

How, and at what costs, can low-level stabilization be achieved?

An overview

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Abstract:

In order to prevent ‘dangerous anthropogenic interference with the climate system’, stabilization of greenhouse gases at low levels (at 550 ppmv CO₂ equivalent or below) might be needed. This paper discusses some of the current literature on whether stabilization at such a low level is possible based on available technologies and on stabilisation scenarios (including their costs). The combined technical potential of different options as reported in the literature seems, in principle, to be sufficient to achieve low-level stabilization. Application of these technologies, however, is more uncertain as it requires further development, technology transfer, and widespread diffusion. Effective and efficient stabilization strategies use a portfolio of options (changing over time) to achieve a least cost approach. For low-level stabilization marginal costs will increase steadily as more and more expensive measures are required. Costs in terms of welfare loss, compared to a situation without climate policy measures, highly depend on the underlying socioeconomic development. If the most efficient implementation (including multi-gas strategies, maximum participation of countries in a global emission trading regime, optimal timing of reduction actions) is chosen, current studies estimate global costs in the order of a maximum of a few per cent GDP loss by the year 2050. Costs for individual countries may highly differ. By looking at mitigation/stabilization costs in a wider context we can help identify co-benefits of policies for achieving sustainable development, energy security or environmental goals, and so reduce costs.

1. Introduction

Article 2 of the UNFCCC calls for stabilization of greenhouse gas concentrations at a level to avoid ‘dangerous interference with the climate system’ (UNFCCC, 1992). Uncertainties in the climate system inhibits the ability to unambiguously determine ‘safe’ concentration levels below which this condition can be considered fulfilled, and in fact, such a step necessarily involves all kinds of value judgements (Rayner and Malone, 1998). Nevertheless, in recent years, literature has been published that suggest that a framework to make Article 2 operational can be developed (Mastandrea and Schneider, 2004) and that limiting global mean temperature change to around 2 degrees C above pre-industrial levels could be interpreted as a reasonable level to avoid some of the most dangerous risks of climate change (Corfee Morlot et al., 2005; ECF and PIK, 2004; IPCC, 2001a; Leemans and Eickhout, 2004; O’Neill and Oppenheimer, 2002; Schneider and Lane, 2005). The EU and several EU member states, in fact, have decided to interpret Article 2 in terms of a maximum temperature increase target of 2 degree Celsius (EU, 1996; EU, 2004; EU, 2005).

The step from limits on global mean temperature to a concentration stabilization target is again beset with uncertainty, of which the most dominant is the uncertainty in climate sensitivity. Recent literature handles these uncertainties by calculating the probability to which various greenhouse gas concentration levels are able to reach this temperature target (Meinshausen, 2005; Richels et al., 2004). While most previous literature concentrated on stabilization of the CO₂ concentration at 450 ppmv CO₂ in order to comply with the 2 degree target, more recent literature points out that stabilization at much lower levels might be necessary to make it ‘likely’ to stay below the 2 degree target. Specifically, attention has shifted from 450 ppmv CO₂ – i.e. 550 ppmv CO₂-eq. if all main greenhouse gases are included¹ - to more ambitious targets in the order of 400 ppmv CO₂ / 450 ppmv CO₂-eq or even lower (Den Elzen and Meinshausen, 2005; Meinshausen, 2005). In the context of these targets, this paper reviews existing literature on technological options and emission scenarios to

¹ The equivalent CO₂ concentration expresses the additional radiative forcing of all greenhouse gases as the equivalent CO₂ concentration that would result in that same level of forcing. This metric will be used throughout this paper, in addition to CO₂ concentration levels, as a metric to capture all major greenhouse gases.

identify what kind of measures could achieve such low levels of stabilization of greenhouse gases in the atmosphere.

The literature on stabilization scenarios was summarized in the IPCC Third Assessment report (TAR) (Morita et al., 2001). Most mitigation studies at the time were looking at CO₂-only policies, and the lowest stabilization level was 450 ppmv CO₂. In fact, the number of studies looking at this lower range level was considerably less than the number of studies looking at higher stabilization levels (see also Swart et al., 2002).

