sulphur injection option, space reflectors may be more vulnerable to agressors aiming at intentional harmful usage.

6. Implications for the Netherlands

This option is very expensive, it will be almost impossible to implement it unilaterally. The Netherlands could take part in research and development, in modelling of the effects on the Earth system, and in monitoring. As this option is vulnerable to intentional harmful usage, the Netherlands could play a role in the creation of a proper legal framework and international institutions, in order to prevent it.

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C.3. Cloud modification through seawater injection

1. Short description of option

The idea to seed low-level maritime stratocumulus clouds with seawater aerosol, in order to increase their solar reflectivity, was proposed by Latham (1990), based on the studies of Twomey (1977), Albrecht (1989), and Slingo (1990), among others. These clouds have albedos in the range 0.3 to 0.7 that can be increased if the overall droplet surface area or the longevity of clouds could be enhanced. Injecting small seawater droplets (NaCl) of around 1 µm in size might contribute to both, because the residues after the evaporation of these droplets can act as cloud condensation nuclei to form new droplets (Twomey effect), and their small size could slow down the formation of raindrops (Albrecht effect) (Latham, 2008). This process occurs also naturally, but there are insufficient condensation nuclei to cause adequate cooling. For a description of the physical base of the process, see Latham (2008). Low-level maritime clouds cover approximately a quarter of the oceanic surface. Doubling their condensation nuclei will result in about 5.5% increase of their albedo – an increase that may offset a doubling in CO_2 concentrations (Salter, 2008). This technology could be used also to counteract only regional impacts, for example, to cool vulnerable regions, such as coral reefs and polar ice (Salter, 2008). But since regional climate change effects are very uncertain, the effectiveness of such regional applications is uncertain, too.

Salter (2008) suggested to use remote-controlled unmanned spray vessels, based on Flettner rotors instead of sails (Figure C.3.1 left). They move perpendicular to the local wind direction and this motion drives underwater ‘propellers’ that can generate electrical energy for spray production. The Flettner rotor was designed in the beginning of 20th century by Anton Flettner, who built two ships with this technology (Figure 1 right).

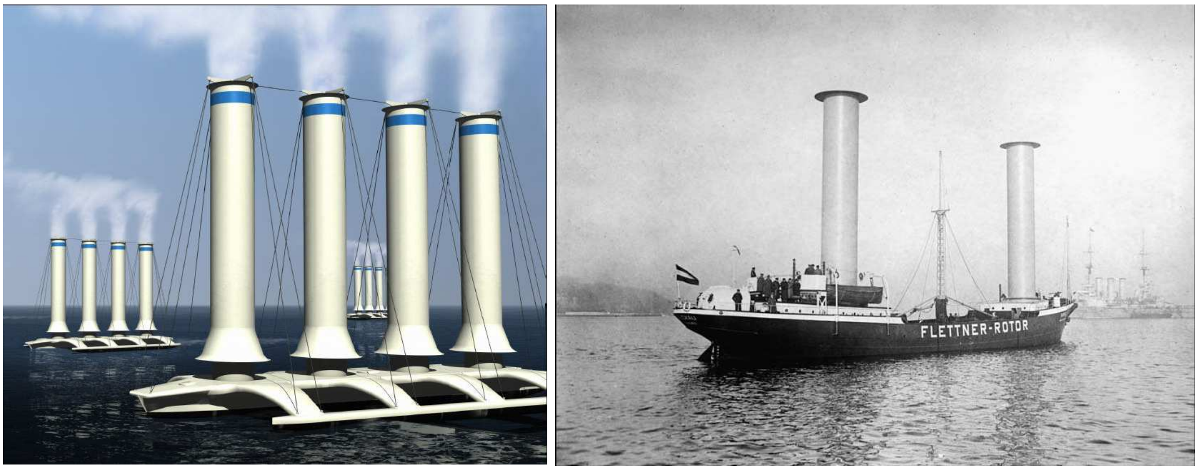

Figure C.3.1. (left) A conceptual model of spray vessels (copyright J. MacNeill 2006) and a Flettner ship (right)

Salter chose this system because of its ‘high lift coefficients, easy control by computer and convenience for housing spray plant and ejecting spray’.

Fifteenhundred of such spray vessels with a spray rate between 30 and 70 m^3/s have to be employed in order to offset forcing of –3.7 W m-2. Salter suggested silicon micro-fabrication technology to be used for spray generation.
Spray vessels would be highly mobile, moving constantly to suitable sites with help of a global positioning system, a list of required positions and satellite communications. Sites would be considered to be suitable if they would have much incoming solar radiation and few high clouds that could reduce it. They would need to have also plenty of low-level marine cloud for whitening, preferably, with low initial density of cloud condensation nuclei. There are also practical considerations in choosing suitable sites, such as avoiding intensive shipping and iceberg routes.

2. Effectiveness

The maximum effect on radiative forcing would be enough to offset at least a doubling of CO_2 emission, or –3.7 W m-2 (Latham, 2008). How fast would this work? The average thickness of the lowest few hundred meters of the atmosphere over the sea is about 800 metres. This atmospheric layer is characterised by high levels of turbulence with velocities of up to one metre per second and even faster. Therefore, mixing and distribution of seawater droplets is very rapid within that layer. Lifetimes of droplets are of the order of a week (Salter et al., 2008). The effectiveness also depends on the time needed to put the system into place. Salter et al. (2008) estimated that only two years of experimental research plus a further three years of research and development of reliable hardware for spray vessels will be needed, before the first full-scale operational prototype is constructed. Applying this technology will have immediate local cooling effect on the sea surface. Ocean currents, being an efficient transport mechanism, will eventually spread the cooler water, worldwide (Salter, 2006). Clouds should be seeded until the concentration of greenhouse gas emissions reaches the desired low level, to be achieved through parallel emissions reduction or sequestration measures.

