Chapter 16

Robust options for decarbonization

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*Note:* Photos and biographies of co-authors can be found in the appendix.

Since 2007, the perceptions of the international community all over the world about the dangers of climate change and about the need for vigorous response strategies have changed dramatically. This change was triggered by the release of the Fourth Assessment Report (AR4) *Climate Change 2007* by the Intergovernmental Panel on Climate Change (IPCC) and by the ongoing scientific progress in the field of global climate change. The scientific consensus reported in the AR4 received an unprecedented echo in the media and subsequently raised the public awareness concerning global climate change and its adverse impacts to an extent never seen before. As a result, the report encouraged numerous initiatives to combat global climate change – most notably the European Union's decision to reduce greenhouse gas (GHG) emissions by 20 % by 2020 (compared to the amount of GHGs emitted in 1990). In addition, more than 100 countries followed the European example and adopted a global warming limit of 2 °C or below (relative to preindustrial levels) as a long-term climate protection goal.

In order to assess the opportunity to stabilize carbon dioxide (CO_2) concentrations at a level that is compatible with the EU climate protection goal, the following issues need to be addressed. Which temperature changes are to be expected in the business-as-usual case, in other words, if no specific measures directed at mitigating climate change are implemented? Is there thus a real necessity to change course? If there is a real necessity, could cheap energy efficiency improvements solve the problem? If we need other, additional climate protection options, then which technologies are available and how great are the potential and available resources for the respective options? And finally, how should these options be combined in order to achieve least-cost climate protection?

Projected energy demand and associated business-as-usual greenhouse gas emissions

An extensive review of recent long-term scenarios (Fisher *et al.,* 2007) revealed that enhanced economic growth is expected to lead to a significant increase in gross domestic product (GDP) during the twenty-first century (see Fig. 1a) – throughout the world but especially in the developing countries and emerging markets. The expected rise in prosperity will reveal itself in a significant increase in the demand for energy services. Motivated by the first oil crisis, humankind was able to reduce the primary energy input required to produce one GDP unit (the so-called primary energy intensity) und is expected to do so further in the future (see Fig. 1b). Unfortunately, the historical improvements in energy intensities were not sufficient to fully offset the GDP growth, resulting in increased energy consumption.

The respective increase in energy efficiency in the scenarios is more than compensated by the anticipated huge economic growth. In the business-as-usual case,

a)   b)
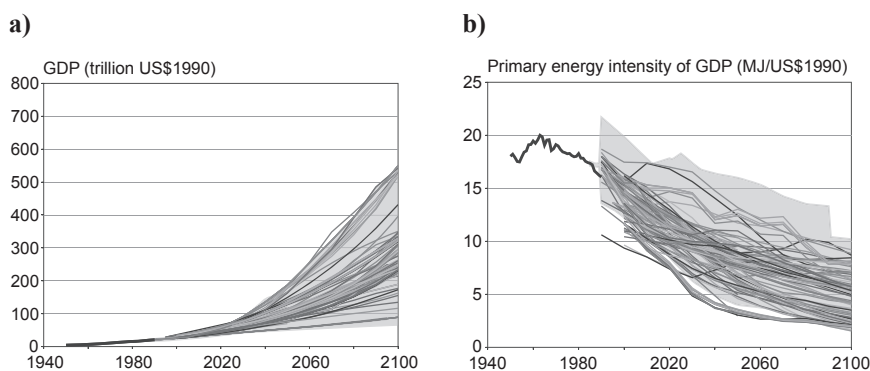
Fig. 1. a) Projected global economic growth and b) changes in primary energy
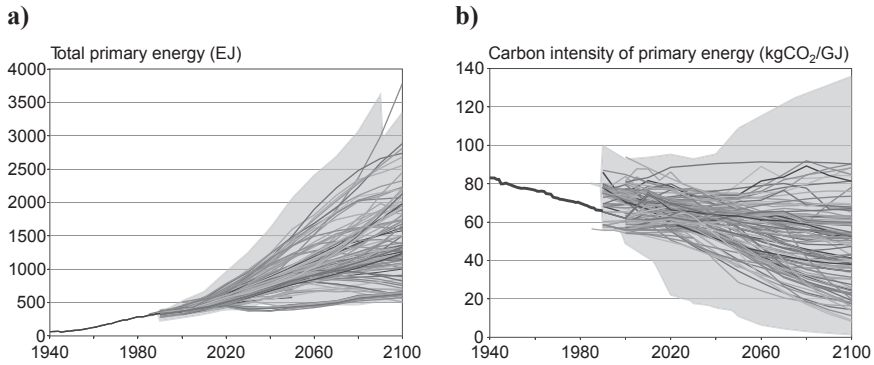intensity. (*Source:* adapted from Fisher *et al.,* 2007, pp. 180 and 184)

the demand for global primary energy is therefore projected to increase substan-
tially during the twenty-first century (see Fig. 2 a).