Figure 1 shows the gap between 450 ppmv CO₂ stabilization scenarios and the various SRES baseline scenarios, based on studies assessed in the IPCC TAR. An important conclusion from this assessment was the significant impact of the socioeconomic development of the various world regions and the underlying preferences on the magnitude of the mitigation challenge. Two low emission baselines from the IPCC set are A1T and B1; in A1T this is a result of very optimistic assumptions on technology development for carbon-free technologies and in B1 this is a result of the assumptions made on environmentally friendly lifestyles and large-scale adoption of energy efficiency. Looking at the A1T and B1 reference scenarios, the gap between baseline emissions and the emissions required for stabilization at 450 ppmv is relatively small. Looking at the high baselines in the SRES set, A2 and A1FI, this gap is large. The A2 scenarios represent a world of low economic growth, slow technology development and high coal use, hence high emissions. A1FI represents a high-growth world, with technology development mostly focussed on fossil fuel use. In terms of cumulative emissions for reaching 450 ppmv CO₂ to be avoided between 2000 and 2100, the mitigation challenge (i.e. the total amount of CO₂ emissions to be avoided in the period 2000-2100) differs from 1500 GtCO₂ (or about 40% of cumulative emissions) from the lower set of baselines, up to 6000 GtCO₂ for the higher set (around 70% of cumulative emissions or more). While acknowledging this broad range of uncertainty, it might be helpful to focus on an average value within this range: i.e. 3000 GtCO₂ for CO₂ alone and 4000 GtCO₂-eq for all Kyoto gases. This is in the order of a 60% reduction of cumulative emissions (by 2100 this means a reduction of annual global emissions of about 80% below

current levels) . For stabilization at 450 CO₂-eq, comparable figures would be a reduction of 4500 GtCO₂-eq, or a 70% reduction of cumulative emissions (implying a 90% reduction in annual global emissions by 2100) (Den Elzen and Meinshausen, 2005).

Is such a reduction feasible? What kind of technologies would be required? Again, uncertainties play an important role. First of all, even if we focus on the technologies that are already available today, their potential and costs in the next 100 years are very uncertain. One element of this is the development of cost. The effectiveness of these technologies also depends on widespread deployment and diffusion – on a scale on which none of these technologies have been previously applied. Social acceptance will play a role as well. Will societies accept the use of nuclear power as a means to reduce emissions? Will they accept large-scale storage of CO₂? In other words, what current technologies can deliver over the next 100 years highly depends on the socioeconomic circumstances that will be prevalent. While realising this, we will nevertheless make an attempt to explore the question of the technical and economic feasibility of stabilization at 550 ppmv CO₂-equivalent without assuming the appearance of radically new technologies beyond the scope of those that are already applied at demonstration scale today.

2. Technology options

A range of technology options exists for reducing greenhouse gas emissions and enhancing sinks and reservoirs (Moomaw et al., 2001):

- Energy efficiency improvement
- Decarbonization of the energy system
 - Increasing the use of low or zero carbon energy sources (gas, nuclear, biomass, wind, solar)
 - Applying CO₂ capture and storage
- Biological carbon sequestration and/or reducing deforestation emissions
- Reducing other greenhouse gases from industry, agriculture, waste

What is the potential of the various technology options for delivering the emission reductions indicated above? The answer to this question depends on the constraints applied. In the literature some guidance is given by differentiation between technical, economic and market (or implementation) potentials of mitigation measures.. The technical potential normally excludes cost considerations. The economic potential looks at what is economically feasible under certain conditions and the market potential is what is actually realized. The latter thus accounts for implementation barriers such as lack of information, limitation in technology diffusion or limited acceptability of certain options. In reality, however, these definitions are not strictly applied and all estimates have scenario-dependent aspects to them.

Here, we focus mostly on the technical potential, but we also provide an indication of the costs associated with these potentials. A crucial scenario-dependent element here is technology development; more specifically, the assumptions made on cost reductions and efficiency improvements. Different assumptions about technology development create a wide range of estimates for the potential of the options discussed. With these considerations in mind, we will briefly discuss the technical potential of the different options, their limitations and include a rough indication of the costs involved.

