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Overview of mitigation scenarios for global climate stabilization based on new IPCC emission scenarios (SRES)

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Abstract This paper provides an overview of new emission mitigation scenarios that lead to stabilization of atmospheric CO_2 concentrations, presented in this Special Issue. All of these scenarios use as their baselines the new IPCC scenarios published in the IPCC Special Report on Emission Scenarios (SRES), which quantify a wide range of future worlds. This means the new mitigation and stabilization scenarios are based on a range of future development paths that have fundamental implications for future emissions reduction strategies. Here, we refer to these new scenarios as "Post-SRES" mitigation scenarios. In addition to providing an overview of these new scenarios, this paper also assesses the implications that emerge from a range of alternative development baselines for technology and policy measures for reducing future emissions and stabilizing atmospheric CO_2 concentrations. Nine modeling teams have participated in this joint effort to quantify a wide range of mitigation and stabilization scenarios. The nine modeling approaches involve different methodologies, data, regional aggregations and other salient characteristics. This pluralism of approaches and alternative baselines serves to cover some of the uncertainties embedded across a range of different mitigation and stabilization strategies. At the same time, several common trends and characteristics can be observed across the set of Post-SRES scenarios. First, the different baseline "worlds" described in the SRES scenarios require different technology/policy measures to stabilize atmospheric CO_2 concentrations at the same level. Second, no one single measure will be sufficient for the timely development, adoption and diffusion of mitigation options to achieve stabilization. Third, the level of technology/policy measures in the beginning of the 21st century that would be needed to achieve stabilization would be significantly affected by the choice of development path over next one hundred years. And finally, several "robust policy options" across the different worlds are identified for achieving stabilizations.

Key words Climate change · Mitigation scenarios · IPCC-SRES · Computer simulation model · Robust policy options

1 Introduction

The future climate change problem will be a result of human activities over the next one hundred years, which determine the future level of greenhouse gas (GHG) emissions such as CO_2, as well as aerosol emissions such as SO_2. These future emission trajectories are dependent on future development paths. Elsewhere in this Special Issue, Rana and Morita have reviewed mitigation scenarios, and concluded that these scenarios are based on a wide range of baselines, primarily caused by different assumptions with regard to economic growth and technology change. This suggests that there is a wide range of policy/technology options to stabilize global climate even at the same level. Clearly, the range increases further when alternative stabilization levels are considered.

In order to assess climate policies, it is necessary to carefully consider the wide range of possible assumptions about future developments that underlie the scenarios. The policy/technology options designed for a high-emission future world are entirely different from those for a low-emission world. Furthermore, it is also required to assess what packages of technology/policy measures are robust against different world views. However, very few studies have been conducted to analyze the relationships between development path and climatic policy/technology measures, as Rana and Morita pointed out elsewhere in this Special Issue.

The first opportunity to start a systematic program for analyzing these relationships was given by the IPCC (Intergovernmental Panel on Climate Change). In 1996, the IPCC decided to develop a new set of baseline emissions scenarios for GHGs and sulfur. A wide range of emission scenarios were quantified based on different future paths for economic, social and technological development, but not including any climate policies or mitigation measures additional to those already in place today. These scenarios are published in the Special Report on Emission Scenarios (Nakićenović et al. 2000), and are called "SRES Scenarios" in short. Modeling teams participating in the process to develop mitigation and stabilization scenarios recognized the necessity to analyze and compare mitigation scenarios using the IPCC SRES scenarios as their baselines. Consequently, the authors of this paper planned and organized a special comparison program to quantify SRES-based mitigation scenarios. These SRES-based scenarios are called "Post-SRES Scenarios".

SRES scenarios do not include any explicit mitigation or stabilization policies or measures. As such they include scenarios ranging from rapidly increasing to decreasing emissions over next one hundred years. The Post-SRES scenarios were quantified, based on the wide range of SRES scenarios, as a set of mitigation (policy intervention) scenarios for stabilizing atmospheric GHG concentrations. Therefore, the policy/technology measures assumed in the Post-SRES scenarios are strongly affected by baseline emission trajectories of SRES scenarios as well as by their socio-economic assumptions. They describe mitigation measures and policies (the additional climate initiatives) that would have to be undertaken, in each SRES scenario "world", to achieve stabilization at different levels (450, 550, 650, and 750ppmv). As a result, the analysis and comparison of Post-SRES scenarios can supply very systematic data to clarify the relationship between the relative contribution of development path and climatic policy/technology measures. Knowledge of these relationships can in turn enable us to assess robust policy/technology options for different future development paths.

In the Post-SRES program, a multi-model approach was adopted, and nine leading modeling teams participated in the program from Europe, United States and Asia. This Special Issue contains eight papers on mitigation scenario simulations submitted by eight of nine modeling teams. This "multi-model" approach is essential to analyze the divergence of future development path, because the huge uncertainties in long-term development cannot be assessed by a single model nor by simple sensitivity analyses. Potential divergence in trends related to economic and technological development, innovation, and cultural transition can be analyzed only by comparison of several model studies, where individual models represent quite particular perspectives on such issues. The comparison of several model studies allows us to compare the results of individual models with other model studies based on a different world view.

This paper provides an overview and comparison of the Post-SRES scenarios. First, IPCC SRES scenarios are briefly introduced, and the Post-SRES program is explained. Second, nine quantification studies of Post-SRES scenarios are compared, and finally, several findings are summarized.

2 IPCC SRES scenarios

For baseline estimates of GHG and sulfur emissions, IPCC has so far developed three sets of emission scenarios. The first two were developed in 1990 and 1992 (IPCC 1990; Leggett et al. 1992). In 1996, after evaluating the usefulness of the 1992 scenarios (Alcamo et al. 1995), the IPCC decided to develop a third set of GHG scenarios, the SRES scenarios (Nakićenović et al. 2000), which are used in this paper as baseline scenarios. The SRES writing team developed 40 individual scenarios based on an extensive literature assessment, based on six alternative modeling approaches, and an "open process" that solicited wide participation and feedback. They cover a wide range of the main demographic, technological and economic driving forces for GHG and sulfur emissions. These scenarios do not include explicit mitigation measures or policies (additional climate policy initiatives), although they necessarily encompass various policies of other types, some of which have the effect of reducing emissions.