Similarly to the development of the primary energy intensity, the carbon inten-
sity (the amount of carbon dioxide emissions per unit of primary energy) is – with
few exceptions – projected to decrease as well (see Fig. 2 b). This development
reflects the global tendency to initially replace coal by oil and subsequently oil by
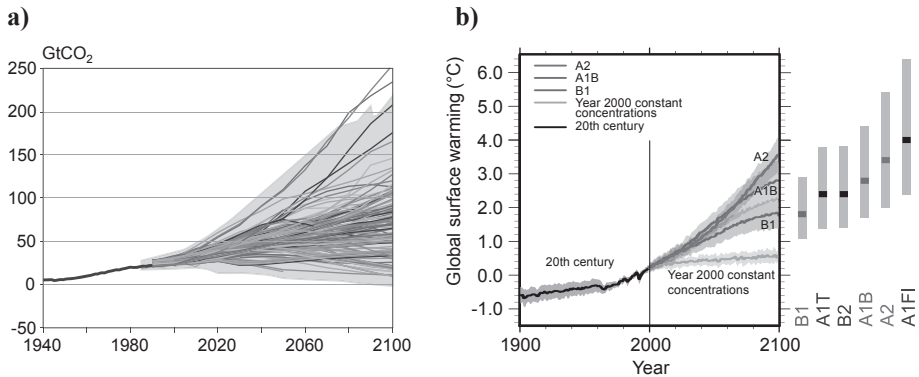gas, nuclear energy, and renewable energies.

Despite the substantial decarbonization projected to take place during the entire
twenty-first century, even in the reference scenarios that do not include any ex-
plicit policies directed at mitigating climate change, the overwhelming majority of
the emission projections exhibit considerably higher emissions in 2100 compared
with those in 2000 (see Fig. 3 a). Due to the long life-time of carbon dioxide, this
implies increasing carbon dioxide concentrations and in turn, increasing changes
in global mean temperature throughout the twenty-first century. Figure 3 b shows
the respective changes (together with the uncertainty range due to differences in
the applied general circulation models, right-hand bars) for representative emis-
sion scenarios (so-called SRES scenarios, see Nakicenovic *et al.,* 2000) taken from
the set of emissions scenarios shown in Figure 3 a.

The threat of global climate change: avoiding the unmanageable

Compared with the preceding Third Assessment Report, the IPCC AR4 reflects a
considerable improvement in our understanding of global warming. The report itself
and the ongoing scientific progress achieved since then show an increasing recog-
nition that the severity of the global climate change problem has been significantly
underestimated in the past (Smith *et al.,* 2009; Meinshausen *et al.,* 2009).

a)

Total primary energy (EJ)

b)

Carbon intensity of primary energy (kgCO₂/GJ)

Fig. 2. a) Projected increase in primary energy supply and b) expected carbon intensity changes. (*Source:* adapted from Fisher *et al.,* 2007, pp. 183–4)

a)

GtCO₂

b)

Global surface warming (°C)

A2
A1B
B1
Year 2000 constant concentrations
20th century

A2
A1B
B1

20th century

Year 2000 constant concentrations

B1 A1T B2 A1B A2 A1FI

Year

Fig. 3. a) Projected growth of carbon dioxide emissions and b) associated global mean temperature changes (relative to the temperature in 2000). (*Source:* adapted from Fisher *et al.,* 2007, p. 187; IPCC, 2007, p. 14)

According to its mandate, the IPCC is charged with summarizing the published scientific findings on global warming, its potential impacts, and opportunities to mitigate them. As a scientific council, the IPCC itself is not allowed to give specific policy recommendations concerning a suitable ceiling on global mean temperature rise to avoid dangerous interference with the climate system. Nevertheless, the information provided in AR4 (see Yohe *et al.,* 2007) supports the prominent climate protection goal that seeks to constrain global mean temperature change to less than 2 °C. This temperature threshold has been recommended by various advisory groups (e.g., the German Advisory Council on Global Change) in the past and became the official climate protection goal of the European Community in 2005.

Since then, more than 100 countries have adopted this global warming limit (Meinshausen *et al.,* 2009).