Energy efficiency improvement

Estimates for the potential of energy efficiency improvement for avoiding GHG emissions vary widely (Moomaw et al., 2001). Technical studies generally focus on possible efficiency improvement in the next few decades, finding a large potential reduction of over 50-70% of current emissions. Obviously, part of that potential is already captured in the baseline, while, in some cases, lifestyle changes may also result in higher emissions. The largest potential is typically found in the building and transport sectors. In the industrial sector, current potential could be somewhat smaller, but history has shown that policies are more effective in promoting efficiency in this sector. For the 2000-2020 period, the potential from efficiency improvement has been estimated at about 200 GtCO₂ – or 25% of

emissions (Moomaw et al., 2001). On the basis of this, a conservative estimate of the potential over the 2000-2100 period would be in the order of 1000-1500 GtCO₂ (assuming a constant potential of 25%). The costs of these options differ widely but typically range from negative costs up to 50 US\$/tCO₂.

Renewable energy

Several estimates have been published for the technical potential of renewable energy (see Berndes et al., 2003; Hoogwijk, 2004; Nakicenovic et al., 2000; WEA, 2000). In the most recent estimate for biofuels, Hoogwijk (2004) estimates the potential for primary biofuels to range from 165 to 655 EJ in 2050 and 275 to 1105 EJ in 2100, which is large compared to the total energy consumption of 400 EJ today. An important factor underlying these wide ranges are the different assumptions on land availability. Wide ranges in the order of a few hundred up to a few thousand EJ (see Table 1) are also reported for wind-based electricity and solar-based electricity. It is important to note, however, that even the lowest estimates are equal to several times the present world electricity consumption. For both PV and wind the problem of integrating it in the existing energy system may play an important role in determining the market potential. Renewable energy options are currently among the more expensive options (about 40-60US\$/tCO₂), but costs are likely to go down substantially over time.

Nuclear power

The potential for nuclear electricity is similarly difficult to quantify. If restricted to current technologies and uranium resources, the potential might be in the order of 300-400 GtCO₂. However, new discoveries of uranium resources, use of thorium, more efficient technologies (including breeders) and production of uranium from sea water could, at least in theory, imply that this option is almost without technical limits. Costs in the next decades could be in the order of 15-120 US\$/tCO₂ when replacing natural gas power plants (Sims et al., 2003). A crucial uncertainty for nuclear energy is the social acceptability of large-scale use of nuclear power.

[insert Table 1 here]

CO₂ capture and storage

The potential for CO₂ capture and storage is also significant. Based on recent assessments (IEA, 2004; IPCC, 2005), total cumulative capacity in geological storage sites (enhanced oil recovery fields, depleted oil and gas fields, unminable coal seams and unused saline formations) can be conservatively estimated to be at least several thousand GtCO₂-eq. Possible additional storage in the deep oceans is not included in these estimates. Costs for this option consist of the transport and storage costs of CO₂, but also the higher investments costs and reduced efficiency of plants using fossil fuels. Despite the fact that this option has only been implemented in a few industrial-scale projects so far, studies are optimistic about the technical feasibility. Overall costs are estimated to be in the order of 20-90 US\$/tCO₂, with possibilities for significant cost decreases in the coming decades (IEA, 2004; IPCC, 2005; Sims et al., 2003). The recent IPCC (2005) assessment indicates that energy and economic models suggest that CO₂ capture and storage will begin to deploy at a significant level in the electricity sector when CO₂ prices begin to reach approximately 25-30 US\$/t CO₂.

Biological sequestration

Enhanced biological sequestration of CO₂ in forests and soils by specific management measures could add another 350 GtCO₂, cumulatively up to 2050 (Kauppi et al., 2001). Several uncertainties play a role here. First of all, land availability is important for sequestering carbon by forestation. For other forms of biological sequestration, the temporary nature of the sequestration and need for land for agriculture may restrict potential. In any case, the costs of biological sequestration are assessed to be relatively low (on the order of 10-50 US\$/tCO₂).

Non-CO₂ gases

The total estimated emissions of non-CO₂ gases covered by the Kyoto Protocol (methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride) during the 21st century come to about 1200-1800 GtCO₂-eq. across a range of different models and scenarios (van Vuuren et al., 2005; Weyant et al., 2005). Most of these emissions originate from agricultural activities (fertilizer use,

animal husbandry, rice production). Recently, attempts have been made to quantify the potential of reduction measures for these gases (Delhotal et al., 2004; Schaefer et al., 2004). For most energy-related and industrial sources of non-CO₂ gases it was possible to identify reduction measures and possible routes of implementation. For agricultural sources, techniques currently identified as being applicable cover a much smaller percentage of total emissions. The total technical potential identified currently covers about 500 GtCO₂ cumulative over 2000 to 2100. Costs of these measures are generally low, and typically in the order of 0-50 US\$/tCO₂ (Delhotal et al., 2004; Schaefer et al., 2004).