Each scenario links one of four narrative "storylines" with one particular quantitative model interpretation. All the scenarios based on a specific storyline constitute a scenario "family". The following Box shows four narrative storylines which describes driving forces of SRES scenarios and their relationships. Each storyline represent the playing out of different social, economic, technological and environmental developments (or paradigms), which may be viewed positively by some people and negatively by others. Possible "surprise" and "disaster" scenarios were excluded. In addition, scenarios in the A1 family were categorized into four groups according to their technological emphasis—on coal, oil and gas, non-fossil energy sources or a balance of all three. The last group, a balanced A1 is simply noted in this paper as "A1".

The main characteristics of the four SRES storylines and scenario families.

- The A1 storyline and scenario family describes a future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. Major underlying themes are convergence among regions, capacity building and increased cultural and social interaction, with a substantial reduction in regional differences in per capita income.
- The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, resulting in high population growth. Economic development is primarily regionally-oriented, and per capita economic growth and technological change are more fragmented and slow compared to other storylines.
- The B1 storyline and scenario family describes a convergent world with rapid change in economic structures toward a service and information economy, reduction in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.
- The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with less rapid, and more diverse technological change, but with a strong emphasis on community initiative and social innovation to find local and regional solutions. While policies are also oriented towards environmental protection and social equity, they are focused on local and regional levels.

Six different models, AIM, ASF, IMAGE, MARIA, MESSAGE-MACRO and MiniCAM, were used that are representative of different modeling approaches and different integrated assessment frameworks in the literature. One preliminary scenario from each family, referred to as a "marker," was posted on the SRES web site, and the markers were intensively tested for reproducibility using different modeling approaches with "harmonized" common assumptions of population growth, GDP growth, and final energy use. Table 1 summarizes the main demographic, technological, social and economic driving forces across the maker scenarios in 2050 and 2100. These drive the energy and land-use changes that are the major sources of GHG emissions.

Table 1. Overview of main driving forces and GHG emissions in marker scenarios

Scenario group	(1990)	A1	A2	B1	B2
Population (billion)	5.3				
2020		7.4	8.2	7.6	7.6
2050		8.7	11.3	8.7	9.3
2100		7.1	15.1	7.0	10.4
World GDP (10^{12} 1990US$)	21				
2020		56	41	53	51
2050		181	82	136	110
2100		529	243	328	235
Primary energy (10^{18} J/yr)	351				
2020		711	595	606	566
2050		1347	971	813	869
2100		2226	1717	514	1357
CO_2 (fossil fuels: GtC/yr)	6.0				
2020		12.1	11.0	10.0	9.0
2050		16.0	16.5	11.7	11.2
2100		13.1	28.9	5.2	13.8
CO_2 (land use: GtC/yr)	1.1				
2020		0.5	1.2	0.6	0.0
2050		0.4	0.9	−0.4	−0.2
2100		0.4	0.2	−1.0	−0.5
CH_4 ($MtCH_4$/yr)	310				
2020		421	424	377	384
2050		452	598	359	505
2100		289	889	236	597
N_2O (MtN/yr)	6.7				
2020		7.2	9.6	8.1	6.1
2050		7.4	12.0	8.3	6.3
2100		7.0	16.5	5.7	6.9
SO_2 (MtS/yr)	70.9				
2020		100	100	75	61
2050		64	105	69	56
2100		28	60	25	48

The 40 SRES scenarios cover most of the range of carbon dioxide, other GHG, and sulfur emissions found in the recent scenario literature. Table 1 summarizes main driving forces and GHG and sulfur emissions of the maker scenarios at 1990, 2020, 2050, and 2100 year. CO_2 emissions in A1 are highest in growth rate in the first quarter of the 21st century, peak at the middle of the century in terms of absolute emission levels, and then decrease toward 2100. In A2, CO_2 emissions are in the middle of the range of scenarios in the first half of 21st century, but become very high in the latter half of the century. In the B1 world, CO_2 emissions decline after the second quarter of the 21st century even without any climate policy, and this scenario group has the lowest emission levels in the latter half of the century. CO_2 emissions in B2 world are lowest in the first half of the 21st century, but continue to increase in the second half, and the emissions reach a similar level to that in A1 in 2100.

3 Post-SRES scenarios

The new mitigation and stabilization scenarios developed in the Post-SRES effort are based on the four SRES scenario families as baselines. A "Call for Scenarios" was sent by the authors of this paper to more than one hundred researchers in March 1999, and modelers from around the world were invited to prepare quantified stabilization scenarios for two or more concentration levels of atmospheric CO_2 in the year 2150, based on one or more of the four SRES scenario families. Alternative concentration ceilings include 450, 550 (minimum requirement), 650, and 750ppmv, and harmonization with the SRES scenarios was required by tuning reference cases to SRES values for GDP, population and final energy demands.

Responding to the call, nine modeling teams participated in the comparison program, included six modeling teams that originally developed the SRES scenarios and three other teams: the AIM team (Jiang, Morita, Masui & Matsuoka), the ASF team (Sankovski, Barbour & Pepper), the IMAGE team, LDNE team (Yamaji, Fujino & Osada), the MESSAGE-MACRO team (Riahi & Roehrl), the MARIA team (Mori), the MiniCAM team (Pitcher), the PETRO team (Kverndokk, Lindhot & Rosendahl) and the WorldScan team (Bollen, Manders & Timmer). The analyses of eight of these teams are summarized elsewhere in this Special Report. Table 2 shows all the modeling teams and stabilized concentration levels, which were adopted as stabilization targets by each modeling team. Most of the modeling teams analysed more than two SRES baseline scenarios, and half of them analysed more than one stabilization case for at least one of these baselines. This allows a systematic review to be conducted to clarify the relationship between baseline scenarios and mitigation policies/technologies. In total, fifty[1] Post-SRES scenarios were analysed by the nine modeling teams.

Because of time constraints, the modeling teams focused their analyses mostly on the energy-related CO_2 emissions. However, half of the modeling teams, including AIM, IMAGE, MARIA and MiniCAM, have also tried to quantify mitigation scenarios in non-energy CO_2 emissions. The modeling teams that did not estimate non-energy CO_2 emissions, introduced exogenous scenarios for these emissions from outside of their models.