As to the net effect on the energy balance (and thus mitigation requirements), Salter et al. (2008) estimated that 'Each vessel would require about 150 kW of electrical energy to atomise and disseminate seawater at the necessary continuous rate (as well as to support, e.g., navigation, controls, and communications), so the global power requirement (for 1500 vessels) would be about 2.3 × 108 Watts. Ideally, this energy would be derived from the wind.' These are preliminary model calculations.

3. Feasibility

This option has not yet been tested, but is at the idea stage, supported by some modelling work. The German wind-turbine manufacturer Enercon will test a Flettner rotor ship in 2009 (Enercon, 2008). According to Salter (2008) 'a development programme has been planned to reduce technical uncertainties'. Research and development costs for the construction of a prototype were estimated at about 27 million GBP. An additional 30 million GBP will be needed for tooling, necessary for the rapid building of a large number of spray vessels. A single spray vessel will cost about 1 to 2 million GBP and will have a lifetime of approximately 20 years. It is expected that about 50 spray vessels could offset a one-year increase in world CO_2 (Salter et al., 2008).

4. Earth system risks and co-benefits

The implementation of this technology will modify the distributions and magnitudes of ocean currents and local meteorology: temperature, rainfall, wind and land-ocean temperature contrast. The temperature structure of the atmosphere will change, too (Latham et al., 2008). The effect of unintentional introduction of sea salt nuclei in higher clouds is very uncertain. Latham (2002) has warned that it can eventually cause warming instead of cooling, because high clouds may contain ice crystals. The impact of increased sea salt nuclei in higher clouds on precipitation is unknown, too. Compared to other geoengineering options, cloud seeding is ecologically relatively benign and except wind and seawater does not require any natural resources (Latham et al., 2008). Nevertheless, possible negative effects might arise, such as:

- Negative effects for land suffering from droughts, if clouds in upwind areas are seeded (Salter et al., 2008). Cloud seeding might reduce the frequency and severity of hurricanes (Salter, 2008);
- Rain, containing NaCl seeding nuclei, will increase soil salinity when it falls on land and if repeated, this will result in salt accumulation;
- Ocean acidification is generally not reduced;
- Some bird species may be affected by spraying.

Salter (2005) emphasized the reversibility of this technology. This reversibility stems from the short lifetimes of droplets (about a week) and the flexibility in the choice of clouds. If CO_2 emissions would continue to increase, however, the rebound effect might make it very difficult to stop, as is the case for sulphur injections.

5. Political implications

The implications for governance and politics are very similar to other geoengineering options influencing the radiative balance (see sulphur aerosols). The difference with sulphur injections is that the scale of application can be smaller, which on the one hand may make it more easy to deal with, but on the other hand also may make it more attractive to apply it unilaterally, with potentially unexpected consequences.

6. Implications for the Netherlands

The Netherlands could take part in research and development, in modelling of the effects on the Earth system, and in monitoring. As the implementation of this option could lead to tension between countries benefiting from it and countries which will be negatively affected, the Netherlands could play a role in the creation of a proper legal framework and international institutions, able to prevent, to deal with and to resolve the emerging international conflicts.

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C.4. Albedo changes on terrestrial systems

1. Short description of option

Land-use practices influence the amount of sunlight reflected by the Earth's surface and, hence, modify the Earth's surface albedo. Betts et al. (2007) showed, for example, that the transition from natural forests to agricultural crops in the northern mid-latitudes during the last two and half centuries increased the surface albedo and, hence, cooled these agricultural regions by up to 2 °C. Therefore, a number of authors (e.g., Gaskill, 2004; Hamwey, 2007; Akbari et al., 2009; Ridgwell et al., 2009) proposed to intentionally change the albedo of deserts, human settlements and/or vegetation, in order to counteract global warming, caused by increasing GHG emissions.

The world's deserts are suggested to be among the best candidates for surface albedo modification, because they are 'uninhabited, sparsely vegetated, flat and stable, with a high solar flux and low humidity (meaning less absorption of solar and IR by water vapour) and generally useless.' (Gaskill, 2004), ignoring desert ecosystems and peoples for simplicity. The available suitable land for this option is 12 million km^2 (Gaskil, 2004). Gaskill (2004) calculated that if the typical desert albedo, which is in the range 0.2 to 0.5 (Tsvetsinskaya et al., 2002) is increased to 0.8 by means of a reflective cover, it could offset the radiative forcing of greenhouse gases, projected to be emitted between 2010 and 2070.

How could this be achieved? Gaskill (2004) proposed to cover the world's deserts with inexpensive, recyclable, tear-resistant, and easy to install and maintain material that would be replaced every three years. The material has to be highly reflective (reflecting >80% of incident sunlight) and could consist of white plastic on the top and aluminised plastic on the bottom, providing 80% reflectivity of sunlight and 90% emissivity of IR. The modified desert albedo has to be monitored by ground stations, unmanned aerial vehicles and satellites.
Mechanical anchors can be used to keep it in place and robotic vacuum cleaners can clean its surface from dust, if necessary. Before the installation, the ground has to be cleaned from everything that could puncture this material.

In order to counteract radiative forcing of 2,75 W/m^2 for the 2010-2070 period, an average annual coverage of about 173,500 km^2 will be required. In the beginning of the period, the coverage could be less, however, if greenhouse gas emissions increase non-linearly. By 2070, when all suitable deserts (about 2% of Earth's surface) would be covered, greenhouse gas emissions would eventually have to be restricted or other geoengineering options deployed. The new area with coverage, that has to be added each year, is comparable with the 207,200 km^2 area that is used annually in the United States for wheat production.