Table 2 shows the overall technical potential to be much larger than the high end of the range needed for stabilising CO₂ concentrations between 350 and 450 ppmv. On this basis of similar calculations, the IPCC Third Assessment report concluded earlier that ‘most model results indicate that known technological options could achieve a broad range of atmospheric CO₂ stabilization levels, such as 550 ppmv, 450 ppmv or below, over the next 100 years or more, but implementation would require associated socioeconomic and institutional changes.’ (IPCC, 2001c). The caveat contained in this statement refers to the necessary conditions for implementation, including the diffusion and transfer of mitigation technologies to developing countries, as well as the willingness to accept the cost of such stabilization strategies. These aspects will be explored in subsequent sections.

[insert table 2 here]

3. Stabilization scenarios

At the time of the Third Assessment Report, the lowest stabilization scenarios found in the literature looked typically at stabilization at 450 ppmv CO₂, more-or-less congruent with 550 ppmv CO₂-eq. In more recent years, a few studies have become available in which more ambitious targets are investigated.

3.1 Option portfolios

The available literature on strategies leading to stabilization at 550 ppmv CO₂-eq, shows that in order to minimize costs and risks, robust mitigation and stabilization strategies will make use of a portfolio of options varying from country to country according to specific national circumstances (Bashmakov et al., 2001). Modelling studies of least-cost approaches to stabilization at various levels show large differences in the optimal portfolio composition as a result of differences in assumptions and coverage of options (Morita et al., 2001).

Figure 2 gives a typical example of the outcome of such studies for a multi-gas stabilization at 550 and 650 ppmv CO₂ eq (Van Vuuren et al., 2003). The contribution of non-CO₂ emission reductions in the portfolios is modest, particularly at lower stabilization levels. However, it shifts the mitigation action somewhat from the energy sector to the agriculture and industry sector and avoids the most expensive options to reduce CO₂ emissions. In this study, energy efficiency is the dominant option for avoiding CO₂ emissions until around 2030, while renewables, nuclear energy and CO₂ capture and storage contribute more to the portfolio later on, with efficiency improvement continuing to be very important. Other studies generally show a similar trend over time, but the contribution of supply-side versus demand-side options may differ. The lower the stabilization level, the earlier the more expensive options will have to be applied.

[insert figure 2 a and 2b here]

Looking into stabilization levels below 550 ppmv CO₂ eq, we see that recent studies (Azar et al., 2005; Nakicenovic and Riahi, 2003) show a much larger contribution from CO₂ capture and storage, and non-fossil energy supply options. This may involve very large penetration levels of renewables, possibly in combination with hydrogen in combination with CO₂ capture and storage. The latter, together with the use of biofuels, allows use of zero carbon fuels in the transport sector. Azar et al. (2005) show that an attractive option for very low stabilization levels is the use of biomass-fuelled power plants in combination with CO₂ capture and storage. Biofuels take up CO₂ during their growth

phase; normally this CO₂ is emitted again when the biofuels are burned, creating a CO₂ neutral option. If these CO₂ emissions are prevented by capturing CO₂ gases from flue gases of electric power plants, followed by secure storage, a system would be created that absorbs CO₂ from the atmosphere on a net basis. The costs are equal to the additional costs of biofuels (compared to fossil fuels) and capture and storage, but for more ambitious stabilization strategies this option could be used very effectively within a larger portfolio of options. Its feasibility depends on costs and the potential for biofuel production. It is important to note that the studies quoted have, in fact, studied mitigation on the basis of already low emission baselines. It is obvious that the very low stabilization levels may be much more difficult to reach when starting from socio-economic conditions that are unfavourable for strong mitigation action, as reflected by the A2 and A1FI reference scenarios.

The assumption in the modelling studies of least cost implementation of mitigation options reflects a system of full emissions trading between all countries, so that measures are taken where costs are lowest. In reality this may not be the case, leading to different outcomes of the global portfolio and a higher cost level than reported in these studies. National circumstances will lead to specific portfolios for individual countries.