In order to check the performance of CO_2 concentration stabilization for each Post-SRES mitigation scenario, a special "generator" (Matsuoka, in this Special Issue) was used by the modeling teams to convert the CO_2 emission into CO_2 concentrations trajectories. In addition, the generator was used by them to estimate the eventual level of atmospheric CO_2 concentration by 2300 based on the 1990 to 2100 CO_2 emissions trajectories from the scenarios. This generator is based on the Bern Carbon Cycle Model (Joos et al. 1996), which was used in the IPCC Second Assessment Report (IPCC 1995). Using this generator, each

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[1] Forty-four scenarios are listed on Table 2, but the MiniCAM team quantified two mitigation scenarios for B2-550ppmv and the WorldScan team did also two scenarios for A1-550, A2-550, B1-450, B2-450 and B2-550ppmv.

Table 2. Stabilization targets (ppmv) for post-SRES participants and quantified scenarios

Baseline scenarios	A1	A2	B1	B2
AIM (NIES and Kyoto University, Japan)	450 550 650	550	550	550
ASF (ICF Corporation, USA)		550 750		
IMAGE (RIVM, Netherlands)	550		450	
LDNE (Tokyo University, Japan)	550	550	550	550
MARIA (Science University of Tokyo, Japan)	550		550	450 550 650
MESSAGE-MACRO (IIASA, Austria)	450 550 650	550 750		550
MiniCAM (PNNL, USA)	550	550	550	550[1]
PETRO (Statistics Norway, Norway)	450 550 650 750	450 550 650 750		
WorldScan (CPB, Netherlands)	450 550[2]	450 550[2]	450[2]	450[2] 550[2]

[1] High and low baselines were used

[2] An early action and a delayed response were quantified

modeling team adjusted their mitigation scenarios so that the interpolated CO_2 concentration reach one of the alternative fixed target level at 2150 year within 5% error. Further constraint was that the interpolated emission curve should be smooth also after 2100, the end of the time-horizon of the scenarios. This adjustment played an important role in the Post-SRES for harmonizing emissions concentrations levels across the stabilization scenarios. The key driving forces of emissions such as, population, GDP and final energy consumption were harmonized in baseline assumptions specified by the four SRES scenario families.

4 Comparison of stabilization scenarios

One of the most important features of the Post-SRES analysis is the adoption of a multi-model approach, so we begin our discussion by looking at how different models achieve the same stabilization targets in the various baseline "worlds". Figure 1 shows the comparison of mitigation scenarios to achieve stabilization at 550ppmv from the A1 baseline at the global, non-Annex I and Annex I countries' level. As shown in this Figure, the A1-based 550ppm stabilization scenarios produce similar shapes among the different models. All the scenarios at global and non-Annex I level, have an inverse-U shape, while Annex I scenarios drop to the right. These shapes are caused by the strong constraint of achieving a 550ppmv atmospheric CO_2 concentration.

However, given this general agreement, there are certain differences in stabilization scenarios among the models. MESSAGE-MACRO and IMAGE-based scenarios are comparatively high, while MARIA-based emission is low at global level (Fig. 1(a)). Regional comparison in non-Annex I[2] region shows the similar trends to the global figure (b), but the results for Annex I region shows some differences: MARIA and MiniCAM-based scenarios are comparatively high, and PETRO and AIM are low (c). One major reason for such variations is a difference in timing to reach the stabilization level. At the global level, another factor explaining the differences is the time allocation of CO_2 reduction policies, while, at a regional level, theregional allocation of CO_2 reduction is a major factor.

Another way to show the results of the mitigation scenarios is contained in Fig. 2, which displays the CO_2 reduction rates required to meet the 550ppm stabilization target from the A1 baseline. The global level comparison (Fig. 2(a)) explains the difference in time series allocation of CO_2 reduction among models. LDNE, AIM and PETRO start CO_2 reductions at an early stage, while the MESSAGE-MACRO model begins most reductions around 2050. These differences are mainly found in Annex I countries (Fig. 2(c)). The reduction rates in the non-Annex I region are surprisingly similar among the models (Fig. 2(b)). Most of the modelers assume that the non-Annex I region starts mitigation with a time lag of 10 to 30 years in comparison with Annex I, and that its reduction rate is less than that of the Annex I region. The reduction rate of LDNE is higher than that of other models, because its baseline CO_2 emission is the highest among them (See Yamaji et al. 2000).

Turning from emissions to primary energy use, Fig. 3, which shows a comparison of the rate of reduction rate in energy consumption from the baseline, is helpful in understanding the difference in CO_2 reduction measures among models. AIM, MiniCAM, IMAGE and PETRO assume effective policies for technological/social efficiency improvements in energy consumption, while MESSAGE-MACRO model does not assume such strong demand-side policies but emphasizes the introduction of carbon free energy in the second half of 21st century. MARIA and LDNE assume the additional introduction of carbon sequestration technologies mainly in the latter half of the 21st century, so that energy consumption is estimated to increase for some mitigation cases in comparison with baseline.

At a more general level, Fig. 4 shows the relationships between SRES baselines and CO_2 reduction rate for all models from all four baselines. The target level is fixed to 550ppm, because the 550ppm stabilization case was most frequently

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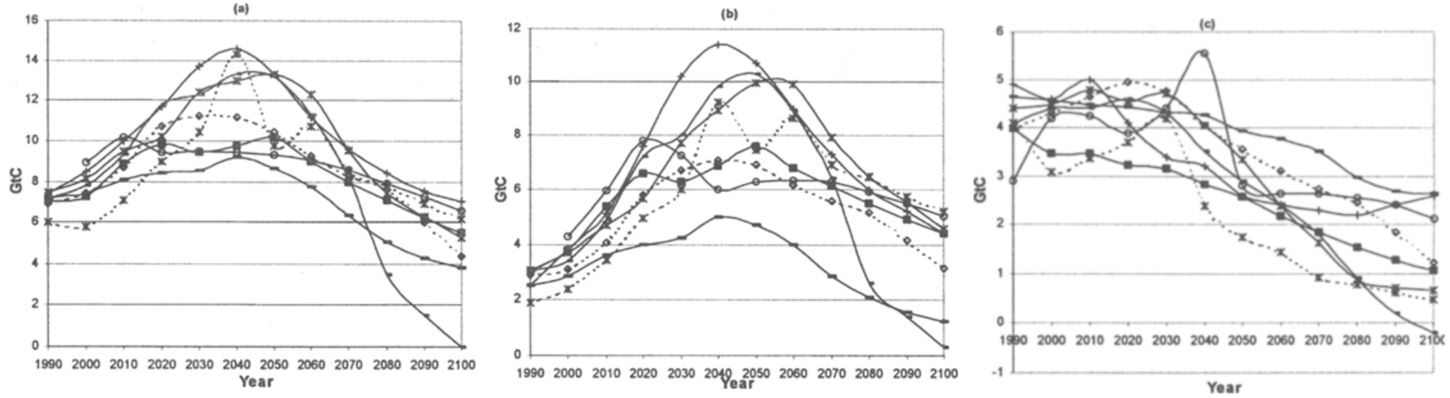
[2] the United Nations Framework Convention on Climate Change defines Annex I region to include all OECD and industrialized countries undergoing economic reform while the Non-Annex I region includes all other countries.