Assuming a best-guess climate sensitivity, staying below 2 °C implies that the CO_2-equivalent concentration would need to be stabilized at below 445 ppm (see Fig. 4 a), compared to current concentrations of about 430 ppm CO_2-equivalent. That effectively means that we are already right at the limit of acceptable GHG concentrations in our atmosphere. Consequently, global emissions must decline significantly over the coming decades, with a global peak in emissions in the next five years. By 2050, emissions need to be reduced well below 50% (compared with the emissions in 2000). Halving emissions by 2050 would still bear the risk of exceeding 2 °C with a probability of up to 50%. Stronger emission reduction and more stringent stabilization goals are obviously necessary to decrease this probability.[1]
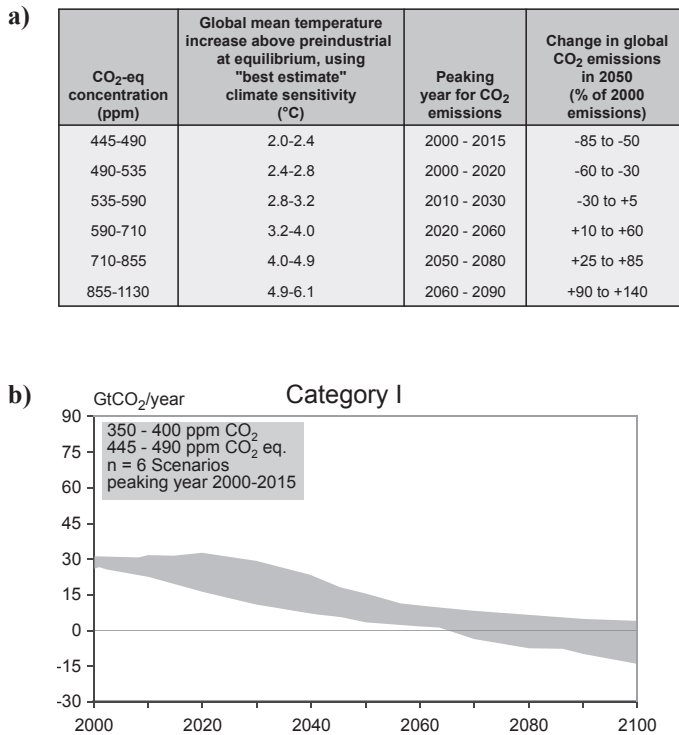
The boundaries of the corresponding emissions corridor shown in Figure 4 b are based on the range of scenarios discussed in the literature that stabilize at 2 °C (with high probability), and are not necessarily admissible emissions paths themselves. Those paths that exhibit high values in the first half of the century have to decline rapidly thereafter and to become low-lying trajectories in the second half of the twenty-first century. A delay in implementing effective emission mitigation measures at an early stage might even require negative emissions in the long term, and would be extremely difficult to achieve. One possibility to achieve negative emissions is by using biomass energy in combination with carbon capture and storage technologies (BECCS) – an option that has recently attracted increasing scientific interest.

Energy efficiency improvement: necessary, but not sufficient

Achieving the deep emission reductions discussed above requires a comprehensive global mitigation effort. Existing climate protection strategies in industrialized countries need to be further tightened. Simultaneously, ambitious mitigation measures need to be implemented in developing countries, where most of the increase in greenhouse gas emissions is expected in the coming decades (Fisher *et al.,* 2007, p. 199). Fortunately, numerous options are available that can facilitate the achievement of this goal:

- Improvement in energy efficiency
- Switching between fossil fuel types (e.g., replacement of coal by gas)
- Zero- or low-carbon energy conversion technologies (e.g., renewable energies)

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[1] A recent discussion of this issue was provided by Meinshausen *et al.* (2009).

a)

CO$_2$-eq concentration (ppm)	Global mean temperature increase above preindustrial at equilibrium, using "best estimate" climate sensitivity (°C)	Peaking year for CO$_2$ emissions	Change in global CO$_2$ emissions in 2050 (% of 2000 emissions)
445-490	2.0-2.4	2000 - 2015	-85 to -50
490-535	2.4-2.8	2000 - 2020	-60 to -30
535-590	2.8-3.2	2010 - 2030	-30 to +5
590-710	3.2-4.0	2020 - 2060	+10 to +60
710-855	4.0-4.9	2050 - 2080	+25 to +85
855-1130	4.9-6.1	2060 - 2090	+90 to +140

b)

Fig. 4. a) Different carbon dioxide concentration ceilings (expressed in terms of CO$_2$-equivalent concentrations), their corresponding global mean temperature changes, latest point in time to shift to declining emissions and percentage emissions reduction in 2050 required to obey the stabilization goal. b) Set of emission pathways which meet the most stringent goal listed in the left-hand table. To meet the low stabilization level some scenarios deploy removal of carbon dioxide from the atmosphere (negative emissions). (*Source:* adapted from Fisher *et al.,* 2007, p. 199 and p. 229)

- Capture and storage of carbon from fossil fuels
- Reduction of non-CO$_2$ greenhouse gases (multi-gas strategy)
- Mitigation through improved land-use (e.g., reduced deforestation and afforestation)

Strategies to reduce multi-gas emissions can help achieve climate protection targets at substantially lower cost compared with emission mitigation efforts that address the release of carbon dioxide only. This is especially the case during the first half of the century, but in the long run it is essential to achieve deep reductions of carbon dioxide in any case, since carbon dioxide has a very long life-time (more than 20 % of emissions remain in the atmosphere over thousands of years, Archer *et al.,* 2009). In addition, land-use mitigation options could provide 15 – 40 % of the total cumulative abatement over the twenty-first century. Most such options are

projected to be cost-effective strategies across the entire century (Fisher *et al.,* 2007, p. 172).