Pavements and roofs in urban areas exert also considerable influence on the amount of solar radiation reflected by the Earth's surface, as they account for more than 60% of urban surfaces (Akbari et al., 2009). The average albedo of standard US roofing is estimated at 0.20. With existing technologies, such as reflective tiles, metal roofing products, white acrylic, elastomeric and cementatious coatings and white thermoplastic membranes it could be enhanced to about 0.55 to 0.60. For the pavements, the increase in solar reflectance could be substantial, too: while the albedo of a freshly installed asphalt pavement is about 0.05, the albedo of a freshly installed light-color concrete is 0.35–0.40, which goes down to about 0.25–0.30 for an aged pavement.

Changes in vegetation cover could alter the regional climate, too. Vegetation colour, waxiness, leaf area, density, and geometries, influence the Earth's albedo and, hence, could be used for intentional alteration of the climate (Hamvey, 2007, Ridgwell et al., 2009). Although their global cooling potential is rather modest (only a decrease of 0.11 °C could be reached by manipulation of waxiness, for instance), the regional effect for the mid-latitudes of North America and Eurasia during the summer months of June, July and August, might be much bigger, about 1 °C (Ridgwell et al., 2009).

It has also been proposed to cover parts of the ocean (10% for a doubling of carbon dioxide from pre-industrial levels to 550 ppmv) with floating reflective solids or spheres (Gaskill, 2004). Although sea ice is the prime example that this option would work, these proposals seem very unattractive and are not discussed here: not only can one question the feasibility of a stable layer on an unstable ocean surface, there are also serious questions as to the ecological and climate risks involved.

2. Effectiveness

Gaskill (2004) estimated the potential of this option to be 2.75 W/m^2, by 2070. According to the calculations of Lenton and Vaughan (2009), however, this potential would only be 1.74 W/m^2. Lenton and Vaughan supposed that this discrepancy may arise because of the assumed incident solar radiation of the deserts being higher than the global average. The desert areas have the second highest reflectivity of all surface areas – only surpassed in albedo by the ice caps. Therefore, the effectiveness of changing their albedo is not very high, compared to other land cover types, but its availability may be higher (Gaskill, 2004).

Apparently, assuming no political difficulties to put the idea into practice, Gaskill supposed that it will take only about eight years to start full-scale implementation. There will be some net effect on the energy balance (and thus mitigation requirements: the production, transportation, installation and recycling of the cover would increase total present day greenhouse gas emissions by 1.8%). This percentage will decrease as global emissions rise. According to Gaskill, the option should be continued for 60 years, when other options can take over. The climate system will respond, instantaneously.

The offset of radiative forcing by variegated plants, light shrubs or bioengineered grasses and shrubs is estimated at 0.59 W/m^2 by Hamvey (2007), and at 0.64 W/m^2 by Lenton and Vaughan (2009) . The potential of modified crop albedo is estimated at 0.44 W/m^2 by Lenton and Vaughan, and at 0.24±0.09 W/m^2 by Ridgwell et al.(2009). This difference is attributed to different canopy albedo changes used in the models, and/or different areas being covered by crops than was assumed in the model (Lenton and Vaughan, 2009). Changes in albedos of all human settlements may contribute 0.17 W/m^2 (Hamwey, 2007) or 0.19W/m^2 ((Lenton and Vaughan, 2009), while only urban areas have a cooling potential of 0.044 W/m^2 (Akbari et al., 2008) or 0.01 W/m^2 (Lenton and Vaughan, 2009).

3. Feasibility

In going from idea to theory to modelled option to prototypes to actual testing, the desert albedo option is at the first, idea stage. There are some technical challenges of developing and producing the cover with the desired characteristics, however, this does not seem to offer insurmountable problems. The proposed vacuum robotic cleaners also have to be developed, because conventional cleaning systems, available now, spread fine particles of soil over the surface that, subsequently, cannot be removed. The foil has to be fixed to the soil, and be sturdy enough to withstand uneven terrain. A main issue is to find areas which do not have other practical uses or high ecological value.

As to the economic challenges, Gaskill (2004) estimated the cost of the whole project at 75 trillion USD: 500 billion USD/year and 19 million USD/mile^2. According to Gaskill, almost 80% of the total cost would be for the plastic film, assumed to be recycled 3 times at 50% the cost of the original. The cost of installation, monitoring and maintenance are between 12 and 14% the cost of the plastic. The estimations are based on the maximum possible coverage of 10 million km^2, carried out equally over 60 years and kept in place for 150 years. Gaskill (2004) noted that where applicable, the land will be provided for free, in return for jobs and cancellation of debt. In his calculations, Gaskill did not take inflation or oil price increases into account.

Roof and pavement modification schemes are categorized as low-tech and a number of products are available on the market. The price of their implementation is estimated at about 15 to 30 USD/m^2 for roofs and 15 to 25 USD/m^2 for pavements. The life cycle of these materials is on average 10 years (HARC 2004). Although there are crops, grasses and shrubs with higher albedo currently available, in the long term, new varieties with desired features may be created, for example, via breeding (Ridgwell et al., 2009). We could not find calculations of the costs of implementation for these options, but most probably they will be very modest. While the urban option can be implemented relatively easily, particularly on new buildings and infrastructure, and have co-benefits of reducing the urban heat island effect, it can only partially affect global radiative forcing. because of the relatively small share of useable urban areas on the global land area.

4. Earth system risks and co-benefits

Again, as other geoengineering options aim at influencing the Earth's radiative balance, it is expected that changes in surface albedo will produce uneven changes in the climate, globally, regionally and seasonally (Gaskill, 2004; Lenton and Vaughan, 2009; Betts al., 2007).