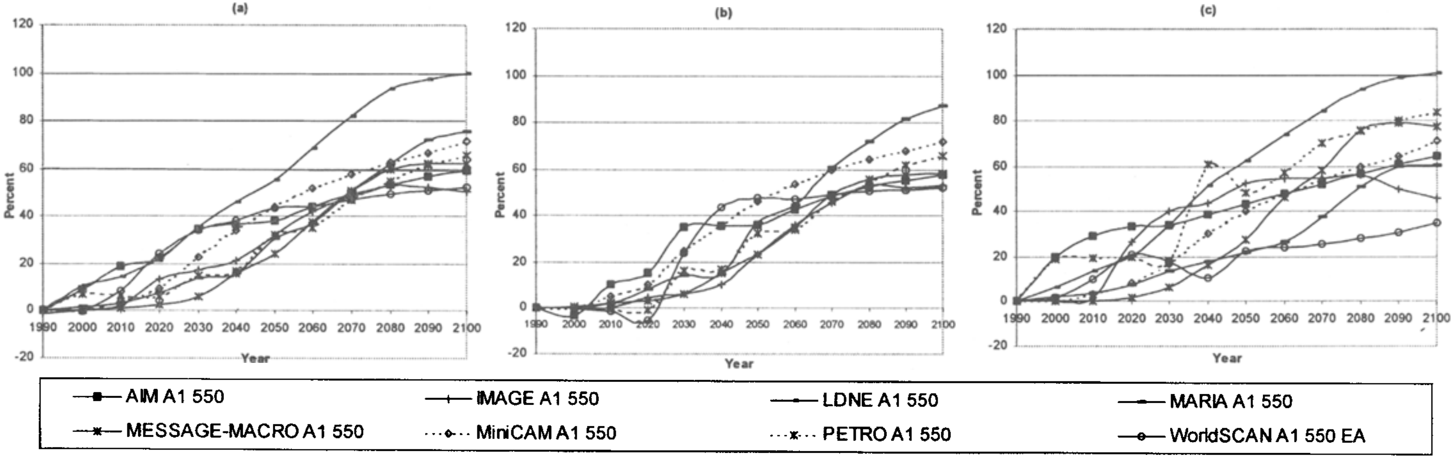


Fig. 1a–c. CO_2 emissions for 550 ppm stabilization in A1 world, **a** global, **b** non-annex 1, **c** annex 1

Fig. 2a–c. Reduction rates of CO_2 emissions from SRES A1 baseline for 550 ppm stabilization, **a** global, **b** non-annex 1, **c** annex 1

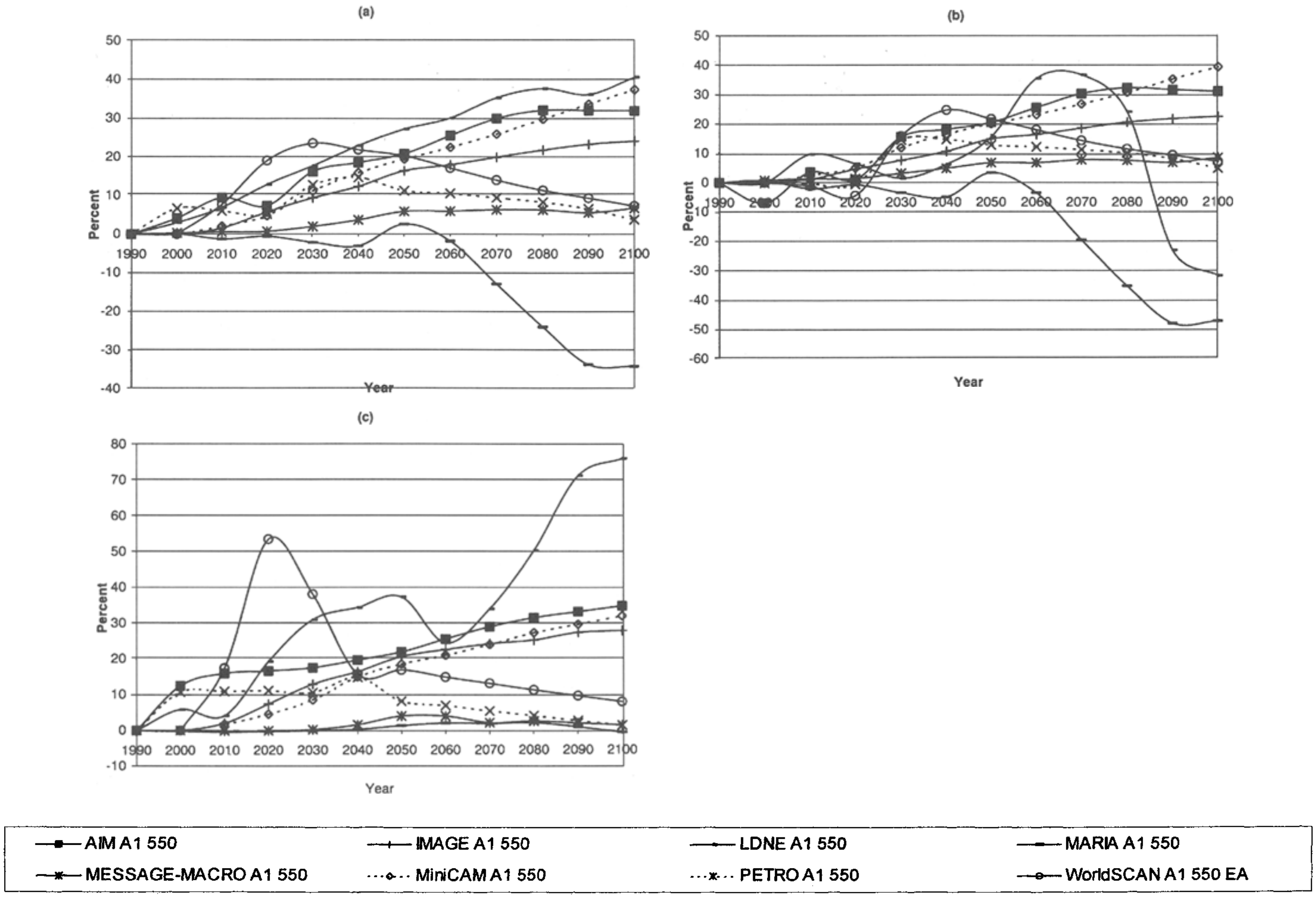


Fig. 3a–c. Reduction rates of primary energy from SRES A1 baseline for 550 ppm stabilization, **a** global, **b** non-annex 1, **c** annex 1