A tremendous decrease in energy intensity in the coming decades is essential if we are not to transgress the aforementioned 2 °C guardrail. Technological improvements and structural changes are expected to result in considerably lower greenhouse gas emissions than would otherwise be experienced. Assuming energy and carbon intensities frozen at current levels, for instance, would imply hypothetical average cumulative business-as-usual emissions that are roughly twice as high (see Fig. 5a) as the baseline emissions projected for the suite of emissions trajectories depicted in Figure 3a. The same message is visualized in Figure 5b. Once again, assuming no improvement in the energy intensity (for instance, in the case of the SRES A2 scenario considered here), would result in considerably higher hypothetical emissions, even under business-as-usual conditions.

Many low-cost options to improve energy efficiency and to change the relative shares of fossil fuels in the provision of end energy are already contained in the baseline development. Therefore, there is restricted potential to achieve deep emission reductions by additional cost-effective energy efficiency improvement and fossil fuel switching measures.

An example showing a stabilization of the carbon dioxide concentration at 550 ppm is given in Figure 5b where the (additional) contribution of demand reductions is small compared with the shares achieved by switching to low-carbon fuels (including shifts to nuclear energy and renewables) and carbon sequestration technologies (scrubbing). In order to achieve deep emission reductions (e.g., more than 50% by 2050 compared to 2000), energy efficiency improvement and fossil fuel switching measures do not suffice. In addition, the application of low-carbon technologies becomes imperative.

Innovative low-carbon technologies

Fortunately, numerous technologies exist which are capable of providing final energy while producing no or significantly less carbon dioxide compared with conventional fossil fuel burning (renewables, nuclear energy, and carbon capture and storage).

As Table 1 shows, there is abundant technological potential for renewable energies worldwide that would, in principle, suffice to meet even the highest projections of the total global primary energy demand in 2100 (see Fig. 2). The available wind potential (600 EJ/yr) alone would hypothetically be able to cover the entire primary energy demand of the world in 2005 (490 EJ). Even higher potentials are estimated for solar and geothermal energy (see Kohn, this volume).

Some important sources (especially wind and solar energy) exhibit an intermittent

a)   **b)**
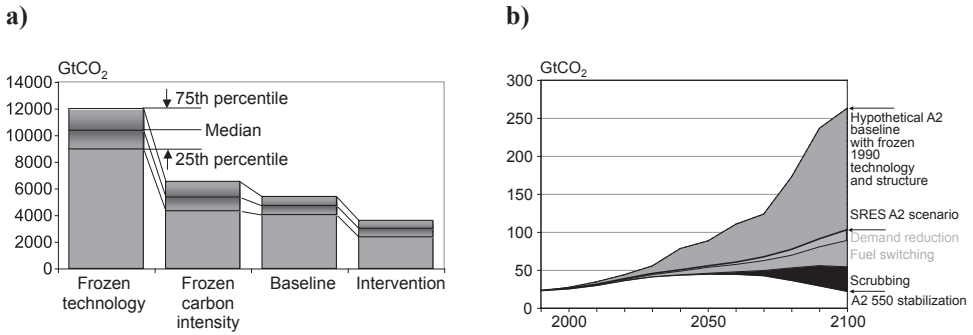
Fig. 5. a) Range of the global cumulative emissions emitted until 2100 for the different non-intervention scenarios shown in Fig. 3 a. 'Frozen technology' refers to the range hypothetical scenarios would exhibit without any improvement in energy and carbon intensities. The next bar shows the cumulative emissions assuming frozen carbon intensities and the third bar exhibits those emissions expected in the baseline (non-intervention) scenarios – where both energy and carbon intensity improvements are taking place. b) Contribution of different mitigation options to achieve a stabilization of carbon dioxide concentrations at 550 ppm (assuming a baseline development according to the IPCC SRES A2 baseline scenario without measures and policies directed at reducing GHG emissions). (*Source:* Fisher *et al.,* 2007, pp. 219–20)

availability dependent on daytime, season and weather conditions. In addition, renewable energy sources (with the exception of large-scale hydro-energy) are widely dispersed compared to fossil fuel deposits. Innovative concepts are available which can mitigate these drawbacks considerably by a combination of distributed usage (including appropriate communication strategies), storage, demand response, increased power system stability through the use of flexible alternating current transmission systems (FACTS) and interregional exchange (see Luther, this volume). Although renewables are in principle able to substitute fossil fuels completely, further research is needed to design integrated systems that exhibit low costs for the systems services envisaged here.