As indicated above, most scenario studies show a portfolio of options as part of their 'optimal' stabilization strategy instead of just one or two big options. There are various reasons for this, including the limited potential of various options compared to the overall mitigation objective, increasing costs with large-scale application, differences between regions and sectors, and timing and implementation issues. A portfolio approach reduces also the risk of choosing a few 'winner' technologies that could turn out to be a failure. On the other hand, there are also risks involved in a portfolio approach in particular, due to spreading R&D budgets, reduced economies of scale and reduced learning-by-doing. Nevertheless, most studies still show a larger portfolio to be more attractive.

In looking at ambitious stabilization scenarios, an important conclusion is that the inertia present in the energy system calls for a smooth and thus early transition. The extended infrastructure that will be installed and/or replaced in the coming decades implies that decision-makers need to plan now for such long-term reduction strategies, since low stabilization targets will otherwise be impossible to reach without premature retirement of capital investments. For higher stabilization targets, in contrast, there is much more flexibility in the timing of reduction.

3.2 Costs

Cost estimates are uncertain. This uncertainty is a consequence of uncertainty in baseline trends, effectiveness of policies, flexibility of economies to adjust to higher energy prices on economic growth, technology development and assumed international policies. Costs of stabilization at levels from 450 ppmv CO₂ upward were assessed in the IPCC Third Assessment Report (Hourcade et al., 2001) for various reference scenarios. While costs only increase moderately, going down from 750 ppmv to 550 ppmv targets, much sharper increases were observed for targets in the range of 450 ppmv, unless baseline emissions are very low.

The global average costs for 450 ppmv CO₂ stabilization (for a global least cost approach) are reported by IPCC to be in the order of a 1-4% lower GDP by 2050 (Hourcade et al., 2001), compared to a situation without stabilization (see Figure 3a). These estimates assume cost-optimal implementation of options without transaction costs, but on the other hand these costs do not reflect the benefits of avoided climate change damages or co-benefits (see further). Azar and Schneider (2002) point out that this translates into a very small reduction of annual global average economic growth rates. However, GDP effects could be higher during parts of a long-term period and for specific countries and regions. Van Vuuren et al. (2003) show that different schemes to differentiate reduction commitments among regions may result in large costs differences between regions and across different schemes. In their results, regions with high per capita emissions and income (OECD) are confronted with medium costs, while regions with high per capita emissions, but a medium income (CIS, Middle East& Turkey, possibly Latin America) are confronted with relatively high

costs, and regions with low per capita emissions and low income (Africa and developing Asia) are confronted with the lowest costs and can even gain from emissions trading. Similar results were also found in other models (Criqui et al., 2003).

A recent study by Bollen et al. (2004) that looked at reductions in 2030 consistent with a 450 CO₂ stabilization trajectory, shows changes in Gross National Income (which includes expenditures or incomes from traded emission allowances) of - 0.6% to -1.8% for the EU-25, -1.4 to -1.8% for Russia, -1.3 to +5.8% for the Middle East and +0.8 to +0.2% for developing countries in Asia and Africa, the first number being for global participation in emission trading and the second number for emission trading without developing countries in Asia and Africa,. Although we cite just one study here, the results are consistent with the larger range of global results reported by IPCC (Hourcade et al., 2001).

Obviously, cost estimates highly depend on the options that are considered. Including non-CO₂ emission reduction in a stabilization strategy lowers the costs (van Vuuren et al., 2005), although at low stabilization levels the emphasis over time shifts to CO₂. On the whole, multi-gas stabilization strategies might be about 30-40% cheaper than CO₂-only strategies (van Vuuren et al., 2005).

Excluding options from a stabilization portfolio or limiting the application of one or more options (such as nuclear energy or CO₂ capture and storage) would still allow us to achieve low stabilization levels, but at a higher cost (Azar et al., 2005; IPCC, 2005; Nakicenovic and Riahi, 2003). IPCC (2005) in its recent assessment of CO₂ capture and storage indicates that costs of stabilisation, for a range of stabilization levels, can be reduced with 30% or more when including CO₂ capture and storage in a portfolio of measures. Azar et al. (2005) indicate cost decreases of 30-50%, when including CO₂ capture and storage in a 450 ppmv CO₂ stabilization case, and 50-80% for a 350 ppmv CO₂ stabilization case.