Changing desert albedo will also have ecological effects, not only in the area covered, but also elsewhere. For example, currently Saharan dust delivers almost all phosphorus needed for the normal functioning of the bromeliad ecology of the Amazon, and half of the iron for the North Atlantic's phytoplankton (Gaskill, 2004). Covering the Saharan desert will alter these nutrient flows for the Amazon and North Atlantic. Ocean acidification would not be avoided, other than perhaps through the effects of a cooler climate.

The reversibility depends on the starting time of the project and the area covered. The rebound effect (if discontinued) has not been studied, but in general would be the same as for the other albedo-changing options.

Changing the human settlement albedo has the positive side effect of cooling the living areas and reducing electricity consumption (Akbari et al., 2008).
The replacement of the current grasses by modified ones will change plant-plant, plant-microorganism and probably plant-animal interactions, in regional ecosystems, which, in turn, may alter the whole ecosystem. However, this effect on the ecosystems is not much studied and is not well-known, yet (Hamvey, 2007). The implications for the nutritional value of the new varieties is, as yet, unknown. The infrastructure necessary to create and propagate plant varieties with required features is currently available. Moreover, as most arable crops are replanted annually, it will be easy to replace current crops and to sustain planting of crops with higher albedos (Ridgwell et al., 2009).

5. Political implications

Because there will be unknown distributional effects, in case desert albedo change would be implemented at a large scale, governance issues are involved. Gaskill (2004) recognised this and called for 'an international treaty, indemnifying all involved with the project from lawsuits resulting from alleged or actual damage to the climate or economy of a country or region' caused by the changes in desert albedo. The risk of unilateral actions will depend on the area covered. Many of the lands considered for this option, are politically unstable or are large emitters, such as China (Gaskill, 2004). This raises the question of whether the rest of the world will rely on these countries.

Modification of urban albedo via introduction of new roofs and pavements, however, depends mainly on the collective voluntary efforts of local actors. (Hamvey, 2007). While this would allow this option to be implemented at lower cost to the governments, it requires behaviour changes which are not always easy to realise. Although Hamvey was confident that local actors would be willing to voluntarily take the necessary measures, dependent on economic and other incentives, this could be a rather challenging task. Hamvey suggested that the costs for albedo enhancement are internalised in the 'economic co-benefits of energy savings and reduced ground level ozone concentration'.

Crop varieties with higher albedo could have lower yields and, thus, may jeopardise food security, although some comparison between the existing varieties shows that this is not always the case (Ridgwell et al., 2009). For the grassland albedo enhancement, Hamvey (2007) envisaged some political implications, as many of them are in developing countries, which cannot possibly pay for the associated biotechnology intellectual property rights. Therefore, he suggested that some of the international financing and technology transfer mechanisms, such as the Clean Development Mechanism be deployed.

6. Implications for the Netherlands

The Netherlands could take part in research and development of new surfaces and crops, in modelling of the effects on the Earth system, and in monitoring. It is necessary to implement appropriate policies for encouraging the introduction of light surfaces and this could be done unilaterally. As the implementation of this option could lead to tensions between the countries which will benefit from it, and the countries which will be negatively affected, if implemented on a very large scale, the Netherlands could play a role in the creation of a proper legal framework and international institutions, able to prevent, to deal with and to resolve the emerging international conflicts.

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Appendix 4 D. Exploring the effectiveness of emergency responses to climate change

Detlef van Vuuren and Elke Stehfest (PBL)

1. Introduction

Most research on mitigation strategies, so far, have concentrated on long-term consistent scenarios that focus on a certain greenhouse gas concentration target (either a peaking or stabilisation pathway). Such climate policies seems to explicitly assume that climate change is a gradual process that allows for a long-term assessment of climate impacts against the costs of climate policies. The uncertainties in the climate system and related impacts are large. Several studies indicate that there are considerable risks of potential catastrophic or abrupt climate change impacts, including melting of the Greenland Ice Sheet (Oppenheimer and Alley, 2005) or the West Antarctic Ice Sheet (Oppenheimer and Alley, 2004), or other abrupt climate change phenomena (Alley et al., 2002). If signs of abrupt, dramatic climate change impacts would become apparent, societies could be faced with the question of whether a rapid response is possible. Obviously, chances of such a situation occurring are higher in a situation where no or only a mild form of climate policy is introduced.

It is important to know the 'response time' in such a situation, given the different response options at hand. This response time depends on both the physical parameters of the climate system and the technical and socio-economic constraints that occur when getting these options in place. Options that can be considered as part of the rapid response to climate change include rapid introduction of new technologies, geoengineering, and rapid lifestyle changes. In this context, we have explored the response time of two alternative responses in the context of the IMAGE model (Bouwman et al., 2006):

- A rapid transition to a low-carbon economy, by implementing all available options in the energy sector, and reducing non-CO_2 emissions, but without pre-mature capital replacement (for the methods, see here Van Vuuren et al., 2007).
- Stabilising or reducing radiative forcing by geoengineering on a global scale. Here, we assumed that this is by introducing sulphur aerosols into the stratosphere.

We explored the typical 'response time' (that is, the time between the introduction of the measure and a substantial improvement in climate change trends) by introducing these options into a scenario that introduces a mild form of climate policy up to 2030. For 2030, we assumed that society would have proof that continuing trends at that time would lead to dramatic impacts. In this scenario, therefore, drastic measures would be introduced from 2030 onwards. The experiments are of a 'what if' nature and only capture some of the relevant aspects of a rapid response (see discussion below). The added value compared to earlier calculations (e.g., by Wigley, 2006) is the introduction of an explicitly modelled mitigation scenario. Calculations are done against a climate sensitivity of 4.5 °C.