Nuclear energy is able to produce electricity with no (if only emissions at the power plant site are considered) or medium to low carbon emissions (if upstream emissions related to fuel supply and the construction of the power plants are taken into account). Under the present design of light-water reactors with a 'once-through' fuel cycle, however, the finite uranium resources (see Table 1) constrain the ability of nuclear energy to be the main lasting alternative to fossil fuel usage. Fast-spectrum reactors operated in a 'closed' fuel cycle by extracting the unused uranium and plutonium produced would solve this problem, albeit by accepting that reprocessing of the spent fuel increases the proliferation risks and security concerns. Beyond the long-term fuel resource constraints without recycling, there

Table 1. *Summary of global energy resources (including potential reserves) and their share of primary energy supply in 2005 (490 EJ). For renewable energies the technical potential is shown which takes into account conversion efficiencies as well as constraints on the available area. In contrast to the economic potential no explicit reference to cost is made.* (*Source:* Sims *et al.,* 2007, p. 264)

Energy class	Specific energy source	Estimated available energy resource (EJ)	2005 share of total supply (%)
Fossil energy	Coal (conventional)	> 100 000	25.0
	Coal (unconventional)	32 000	
	Gas (conventional)	13 500	21.0
	Gas (unconventional)	18 000	
	Coalbed methane	> 8 000	0.3
	Tight sands	8 000	0.7
	Hydrates	> 60 000	
	Oil (conventional)	10 000	33.0
	Oil (unconventional)	35 000	0.6
Nuclear	Uranium	7 400	5.3
	Uranium recycle	220 000	
	Fusion	* 5×10^9	
Renewable	Hydro (>10 MW)	60/yr	5.1
	Hydro (< 10 MW)	2/yr	0.2
	Wind	600/yr	0.2
	Biomass (modern)	250/yr	1.8
	Biomass (traditional)		7.6
	Geothermal	5000/yr	0.4
	Solar Photovoltaics	1600/yr	< 0.1
	Ocean (all sources)	** 7/yr	0.0

* estimated ** exploitable

are major barriers to an extended usage of nuclear energy. They comprise huge investment costs associated with investment uncertainties, unresolved waste management issues, security aspects in general, and – for some countries – the resulting adverse public opinion (Sims *et al.,* 2007, p. 254). As in the case of renewables, for advanced nuclear systems to make a higher contribution to the total share of energy would also require substantial cost reductions. Worldwide, only a few consortia are able to build nuclear power plants. With the current generation of power plants rapidly approaching the end of its lifetime, a significant share of the capacity of the nuclear industry is already needed even to secure a constant contribution made by nuclear energy to overall electricity production. On a global scale, sharing nuclear know-how is significantly constrained by commercial interests and security concerns. This could cause a significant bottleneck in attempts to solve the climate problem involving a pronounced contribution from nuclear energy.

Fossil fuel usage in combination with carbon capture and storage (CCS) technologies is a further option whereby a share of the future global energy supply could be produced with significantly lower carbon dioxide emissions. From a resource perspective, lower power plant efficiencies would result in an accelerated depletion of the fossil fuel resources. Due to the abundant availability of coal and potentially also hydrates (see Table 1), this, however, would not impose a major restriction on extensive application of coal-fired CCS technologies.

Although CCS can play a role in mitigating global climate change – at least as a transitional technology – its actual contribution may nevertheless be limited by the restricted availability of suitable geological disposal opportunities as well as by concerns about unintended leakage, risks associated with an accidental release of carbon dioxide, and environmental consequences. While deep ocean sequestration is another option, ocean eddy diffusion could potentially lead to a much larger region being affected with undesirable consequences than would be the case for sequestration in geological formations. Moreover, residence times of sequestered carbon dioxide are expected to be in the order of hundreds of years in the ocean, while potentially orders of magnitudes larger in formations. Finally, some of the authors (Edenhofer *et al.,* 2005; Held *et al.,* 2006) have suggested bond schemes to utilize the investigative power of the capital market to search for the most trustworthy combinations of CCS operators and geological formations. Such schemes are much harder to envisage for ocean sequestration. For all of these reasons, current schemes to operationalize CCS focus on geological formations rather than the deep ocean. CCS technologies imply higher costs compared to conventional fossil conversion, so that substantial cost reductions would be necessary to make this option an attractive one.

Low-concentration stabilization scenarios
### *The role of oil/gas prices*

Currently the world experiences significant changes in the prices of raw materials and energy in particular. Though primary energy prices have returned to moderate levels, the future availability of fossil energy carriers is unclear. Scarcity of resources is reflected in high extraction costs, which in turn imply high energy prices. Increasing oil and gas prices influence technological change in the following ways. First, they foster additional investments in exploring and exploiting new and more costly oil fields including those holding non-conventional oil. Second, increasing oil prices make options like coal-to-liquid profitable if coal is relatively abundant and cheap. In a climate protection scenario, the extensive use of coal can only become an option if it is combined with CCS. In a scenario assuming relatively cheap coal and expensive oil and gas, the 'clean' coal option becomes more important

compared to a scenario exhibiting low costs for all fossil fuels (see Fig. 6). Third, high oil prices may also improve overall energy efficiency, reducing the emissions up to the end of the century even in scenarios without any explicit mitigation policies or measures. It should be noted that long-term price trajectories of fossil fuels are quite uncertain. It is less uncertain that prices of oil and gas will increase faster than the price of coal because of the large coal reserves. However, large negative externalities associated with coal production and coal usage are likely to increase the cost of coal in the long run.