3.3 Implementation issues

Implementing stabilization strategies, particularly for low atmospheric concentration stabilization levels, requires a broad and extensive array of policies and measures sustained over a long period of

time. Experience so far with modest action, as a result of national programmes in the light of Kyoto Protocol commitments, shows that such policies and measures are hard to introduce and implement. Several studies analyse the many barriers to introducing such policies and spreading the use of emission abatement technologies within countries and between industrialized and developing countries (Sathaye et al., 2001). There is a multitude of potential obstacles, ranging from lack of awareness, vested interests, prices not reflecting environmental impacts (externalities), cultural and behavioural barriers to change and (in the case of spreading technologies to developing countries) the lack of an effective enabling environment for new investments. Above all, stabilization at low levels will require an awareness of the importance of climate change policies in different parts of the world to increase the socioeconomic and political circumstances to implement the type of measures discussed above.

3.4 Co-benefits

Climate change mitigation policies cannot be seen in isolation from other policies to achieve development goals, energy security goals or other environmental objectives. There are sometimes trade-offs because of conflicting interests (strong climate change mitigation may interfere with maintaining a strong export position on coal or oil), but there are also many potential synergies that can make implementation of mitigation policies easier and cheaper (IPCC, 2001b).

Several studies have looked at the synergies between climate change mitigation and air pollution control. Many air pollutants and greenhouse gases have common sources, implying that controlling one of them can also reduce emissions for the other. The most typical response for controlling air pollution (caused by such substances as sulphur dioxide and nitrogen oxides) is to add end-of-pipe emission control technologies. These technologies generally do not have synergistic value. For control of greenhouse gas emissions, in contrast, systemic changes in the energy system are required that also reduce emission of air pollutants. Synergies between climate change and air pollution control can

become apparent in terms of additional emission reductions for air pollutants and/or reduction of air pollution control costs when implementing climate policies.

In low-income countries, taking care of the potential synergies of climate change policies and air pollution policies could be even more important than in high-income countries. An example of this is given by Van Vuuren et al. (2003). In this study, reduced acidification risks in Asia as a consequence of climate policies were identified by coupling the global energy model TIMER to the RAINS-Asia model. In 1995, 4% of the ecosystems in the total RAINS Asia region experienced high acidification risks due to deposition of sulphur dioxide above the critical loads. The risks are unevenly distributed across the region, and are especially high in East China with areas where up to 100% of the ecosystems are threatened. Under the baseline assumptions, the number of ecosystems with a sulphur deposition above the critical loads will increase substantially (see Figure 4). The largest increase occurs in China (from almost 6% to almost 10% of total ecosystem). In addition, a large share of ecosystems will receive deposition above critical loads in Thailand, Malaysia, Indonesia, the Korean peninsula, Japan and India in 2030. By introducing climate policies, the situation improves considerably, as shown for the 550 ppmv CO₂-eq stabilization case. As a result of climate policies for Asia as a whole, the exceedance of critical loads is reduced to approximately the 1995 level (or about a 50% reduction compared to baseline). While the exact results reported in this study are obviously uncertain, the fact that the changes in the energy system induced by climate policies will create co-benefits for other environmental problems is relatively uncontroversial.

Climate policy measures also interact with energy security objectives. There could be both co-benefits and trade-offs. Long-term energy security is, amongst other factors, influenced by the diversity of energy sources used, the remaining energy resources and their quality, the share of energy imported and the political stability of exporting regions (Jansen et al., 2004). Climate policy measures that reduce coal use could therefore lead to a decrease of long-term energy security. Introducing CO₂ capture and storage could counteract this effect. Renewable energy use and energy efficiency too could lead to an increase in energy security. The number of studies on climate policies reporting

quantitatively on the relationship with energy security is still limited, but there seems to be a growing interest in this area.

4. Conclusions

The discussion of the technical potential of different options to reduce greenhouse gas emissions suggests that stabilization of atmospheric concentrations at low levels, i.e. 550 ppmv CO₂-eq or below, is technically feasible with the technologies known today. However, it requires a very broad portfolio of policies and appropriate socio-economic and political circumstances. Without these circumstances, the implementation and diffusion prospects of these technologies are highly uncertain. More sustainable development and a high level of innovation and international cooperation (as included in the IPCC B1 (sustainable development) or A1T (high-tech) SRES scenarios – see Figure 1) make it easier to reach low-level stabilization, while a very fossil-fuel intensive economy or lack of international cooperation (as included in the A1FI (fossil-fuel intensive) or A2 (regional focus; low-tech) IPCC SRES scenario – see Figure 1) would make it very difficult. For all stabilization strategies, the biggest problem does not seem to be the technologies or the costs, but overcoming the many political, social and behavioural barriers to implementing mitigation options.