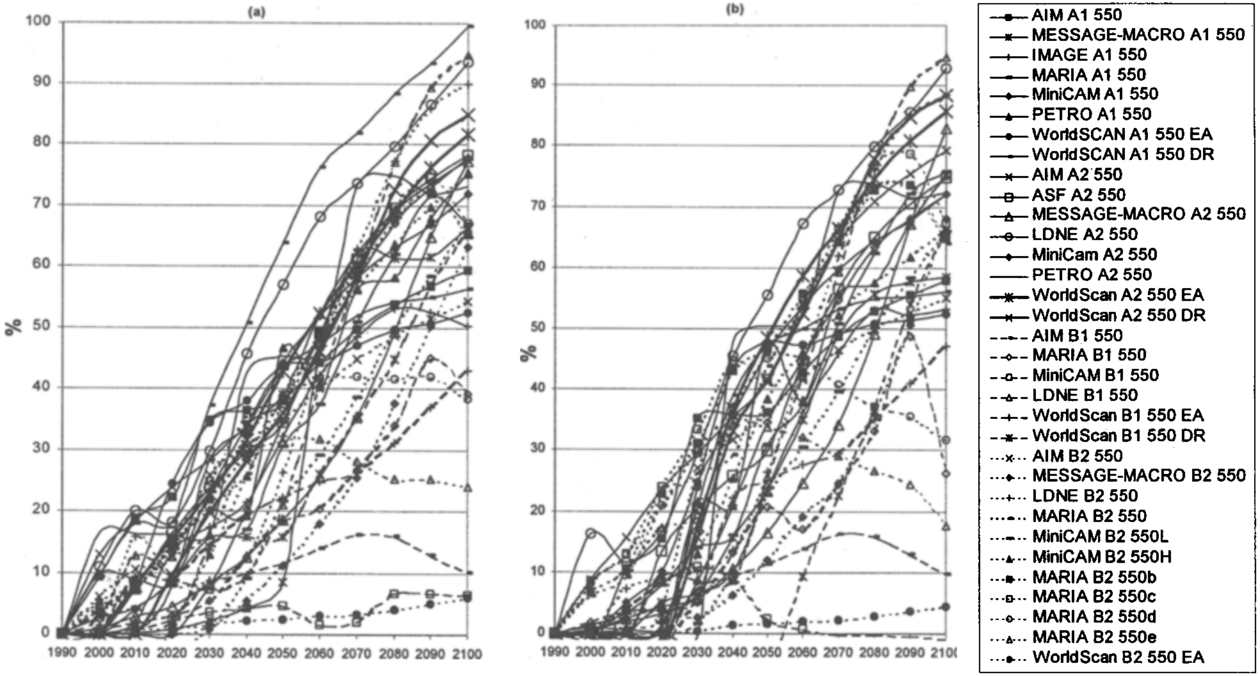


Fig. 4a,b. Reduction rates of CO_2 emissions from all SRES baselines for 550 ppm stabilization, **a** global, **b** non-annex 1 analysed in the Post-SRES analysis. Though the Figure shows a wide range of stabilization scenarios even within the same baseline, some important trends and characteristics are illustrated by the Figure:

First, for achieving stabilization at 550ppm, higher rates of reduction in CO_2 emissions are required, respectively in the A2, A1, B2 and B1 families. With the exception of LDNE, for which the estimates of CO_2 reduction in all scenarios are more than 90%, CO_2 reduction in A2 ranges between 75% to 80% at the end of the 21st century, A1 between 50% to 75%, B2 between 20% to 70%, and B1 between 5% to 40%. The global ranges are similar to those for the non-Annex I region. Second, for all models, the A1 and A2 baselines require high emission reductions from 2000 to 2020 compared to B1 and B2. AIM, LDNE and PETRO indicate a need to reduce global CO_2 emissions by 10% to 20% from the A1 and A2 baseline in this period. Third, mitigation scenarios for the A1 and A2 baseline indicate that the non-Annex I region must start CO_2 reduction at the beginning of the 21st century. AIM and LDNE estimate 10% to 15% reduction from baseline for the A1 and A2 case.

The comparison in energy consumption reductions shown in Fig. 5 is more complicated among models, because the reduction levels are dependent not only on the level of baseline CO_2 trajectory, but also on the timing and level of the introduction of carbon-free or low-carbon energy, as well as carbon sequestration technologies. Figure 5 shows only that B1 baselines (indicated by broked line) require very small reduction of energy consumption while other baselines illustrate divergent possibilities. Mitigation scenarios that show increased energy consumption are caused by the introduction of carbon sequestration technologies.

Figure 6 compares the macroeconomic cost required to reduce CO_2 emissions for 550ppm stabilization, indicated by reduction rate of GDP from baseline. This Figure suggests that different baselines would give rise to different macroeconomic costs to reach 550ppm stabilization. While there is a wide range among model results, in general A2 would be the most expensive and B1 would require the least cost for stabilization. The GDP loss in B1 would be less than one tenth of the A1 case, and less than on twentieth of the A2 case. It should be noted that these comparisons are in terms of GDP loss, which does not mean the direct costs per unit reduction in B1 are lower than in A2. In some scenarios, marginal direct costs in B1 to reduce CO_2 are apparently higher than in A2. MARIA and a few other models suggest the possibility to increase GDP by the introduction of climatic policies. These GDP increase can be explained by the assumption that mitigation policies could lead to some unknown improvement of technologies that would not occur without mitigation, and that these technologies would reduce energy system costs in the long term.