Figure 6 reveals the relative importance of different emission mitigation options in achieving a stabilization of the carbon dioxide concentration at 450 ppm as obtained with the model REMIND, developed at the Potsdam Institute for Climate Impact Research (see Bauer *et al.,* 2008; Leimbach *et al.,* 2009).[2]

The upper boundary of the corridor shows the business-as-usual emission trajectory which is dependent on the costs of fossil fuels. It is noteworthy that the increase of oil and gas prices does not alter the portfolio of mitigation measures substantially. Energy efficiency improvements (here including shifting between use of different fossil fuels, co-generation, and changing demand for final energy) play an important role in meeting this goal. A further considerable reduction of the emissions is realized through the application of CCS technologies, applied to both fossil fuels and biomass. Other renewables, especially solar photovoltaics and wind energy, as well as nuclear energy (light-water reactors), contribute significant shares. Although included in the general analysis, fast breeder reactors did not find application here because of their high capital costs compared to other mitigation options.

[2] REMIND comprises a top-down optimal growth model of the world economy combined with a bottom-up technology-rich description of the global energy supply system. In addition, the model contains a carbon cycle and climate system sub-module. Taken together, these modules are able to determine least-cost climate protection paths that are compatible with prescribed ceilings on global mean temperature change (e.g., the 2 °C EU climate protection guardrail). In contrast to traditional integrated assessment models, the model especially takes into account the possibility of induced technological change. In order to achieve this goal, learning curves are used in an endogenous way. This specific feature allows the determination of long-term cost-efficient strategies that minimize the integral climate protection cost over the entire time span considered (e.g., 150 years).

a)

b)
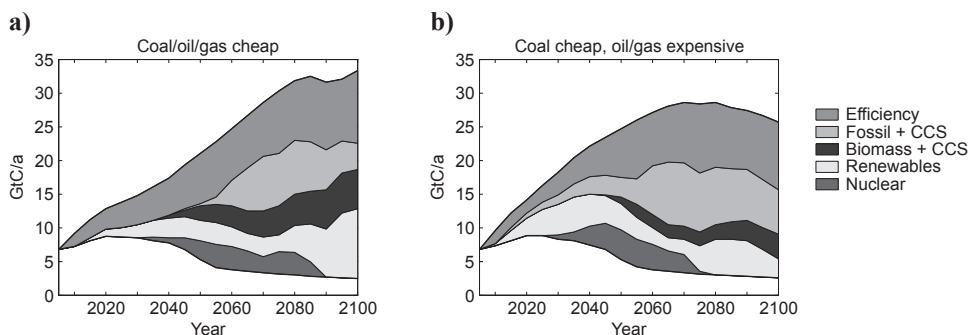
Fig. 6. The contribution of various mitigation options computed with the model REMIND for achieving the climate change stabilization target (450 ppm carbon dioxide). The upper boundary indicates the business-as-usual emissions, while the lower boundary represents the emissions in the mitigation scenario. The gap in between is filled by the contributions (so-called 'wedges') of emission mitigation options distinguished by the differently shaded areas. Panel a) shows the results for the case with cheap fossil fuels; panel b) shows the case with high costs for oil and gas. The pure rate of time preference for both cases is 3% per year (see below).

The role of discounting

The Stern Review (2006) has launched an exciting debate about the appropriate pure rate of time preference.[3] The report argued that the pure rate of time preference is an ethical value judgment about the weight and importance of future generations in current investment decisions. It points out that there is no ethical reason why future generations should be regarded as less important in current investment decisions than the current generation. However, the pure rates of time preference observed on capital markets are much higher than the rate derived from ethical considerations. The Stern Review states that a pure rate of time preference of 0.1% is in accordance with intergenerational justice. Some authors choose a pure rate of time preference of 3% in accordance with empirically observed behaviour on capital markets (see for example Toth, 1995). However the issue is much more complex, as Frederick *et al.* (2002) showed in an overview on the concept and measurement of discounting.

A lower pure time preference rate (1% per year) favours – already in the business-as-usual (BAU) scenario – the application of emerging technologies for using renewable energies (especially wind and biomass energy sources in early decades of

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[3] In economics, the pure rate of time preference is used to quantify how present consumer utility is valued compared to future consumer utility. Someone with a high time preference is focused substantially on his well-being in the present and the immediate future, while someone with low time preference places more emphasis on his well-being in the distant future. In this subsection only the issue of the pure rate of time preference is discussed and not the related issue of the inter-temporal elasticity of substitution, which is assumed to be equal to one.

the twenty-first century, see Fig. 7) while reducing, in part, the necessity to use CCS technologies.

Figure 8 shows the influence of excluding some of the different low-carbon technologies discussed above. As can be clearly seen, the exclusion of CCS technologies would result in a significant increase in the emission mitigation costs computed with the model REMIND. Compared to that, abstaining from applying additional renewables in order to combat global climate change would have a small influence, whereas the exclusion of nuclear energy would result in additional costs that are almost negligible compared to the overall mitigation burden.