2. Rapid mitigation

The result of the effectiveness of a rapid mitigation response in slowing down climate change (as measured, for instance, by global mean temperature) depends on the maximum emission reduction rate. Unfortunately, such a rate cannot be defined unambiguously. In the real world, it would depend on many complex factors, such as the inertia included in a decision-making processes, the time to change investment decisions and behaviour, lifetime of capital, decisions to retire capital prematurely and inertia in replacing or expanding production capacity (e.g., factories for solar cells or more efficient cars). Typical lifetimes are in the order or 40 years for power stations, 20 to 40 years for manufacturing equipment, 10 years for cars and much longer than that for transport infrastructure, decades up to centuries for building stock and urban infrastructure, but much smaller for heating devices (maybe 20 years). In models, some of these factors also play a role. In many models, exogenous assumptions are made on the speed at which technologies may be introduced. In other models, such as the PBL IMAGE/TIMER model, emission reduction is bound by the lifetime of capital in different sectors. Some models even weigh the option of premature capital requirement against the costs of using current capital.

CO_2 emissions from fossil-fuel combustion

Concentrating first on the CO_2 emissions from fossil-fuel combustion (the lion's share of greenhouse gas emissions), some idea on the maximum rate of greenhouse gas reduction can be obtained by looking at the existing literature on mitigation scenarios. We have used the database of existing mitigation scenarios to explore how the rate of CO_2 emission reduction varies across models; this database consists of the scenario developed for IPCC AR4, plus scenarios published in the last three years (Clarke, 2009; Fisher et al., 2007; Knopf et al., 2009; Rao et al., 2008). We showed the ten-year average emission reduction rates of a few hundred scenarios in the 2010-2100 period (nine data points per scenario) published in literature for various stabilisation levels (consistent with the categories used in IPCC AR4 (Fisher et al., 2007)).

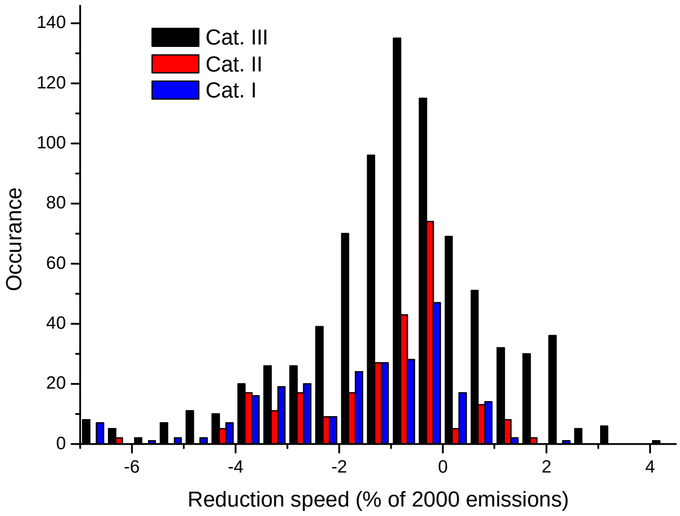

Figure D.1. The global emission growth rates of CO_2 *emission (expressed as percentage of emissions in 2000) in mitigation scenarios (categories I, II and III corresponding to scenarios aimed at stabilising greenhouse gas concentration of 2.5 to 3.0* W/m^2*, 3.0 to 3.5* W/m^2 *and 3.5 to 4.0,* W/m^2*, respectively). Negative numbers indicate emission reduction*

The figure shows that in literature hardly any scenario can be found with a reduction rate beyond 4 to 5% of 2000 emissions, annually, over a ten-year period. Obviously, most models have used some form of optimal pathway for emission reductions, over time (either formal optimisation or more ad-hoc rules), which is likely to lead to rather smooth reduction pathways, over time – nevertheless, as these scenarios aim for the lowest targets in literature, the information is indicative. It should also be noted that for a reduction rate of, for example, 3%, the associated decarbonisation rate is in the order of 5 to 6%, as GDP continues to grow.

In TIMER, we can simulate an all-out response by deliberately bringing the carbon price to the maximum value of 1000 USD/tC in a single year. The model then reduces the CO_2 emissions at the maximum rate possible – bound by the lifetime of the capital stock (capital turnover rate). In the model, different lifetimes are used for different types of capital –the rates shown in Figure D.2 are aggregated results of these. Calculations show the rate of reduction to be around 4% per year for the period of 20 years after the introduction of the high carbon price, in the standard model set-up, and 6% per year if also the option of bio-energy with carbon capture and storage is allowed.

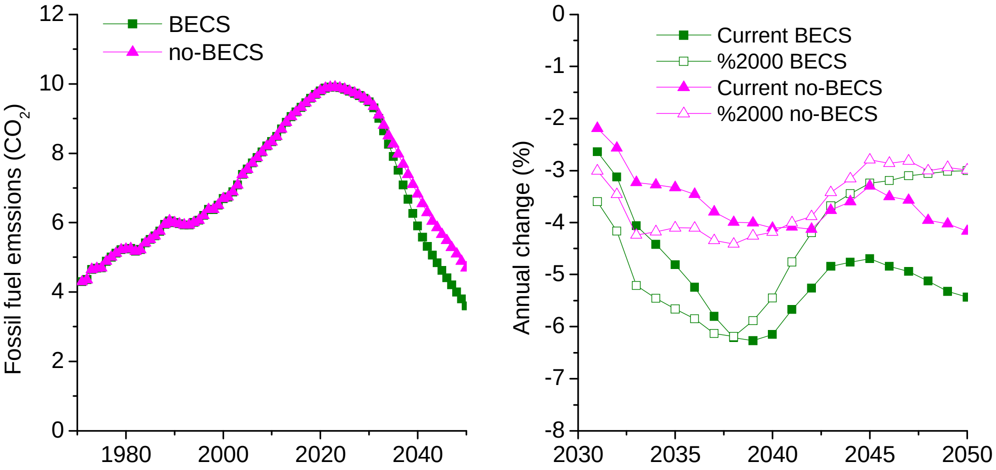

Figure D.2. Fossil-fuel related CO_2 emissions (PgC) and annual emissions reduction (%) under a rapid emission reduction from 2030 onwards, using the energy model TIMER