The CO_2 reduction rate is also significantly affected by the target stabilization level, even assuming the same baseline scenario. Figure 7 summarizes the comparison of CO_2 reduction among different stabilization levels. The baseline is fixed to A1 because of the number of available Post-SRES scenarios for that baseline. The Figure shows a predictable relationship that CO_2 reduction rates

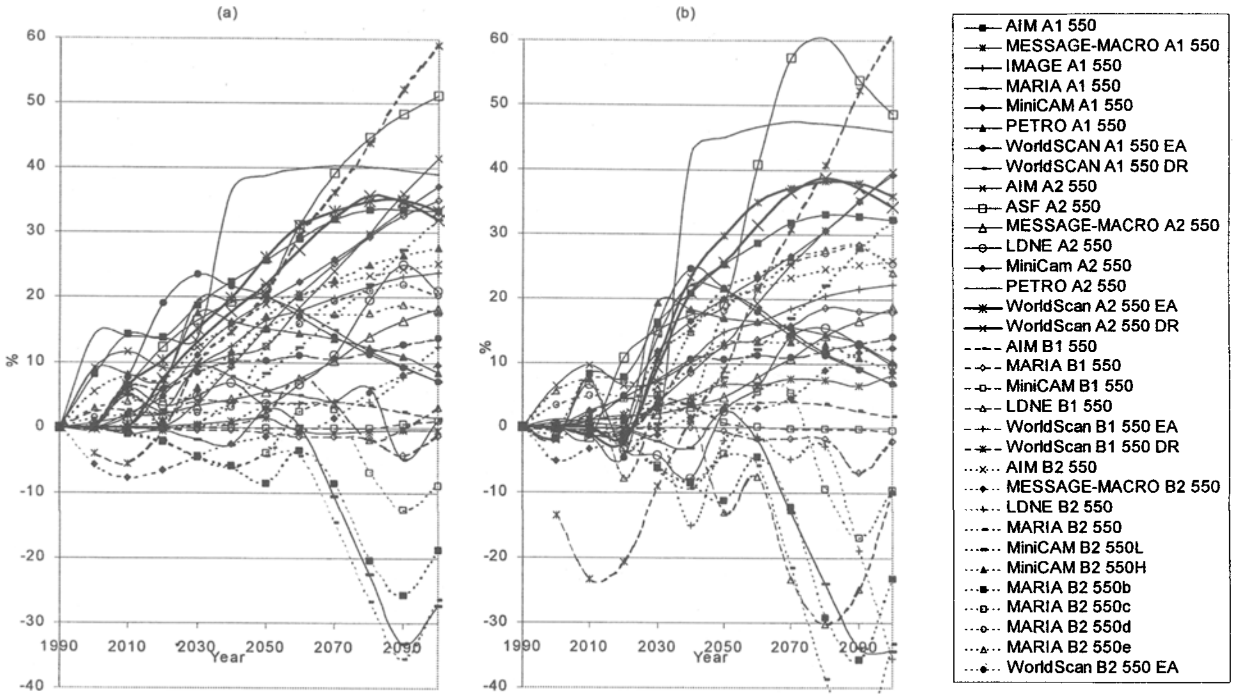


Fig. 5a,b. Reduction rates of primary energy from all SRES baselines for 550ppm stabilization, **a** global, **b** non-annex 1

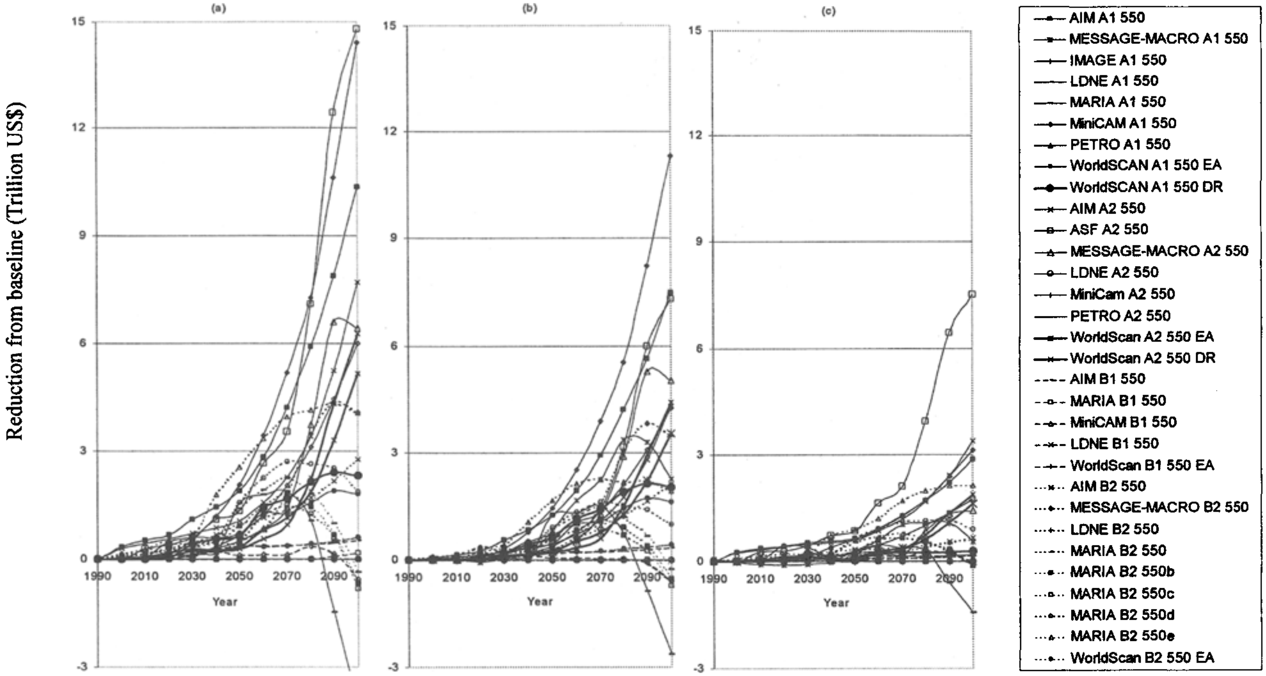


Fig. 6a–c. GDP losses from all SRES baselines for 550ppm stabilization, **a** global, **b** non-annex 1, **c** annex 1