Excluding options from a portfolio of actions does increase the cost of stabilization. Current studies on mitigation strategies indicate that multi-gas strategies, emission trading, optimal timing and strong technology development, diffusion and transfer are essential to keep costs of low-level stabilization relatively low. Although considerable uncertainties exist, least-cost strategies are estimated to reduce global average GDP by 2050 by 1-4% for 550 ppmv CO₂-eq stabilization. For specific regions, countries or sectors costs could be higher. In considering costs it is important to take into account potential co-benefits or interactions of climate policies in terms of other environmental objectives (air pollution, acid deposition), energy security or other development goals.

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FIGURES

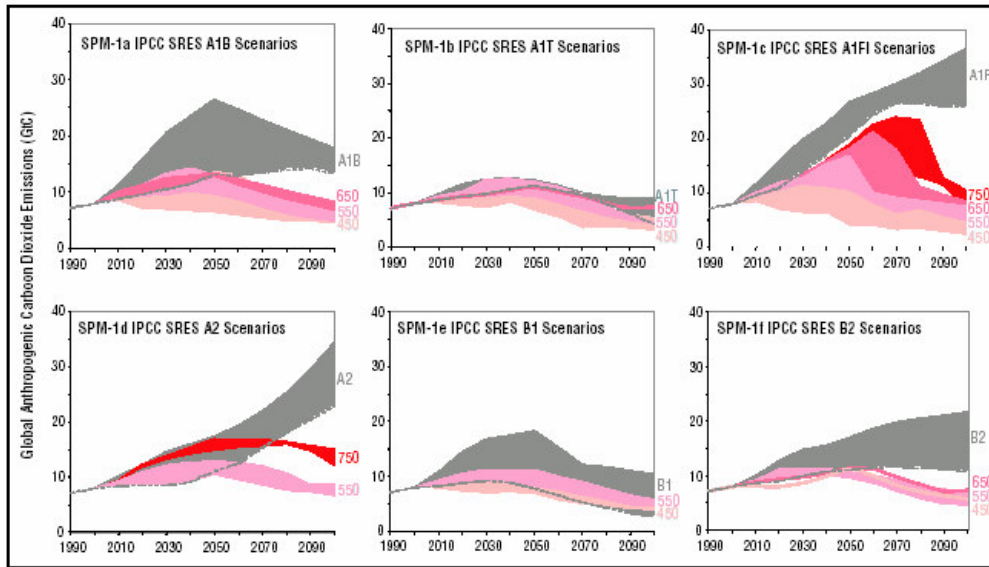


Figure 1: Comparison of the IPCC SRES scenarios and emission scenarios for stabilising CO₂ concentration at 450-750 ppmv (Source: (IPCC, 2001b)).