There are several important remarks to be made regarding the TIMER runs, and also the maximum reduction rates suggested by the literature:

- Information does not focus on premature replacement of capital. Although an expensive option, in fact, under high prices premature replacement might actually be attractive. We have not evaluated this further.
- We did not investigate any global policy requirements or social and financial implications related to implementing such high rates of emission reductions.
- We have not considered lifestyle changes as an additional mitigation option . This would allow faster reduction rates.
- Both existing literature and the TIMER calculations limit the rate of reduction by the rate of capital turnover. In reality, there might be more inertia (decision-making processes, rate of building PV factories etc). As a result, the maximum rate of reduction might actually be overestimated.
- The discussion above only concentrates on CO_2 emission from fossil-fuel burning. In the implementation runs, we have also included non-CO_2 gases and CO_2 from land use. As the potential for some non-CO_2 greenhouse gas sources is smaller than for CO_2, and as we have not explicitly considered measures to reduce emissions from land use, the impact on total greenhouse gas emission is somewhat smaller in relative terms.

On the basis of the literature survey and the TIMER calculations, we concluded that the emission reduction rate for fossil-fuel related CO_2 emissions of about 6% per year is probably the maximum technically achievable rate of a prolonged period of time without any accelerated depreciation of capital stock. The TIMER results fit in the bandwith of rates in the literature.

All greenhouse gases
When we implemented the rapid mitigation strategy in the IMAGE model (that is, the rapid response shown in Figure D.2 and applying the same rapid carbon price increase on non-CO_3 emission) resulted in a greenhouse gas emission pathway as depicted in Figure D.3. CO_2 from energy was reduced by a rate that is determined by the turnover time of capital in the energy system. CO_2 from land use somewhat slowed down the rapid reductions in the energy system – among other things, as a result of the bio-energy expansion (the next impact of bio-energy was positive, but consisted of a reduction in fossil fuel-related emissions and an increase in land-use related emissions). Reductions in methane emissions were somewhat comparable to the overall greenhouse gas emission reduction, but emissions from N_2O were merely stabilised (and not reduced) as a result of limited technical (identified) emission reduction options. For these gases, not only the rate of change was limiting, but also the total identified reduction potential.

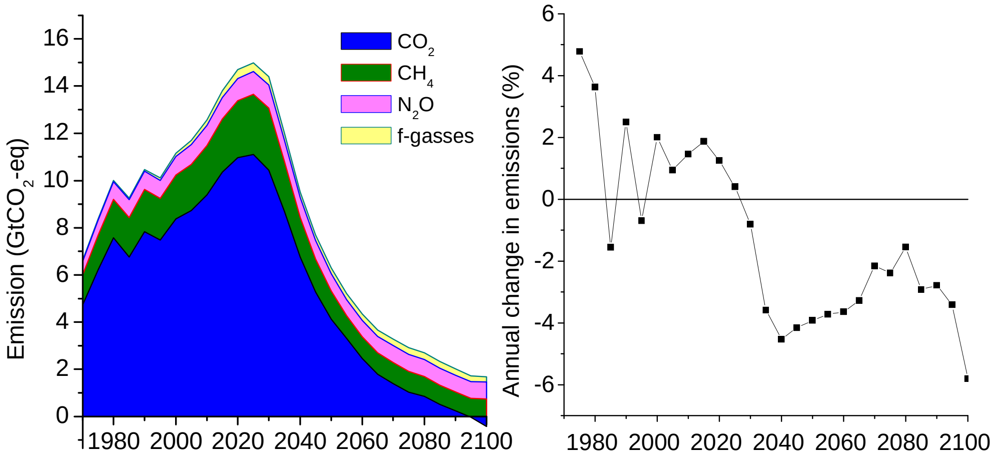

Figure D.3. Greenhouse gas emission pathway following the rapid emission reduction strategy

3. Sulphur aerosols as a means to stabilise radiative forcing

Various forms of geoengineering have been proposed to reduce the impacts of climate change. One option is the introduction of sulphur aerosols into the stratosphere, which would, by scattering incoming radiation, reduce radiative forcing (Crutzen, 2006; Schneider, 2008). The lifetime of sulphur aerosols in the stratosphere is one to two years, considerably longer than in the troposphere. This is long enough for the introduction of sulphur aerosols to be effective, but at the same time short enough to be seen as reversible. The amount of sulphur aerosols needed is, as a result of the effective radiation scattering of aerosols in the troposphere, rather limited (only a per cent or so of current anthropogenic sulphur emissions). Interestingly, also the costs would be relatively cheap, and are estimated from billions of USD, up to tens of billions, per year (Bles, 2009), which is much lower than estimated costs for emissions reduction measures. Earlier, Wigley found, using MAGICC model calculations, that injecting a Pinatubo-sized batch of sulphates into the stratosphere every one to four years could buy up to 20 years before major cutbacks in emissions would be required (Wigley, 2006). An important feature of increasing planetary albedo by injecting stratospheric aerosols is also that, in principle, it could be scaled up from a small reduction of radiative forcing up to a reduction of 3 W/m^2 or more.