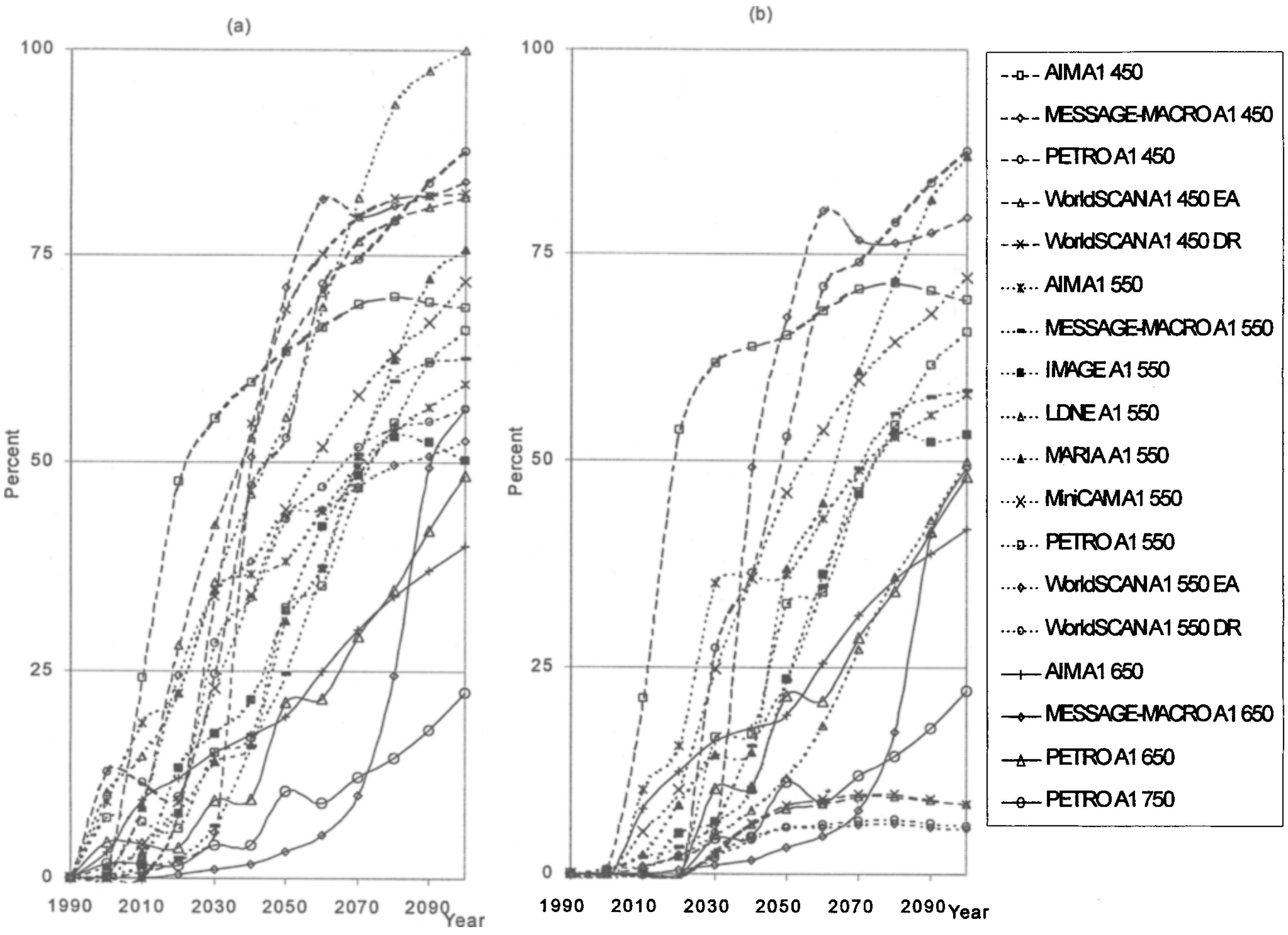


Fig. 7a,b. Reduction rates of CO_2 emissions from A1 SRES baseline for all stabilization levels, **a** global, **b** non-annex 1 are higher, in order, for the 450ppm stabilization case, the 550ppm, and the 650ppm case. In the 450ppm stabilization case, the reduction rate reaches to 70% to 100% of A1 baseline by the end of the 21st century. Even the 660ppm stabilization target requires a 40% to 60% reduction from the baseline at the same point. The economic loss for 450ppm stabilization would be around three times of that for 550ppm, and six to eight times of 650ppm case. These relationships can be observed both at global and regional levels.

The different stabilization target also leads different timing and speed to introduce reduction policies. As shown in Fig. 7, the 450ppm stabilization case requires strong emission reduction at an earlier time than the 650ppm case. Very rapid increases in emission reduction over a 20 to 30 year period are also observed in the 450ppm stabilization case.

The differences in reductions in overall energy consumption are more complicated among the models, because the reduction levels are dependent on the level of baseline CO_2 trajectory, the introduction of carbon-free or low-carbon energy, and the assumed carbon sequestration technologies. Furthermore, the regional aggregation determines the path of energy consumption reductions at global level as well as at Annex I or non-Annex I level. For example, a “waving” path in energy consumption reduction is indicated by AIM, LDNE and MARIA since they allow a significant difference in energy consumption reductions among regions. However, it can be generally observed that each model estimates higher reduction of energy consumption, in order, for the 450ppm, 550ppm and 650ppm stabilization cases.

The analyses described above focus mainly on CO_2 emissions caused by energy consumption. Although it is also important to analyze non-energy related CO_2 emission as well as non-CO_2 emissions, this work remains to be done.

5 Comparison of technology/policy measures and assessment of robustness

In order to reduce CO_2 and other GHG emissions, each modeling team assumed specific technology/policy measures for their scenario quantification. Table 3 summarizes all the technology/policy measures focusing on energy sectors. This Table classified the measures into carbon taxes, energy efficiency improvement in conversion and end use sectors, introduction of energy supply technologies in renewable, nuclear, natural gases, syn-oil and syn-gas, as well as carbon sequestration. As shown in Table 3, assumed technology/policy options are different among models. These differences are strongly dependent on model structure. As MESSAGE-MACRO, LDNE and MARIA are dynamic-optimization type models considering supply-side detailed technologies, the technology/policy introductions are easily managed by providing a constraint on CO_2 emission or concentration, and then an optimal set of technology/policy measures focusing on supply-side energy are automatically selected in the model. AIM and IMAGE are recursive simulation-type models which integrate physical and land-use modules, and focus strongly on demand-side energy options. For these models, very detailed technology/policy measures were assumed for each region and time as exogenous scenarios. ASF, MiniCAM, PETRO and WorldScan are another type of integrated models focusing on energy system, and they simply introduced a carbon tax for Post-SRES analyses.