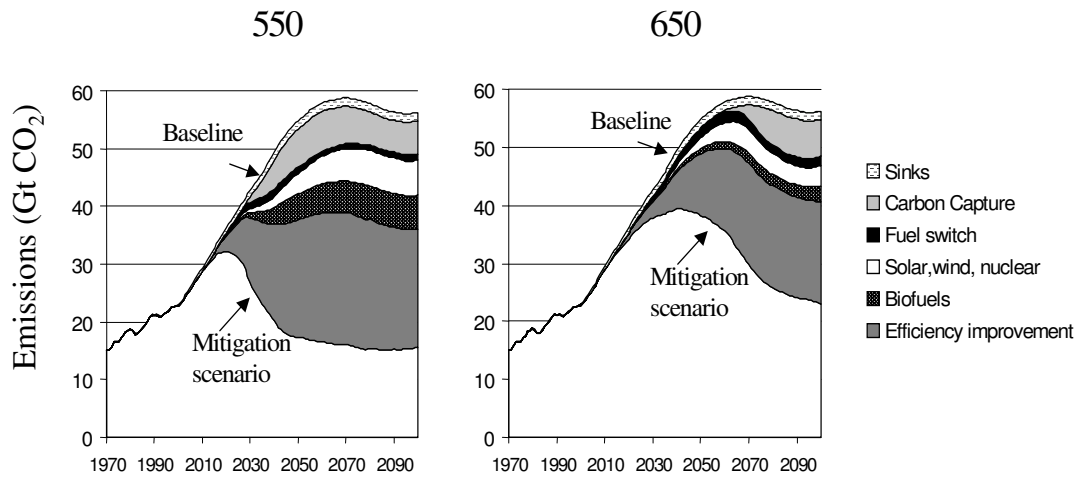


Figure 2a and b : Emission reduction through mitigation measures for stabilising GHG concentrations at 550 (left) and 650 (right) ppmv CO₂-equivalent (PCC2050 case) (Source: (Van Vuuren et al., 2003)).

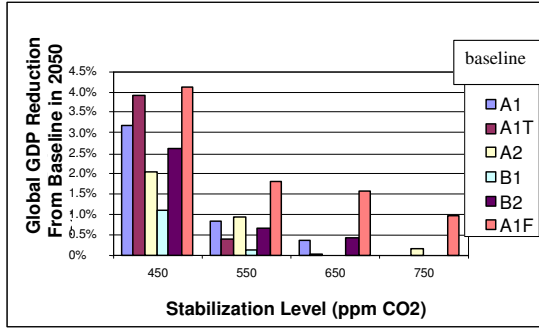


Figure 3: Costs for different stabilization scenarios. GDP losses in 2050 for stabilizing CO₂-concentration from various SRES baselines (CO₂-only) (Source: (Hourcade et al., 2001)).

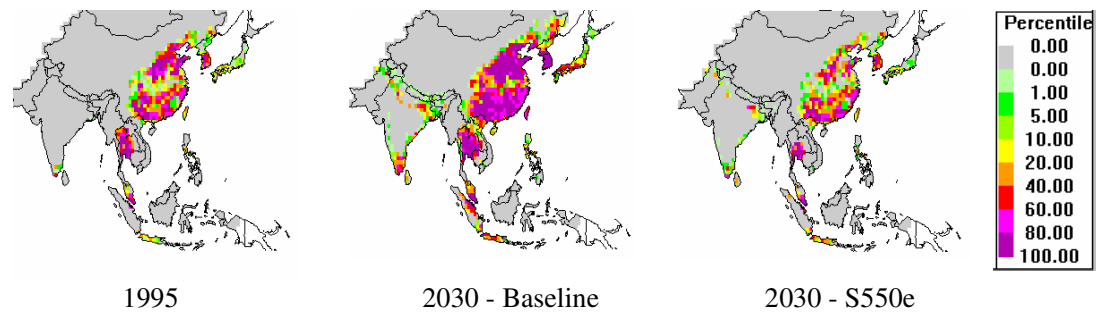


Figure 4: Risks of acidification in Asia: a) in 1995, b) under the baseline scenario and c) in the case of stabilization at 550 ppmv (assuming the same air pollution control policies as under b) (Source: (Van Vuuren et al., 2003)).

Table 1 Estimated technical potential of renewable energy sources.

Energy source	Potential by 2020-2025	Long-term technical potential (EJ/yr)
Hydro	35-55 ¹	>130 ¹ , 30-50 ²
Geothermal	4 ¹	>20 ¹
Wind	7-10 ¹	>130 ¹ , 230-640 ² , 340 ³
Ocean thermal	2 ¹	>20 ¹
Solar	16-22 ¹ , 2-230 ²	> 2600 ¹ , 160-5000 ² , 1330 ³
Biomass	72-137 ¹	>1300 ¹ , 280-450 ² , 275 to 1105 ³
Total renewables	130-230 ¹	640 ¹ - >7000

Estimates as reported in ¹ (Nakicenovic et al., 2000), ² (WEA, 2000), ³ (Hoogwijk, 2004)

Table 2 Cumulative technical potential for avoiding GHG emissions in the 2000-2100 period (in Gt CO2 equivalent).

Technology option	Cumulative technical potential 2000-2100 (Gt CO2 equiv)
Energy efficiency improvement	>1000
Renewables	>3000
Nuclear	>300
CO ₂ capture and storage	>2000
Biological sequestration	>350
Non-CO ₂ GHG reduction	>500