Although the effect of the measure would be to reduce average radiative forcing, the real impacts are still fairly unknown. One aspect is that – like the impacts of increased greenhouse gas concentrations – also the impacts of 'sulfur cooling' are not equally distributed across the planet. Therefore, there will not be an exact compensation, on a local scale. But there clearly may be unwanted side effects, such as stratospheric ozone depletion, changes in precipitation rates (some studies indicate a reduction of precipitation in tropical countries (Matthews and Caldeira, 2007)) and sulphur deposition. These impacts could be worse than the climate change impacts that one aims to avoid. Also, if not combined with mitigation, 'sulfur cooling' will have to be applied continuously, in the future, in order to retain effectiveness. Stopping might lead to an unprecedented rapid increase in global temperature. Finally, it would not avoid other impacts associated with the increased greenhouse gas concentrations in the atmosphere, such as ocean acidification, as a result of increasing levels of dissolved CO_2 in the ocean.

Based on the (unkown) risks and uncertainties that are involved in geoengineering, most authors consider this option at best an additional measure to mitigation action, in most cases 'to buy a little more time'. In our experiments, however, for simplicity, we introduced the measure as a stand-alone case. We assumed an introduction in 2030 and explored two targets for radiative forcing levels: 2 W/m^2 and 3.5 W/m^2. Aerosols are introduced in the stratosphere, in order to achieve these targets immediately. As greenhouse gas concentrations would increase, the amount of sulphur required, therefore, increases with time.

4. Results for climate parameters

Figure D.4 shows the radiative forcing pathway that coincides with the emission pathway and geoengineering strategies discussed, so far (Figure D.3 and Section 3). Concentrating first on the rapid mitigation response, Figure D.3 shows that emissions peak in 2030. Figure D.4 in contrast shows that radiative forcing continues to increase for about 10 years and only starts to significantly decline 15 to 20 years after the peak in emissions. From then on, radiative forcing declines at a steady rate, to reach a level of 2.9 W/m^2 by the end of the century. The decline is partly a result of a decline in atmospheric CO_2 concentration – and partly a result of the decline in forcing from other greenhouse gases, most notably CH_4.

The associated temperature profile is even a bit slower. With the assumed climate sensitivity, temperature increase is around 2 °C (above pre-industrial) by 2030. The mitigation scenario is able to limit further increase to 0.4 °C – reaching a temperature peak in 2060 (30 years after the emission peak). By the end of the century, temperatures will be 2.3 ºC above pre-industrial level. In other words, if emissions can be reduced at such a rate, it is possible to constrain further temperature increase to 'only' 0.3 ºC after implementing the rapid reduction strategy – but, for a long time, temperature cannot be reduced. Even slower processes, such as sea level rise, would still continue to increase at a considerable rate.

Earlier, Solomon et al. (2009) showed that any strategy that hopes for a rapid policy response is bound by the inertia of the climate system, both in terms of CO_2 concentrations and temperature. For CO_2, slow CO_2 uptake by the ocean implies that, even after a sudden reduction in emissions, a large part will remain in the atmosphere (after an early faster decline). Moreover, in terms of temperature, the slow heat uptake by the oceans also implies that global mean (atmospheric) temperature will not drop significantly on policy-relevant time scales. This indicates that, therefore, several climate impacts (such as dry season rainfall reduction in some regions and sea level rise) are virtually irreversible over the next millennium. This could even be compounded by irreversible changes, such as ice sheet collapse or CH_4 emissions from tundra. Our results, are bound by the same phenomena as the simple climate and carbon cycle models we used are calibrated against the larger models. Realising that our paper also captures socio-economic inertia, one might think the results look slightly more favourable. There are three reasons for this: 1) we concentrated only on the 21st century (which includes the first slightly more rapid response to declining emissions, 2) we also included non-greenhouse gases, in particular, methane that shows much more reversible dynamics, and 3) our CO_2 emissions, in the long run, were not only brought to zero – but to even less than zero. Still, the runs illustrate the limitations of any strategy that counts on delayed action followed by rapid reduction later.

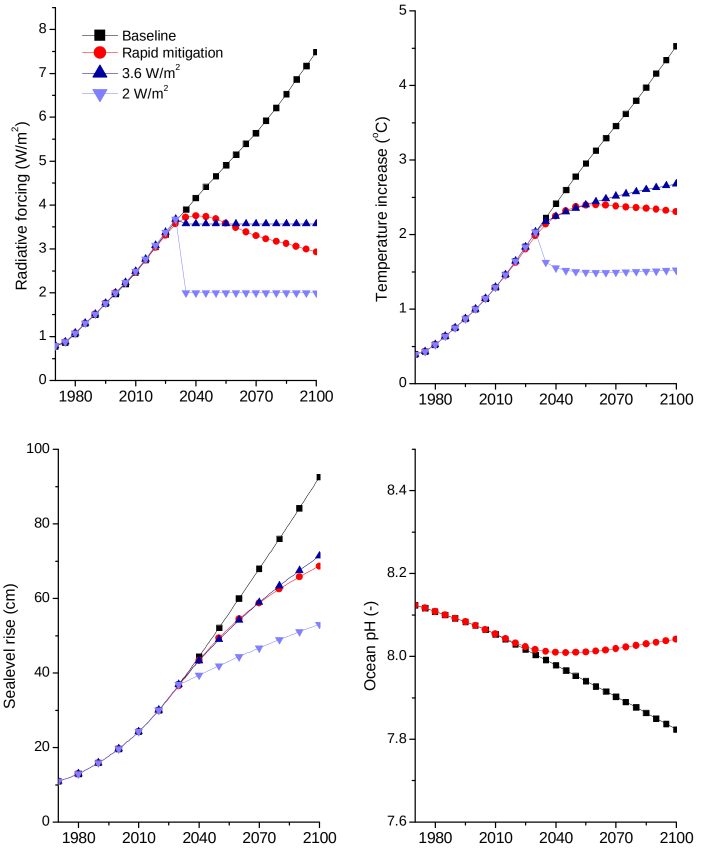

Figure D.4. Radiative forcing, global mean temperature change, sea level rise and ocean acidity in the various scenarios.