### Creating a novel global energy system: the challenge ahead

As already pointed out above, achieving deep emission reductions requires a comprehensive global effort which includes both a complete change in the energy supply of industrialized countries and the establishment of low-carbon systems in developing countries and emerging markets – in short, nothing less than the creation of a completely novel global energy supply system. This would represent a true paradigm change compared with the current fossil-based energy systems and would take several decades to implement. In order to achieve this goal, the emissions mitigation measures must start immediately and rapidly engage the entire world. There is no time to waste. In a common effort, industrialized countries have to use their scientific capacity and creativity to develop and apply low-carbon technologies and to prove that a high standard of living can be sustained while producing considerably lower emissions in order to facilitate the early adoption of these technologies in the fast-growing emerging markets. The ultimate goal is a global carbon-free society.

Designing a cost-effective strategy to meet the climate protection targets discussed above (e.g., to limit global mean temperature increase to less than 2 °C relative to the preindustrial value) is a complex and dynamic problem. Although some conventional technologies (most notably, combined heat and power) might become economically viable once the costs of emission certificates increase, a major contribution towards achieving deep emissions reductions must be provided by the application of innovative low-carbon technologies. Unfortunately, some of these technologies are still prohibitively expensive. Anticipating learning capability and associated cost-reduction potential, however, is a key to resolving this problem.

While from an aggregated economic point of view, instantaneous massive investments into low-emission technologies seem to be optimal (Edenhofer *et al.*, 2006), more myopic agents (such as energy suppliers) may collectively act in such a way that the present-day energy system is conserved and consequently the global economy remains trapped in a suboptimal state.

a)   b)
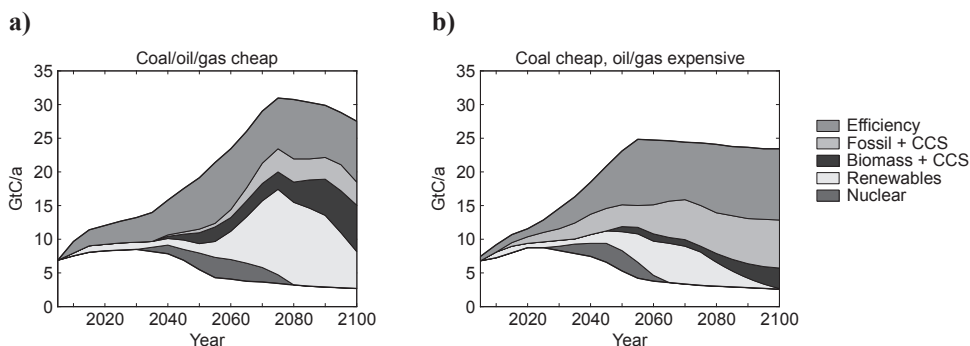
Fig. 7. Results of REMIND computations based on the same model assumptions as in Fig. 6 with the difference that a pure rate of time preference of 1% per year is applied.
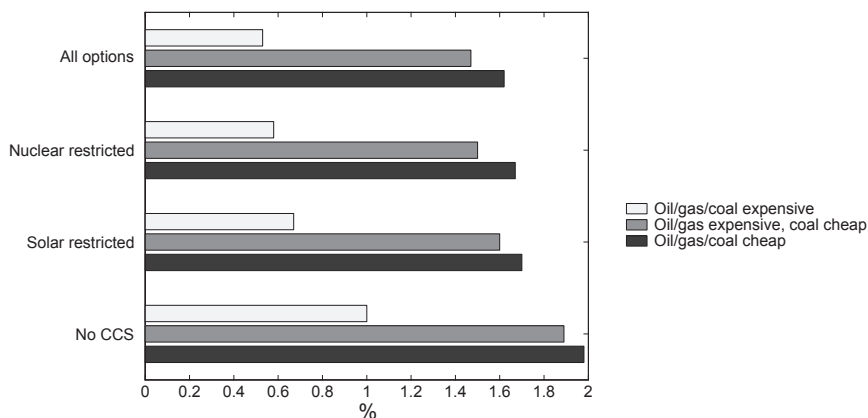
Fig. 8. (Monetary) consumption differences (i.e., relative reduction of per capita consumption in the stabilization case compared to the business-as-usual scenario). In the 'all options' case, all greenhouse gas mitigation opportunities discussed in Figures 6 and 7 (energy efficiency improvement combined with fuel shifting, renewables, nuclear energy and the application of CCS) are taken into consideration irrespective of their business-as-usual usage. In the other cases, some options are restricted to their respective usage in the business-as-usual scenario (REMIND model results, pure rate of time preference of 3% per year).

Therefore, low-carbon technologies can only enter the market place if the cost of fossil fuel usage is increased significantly (e.g., through a worldwide carbon certificate market or carbon tax, see Edenhofer *et al.,* this volume). Without a reasonable price for carbon there are simply not enough incentives for firms and investors to foster a search process for the most cost-effective low-carbon technologies.