The two ‘radiative forcing’ stabilisation scenarios have clearly different results. The strategy that immediately freezes radiative forcing at the level of 2030 (3.6 W/m^2), initially, in terms of temperature increase, has almost similar results as the emission reduction scenario (in other words, the 10 to 15 year increase in radiative forcing in the mitigation scenario has little impact). In the long run, this scenario in fact has worse results than the rapid mitigation scenario, as the continuous emission reductions in the latter case lead to a decreasing radiative forcing (and associated temperature), while the radiative forcing stabilisation in the former case implies a continuing temperature increase.

The second radiative forcing case immediately reduces radiative forcing to only 2 W/m^2 (400 ppm CO_2 eq, a level that the mitigation scenario may reach in the long run). This reduction is so dramatic that, according to MAGICC, it actually leads to an immediate response in temperature. Global mean temperature drops to around 1.5 °C above pre-industrial level in just 10 to 15 years[31]. After this – it remains more-or-

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[31] Note that we implemented the strategy, for illustrationary purposes, rather rapidly, if a sudden drop in temperature would be considered dangerous by itself, introduction can also be more smoothly

less constant at this level. Sea level rise, in contrast, continues to increase over the whole scenario period – but at a reduced rate.

It should be noted that the geoengineering variants do not prevent the increase in CO_2 concentration – and thus neither prevent ocean acidity. We estimated ocean acidity using a direct relationship with the atmospheric CO_2 concentration[32]. The baseline scenario and both geoengineering variants show a decrease in ocean pH (increase of acidity) from 8.1 now to 7.8 by 2100 (and still declining afterwards). While the full ecological consequences of these changes in calcification are still uncertain, it appears likely that many calcifying species will be adversely affected. The drastic mitigation strategy does prevent most of the pH decrease. Obviously, if geoengineering is only introduced as a temporarily solution to support mitigation, the decrease in ocean pH can also be slowed down under scenarios with geoengineering.

Finally, it should be noted that if geoengineering is implemented as an alternative to mitigation – as assumed in the scenarios implemented here – action will need to be continued forever. We illustrate that here by implementing a variant of the most extreme case (2 W/m^2) in which 'sulphur cooling' is ceased by 2060 (Figure 2.5). The results are meant to be illustrative, but they show that this would result in extremely rapid climate change – as climate system would 'suddenly' see the radiative forcing consistent with the atmospheric greenhouse gas concentration. This would lead to a return to the original baseline in just a few decades, but even more dramatically. to an extreme jump in temperature of more than 1 °C in just 5 years, between 2060 and 2065. While the MAGICC model might not be calibrated to exactly represent these cases, the results do indicate the dramatic consequences of such a scenario.

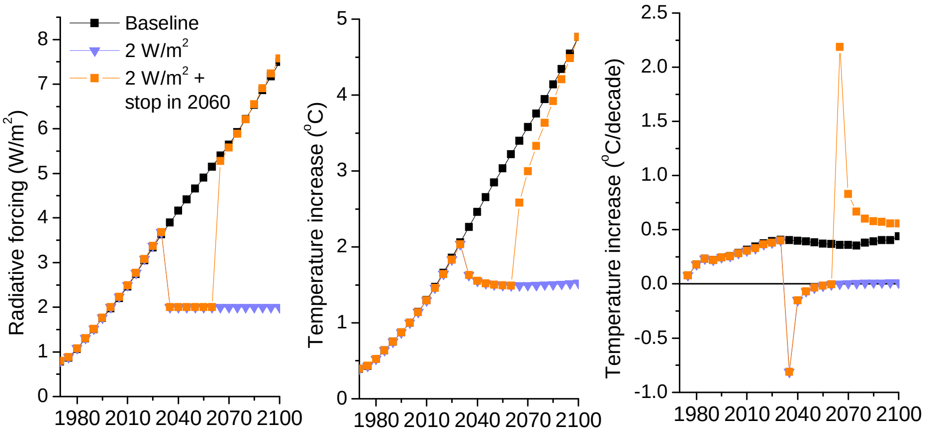

Figure D.5. Radiative forcing, average global temperature increase, and rate of temperature increase in a situation in which the measures compensating GHG radiative forcing would be stopped

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[32] Results are only meant to be indicative. To simplify equations, we have assumed the upper ocean layers to be in equilibrium with atmospheric CO2. In time (century scale), mixing of different ocean layers will reduce the CO2 concentration in the upper ocean leading to a higher pH. We have used published numbers for atmospheric CO2 concentration and the pH of the upper ocean layer to derive the following relationship: pHocean = 10.498*[CO2]atm-0.0443 (Caldeira and Wickett, 2003; Orr et al., 2005; Raven, 2005).

5. Conclusions

Implementing a dramatic rapid mitigation strategy globally, in 2030, that reduces greenhouse gas emissions by around 4%, per year, can effectively limit temperature increase to only a few tenths of a degree after the introduction of the policy. However, inertia in the climate system implies that a peak in temperature will only occur around 30 years after the introduction of the policy – and after 70 years, temperature will not yet have returned to the level of the year of introduction.

A geoengineering strategy that is able to directly impact radiative forcing can lead to more rapid results, depending on the stringency with which the measure is introduced. A modest strategy to limit radiative forcing would not do much better than the rapid mitigation strategy. However, an extreme strategy that reduces radiative forcing back to a low level (here 2000 radiative forcing), at once, could have more immediate results. This does obviously also significantly increase the risks that are associated with such a strategy. Both the modest and stringent geoengineering strategies are not likely to offer an ultimate solution, as it would be necessary to continue activities indefinitely. Therefore, if implemented at all, they would more likely be combined with some form of mitigation strategy.

The socio-economic and climate inertia that limit the effectiveness of a rapid response strategy can obviously be mitigated by an earlier reduction in greenhouse gas emissions.

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