Fortunately, there are some recent promising initiatives in this direction: Chancellor Merkel has proposed a global carbon trading system, which would allow the reduction of emissions according to the 2 °C limit, at the same time implementing an allocation scheme that endows each citizen with the same emission rights. This proposal presupposes a global carbon market – otherwise the costs imposed on industrialized countries would not be acceptable. Negotiations have already started to harmonize and link the European Emission Trading Scheme with emission trading schemes emerging in California and elsewhere in the United States. The appropriate timing is essential because of the need for a continued signal to the carbon markets. Emissions trading, and related flexible mechanisms, are likely to remain a core element of any post-2012 regime.

Admittedly, emissions trading is only one necessary condition for achieving low stabilization targets. In fact, the Stern Review found that only 40% of the low-carbon future can be financed through the carbon market (Stern, 2006). What is needed is a comprehensive suite of policies to shift the International Energy Agency's estimated figure of USD 20 trillion of energy investments by 2030 into low-carbon technologies and to assure these investments in the first place. On the national level, policy frameworks such as quota schemes or feed-in tariffs – or even a reasonably designed technology policy supporting demonstration projects for CCS but also for solar thermal power plants and other innovative technologies – are recommended. These would in particular allow the cost reductions inherent in technologies with high learning potential to be realized. On the international level, new innovative technology co-operation mechanisms will be required to both deploy existing technologies in emerging economies and develop and share new low-carbon technologies.

From a long-term perspective, a comprehensive global emission mitigation effort requires enhanced innovation to create novel low-carbon technologies, incentives to support their initial diffusion and the internalization of external costs (e.g. through emissions trading). Such a response to the dangers of global climate change would induce a transition towards a truly sustainable global energy system as a glorious 'side effect'.

References

Archer, D., Eby, M., Brovkin, V. *et al.* (2009). Atmospheric lifetime of fossil-fuel carbon dioxide. *Annual Reviews of Earth and Planetary Sciences,* **37,** 117–34.

Bauer, N., Edenhofer, O. and Leimbach, M. (2009). Low-stabilisation scenarios and technologies for carbon capture and sequestration. *Energy Procedia,* **1**(1), 4031–8.

Edenhofer, O., Held, H. and Bauer, N. (2005). A regulatory framework for carbon capturing and sequestration within the post-Kyoto process. In Rubin, E. S., Keith, D. W. and Gilboy, C. F., eds., *Greenhouse Gas Control Technologies: Peer Reviewed*

Papers and Overviews. Vol. I of *Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies (5–9 September 2004, Vancouver, Canada).* Amsterdam, 989–97.

Edenhofer, O., Carraro, C., Köhler, J. and Grubb, M., guest eds., (2006). Endogenous technological change and the economics of atmospheric stabilization. *Energy Journal,* **27**(Special Issue 1).

Fisher, B. S., Nakicenovic, N., Alfsen, K. *et al.* (2007). Issues related to mitigation in the long term context. In: Metz, B., Davidson, O. R., Bosch, P. R. *et al.,* eds., *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, 169–250.

Frederick, S., Loewenstein, G. and O'Donoghue, T. (2002). Time discounting and time preference: a critical review. *Journal of Economic Literature,* **40**(2), 351–401.

Held, H., Edenhofer, O. and Bauer, N. (2006). How to deal with risks of carbon seques- tration within an international emission trading scheme. In *Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies (19–22 June 2006, Trondheim, Norway),* issued on CD-Rom (ISBN 0-08-046407-6), Amsterdam.

IPCC – Intergovernmental Panel on Climate Change (2007). Summary for policymakers. In Solomon, S., Qin, D., Manning, M. *et al.,* eds., *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, 1–18.

Leimbach, M., Bauer, N., Baumstark, L. and Edenhofer, O. (2009). Mitigation costs in a globalized world – climate policy analysis with REMIND-R. *Environmental Modeling and Assessment* (in press).

Meinshausen, M., Meinshausen, N., Hare, W. *et al.* (2009). Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature,* **458**(7242), 1158–62.

Nakicenovic, N., Alcamo, J., Davis, G. *et al.* (2000). *Special Report on Emissions Scenarios.* A special report of Working Group III of the Intergovernmental Panel on Climate Change (IPCC). Cambridge.

Sims, R. E. H., Schock, R. N., Adegbululgbe, A. *et al.* (2007). Energy supply. In Metz, B., Davidson, O. R., Bosch, P. R. *et al.,* eds., *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, 251–322.

Smith, J. B., Schneider, S. H., Oppenheimer, M. *et al.* (2009). Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) "reasons for concern". *Proceedings of the National Academy of Sciences of the United States of America,* **106**(11), 4133–7.

Stern, N. (2007). *The Economics of Climate Change: The Stern Review.* Cambridge.

Toth, F. (1995). Discounting in integrated assessments of climate change. *Energy Policy* **23**(4–5), 403–9.

Yohe, G. W., Lasco, R. D., Ahmad, Q. K. *et al.* (2007). Perspectives on climate change and sustainability. In Parry, M. L., Davidson, O. F., Canziani, J. P. *et al.,* eds. (2007). *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge,* 811–41.