As indicated in their papers published in this Special Issue, most of the modeling teams concluded that the different SRES baseline worlds require different technology/policy measures. The A1 and A2 worlds require a wider range of technology/policy measures, which aremore strongly implemented, than B1 and B2. For example, energy efficiency improvements in all sectors, and the introduction of low-carbon energy, would both be required in the A1 and A2 worlds in the first half of the 21st century, with additional introduction of advanced technologies in renewable energy and other energy fields in the second half of the century. Even between A1 and A2, the carbon tax rate in A2 would be much higher than in A1. In an A1 or A2 world, much more severe mitigation measures would have to be introduced during the period 2000 to 2020 in order to avoid a drastic increase in the burden faced by the next generation. Developing countries would also be required to mitigate growth rate in GHG emissions at the beginning of the 21st century in the A1 or A2 worlds to achieve target stabilization levels.

The modeling teams also concluded that the particular stabilization level chosen also significantly affects the technology/policy measures needed. As might be expected, a wider range of technology/policy packages is required in climate policy for 450ppmv stabilization, as compared to the 550 or 650ppmv stabilization case (AIM). In fact, the PETRO model shows that the carbon tax rate approximately doubles for each 100ppmv decrease in the target level of stabilization.

It is also apparent from these analyses that no single measure will be sufficient to achieve stabilization. This means that the CO_2 problem cannot be easily settled by any single technological option considered here.

The papers in this Special Issue give us some divergent suggestions on the issue of the appropriate timing of policy. The AIM team concluded that early GHG reduction is essential for the A1 and A2 worldviews as well as for 450ppmv stabilization to avoid serious pressure on social development and technological progress in the second half of the 21st century. On the contrary, the LDNE team suggested that the optimal CO_2 emission trajectory indicates that relatively modest abatement actions are expected, especially in the near future, allowing global CO_2 emissions to continue to rise until around the middle of the 21st century. The WorldScan team suggested that the advantages of delayed response versus early action depend on the baseline and on the concentration level, once all regions participate. All modelers agreed, however, that the level of technology/policy measures in the beginning of the 21st century would be significantly affected by the choice of development path over next one hundred years. Most indicated that the period of greatest stress in meeting climate targets is the second quarter of the 21st century.

Perhaps the most exciting result from the Post-SRES program is the identification of "robust policy options" across the different worlds for climate

Table 3. Policy options used in Post-SRES stabilization scenarios

Model	Scenarios	Policy options				
		Carbon tax			Energy	
		Level	Annex 1 Start yr	Non-Annex 1 start yr	Conversion efficiency	End use efficiency
AIM	A1 450	$100–200/tC	2000	2030	Power gen.: 0.13% ↑	SEI: 0.3% ↑, +0.2% ↑ for DC 2030–50.
	A1 550	$50–200/tC	2000	2030	Power gen.: 0.13% ↑	SEI: 0.2% ↑, +0.1% ↑ for DC 2030–50. TEI: 0.14% ↑
	A1 650	$20/tC	2000	2030	Power gen.: 0.11% ↑	SEI: 0.1% ↑, +0.1% ↑ for DC 2030–50. TEI: 0.1% ↑
	A2 550	$80/tC	2000	2000	Power gen.: 0.15% ↑	SEI: 0.2% ↑, +0.1% ↑ for DC 2030–50. TEI: 0.14% ↑
	B1 550	$30–80/tC	2000	2030	Power gen.: 0.1% ↑	TEI: 0.14% ↑, OEI: 0.1% ↑
	B2 550	$60/tC	2000	2000	Power gen. eff.: 0.1% ↑	SEI: 0.2% ↑, +0.2% ↑ for DC 2030–75. TEI: 0.1% ↑, OEI: 0.15% ↑.
ASF	A2 550, A2 750	Specific estimate	2005	2015		
IMAGE	A1 550	Applied on secondary fuels for non-electric purposes and for utilities			High-eff. gas-based electric power options e.g., STAG-units & cogen.	Government subsidies; assuming longer acceptable payback times for energy savings investments
LDNE	A1 550 A2 550, B1 550, B2 550	Shadow price			Price-induced demand ↓	Price-induced demand ↓
MARIA	A1B 550	$70.0/tC in 2020; $248.3/tC in 2050 $823.6/tC in 2100			Middle	Middle
	B1 550	$45.5/tC in 2020; $99.8/tC in 2050; $308.8/tC in 2100			High	High
	B2 450	$356.9/tC in 2020; $936.0/tC in 2050 $746.2/tC in 2100			Low	Low
	B2 550	$86.5/tC in 2020; $228.3/tC in 2050; $642.6/tC in 2100			Low	Low
	B2 650	$54.2/tC in 2020; $114.7/tC in 2050; $226.5/tC in 2100			Low	Low

Policy options					
Energy					Carbon sequestration/ absorption
Renewable	Nuclear	Nat. gas	Syn-oil	Syn-gas	
	0.2% ↑				
Biomass: 0.1% ↑					
√					
Biomass: 0.2% ↑	0.5% ↑	0.4 ↑	0.15% ↑	0.16% ↑	
0.1% ↑	0.1% ↑		0.1% ↑	0.1% ↑	
Biomass: 0.2% ↑ Solar: 0.1% ↑.	0.2% ↑	0.2 ↑	0.15% ↑	0.16% ↑	
Forced introduction of non-fossil supply options					CO$_2$-removal and storage in fossil-fuelled power gen. plants
PV, hydropower, geothermal power, wind power, Biomass (forest) Solar, wind power gen.	LWR Nuc. fusion tech.	Available from hydrocarbon resources including biomass			CO$_2$ separation (2 methods), CO$_2$ disposal (4 methods),
Potential cropland ↑, Land use management ↑	Nuc. fuel recycling	Main role by 2050			Carbon sequestration
Potential cropland ↑, Land use management ↑		Biomass and nuc. are mainly used; not so high			
Potential cropland ↓, Land use management middle					
Potential cropland ↓, Land use management middle					
Lower potential cropland, Land use management middle					

Table 3. *Continued*

Model	Scenarios	Policy options				
		Carbon tax			Energy	
		Level	Annex 1 Start yr	Non-Annex 1 start yr	Conversion efficiency	End use efficiency
MESSAGE-MACRO	A1 450 A1 550 A1 650	Shadow price				√
	A2 550 A2 750	Shadow price			Global demand ↓ 14% Global demand ↓ 12%	√
	B2 550	Shadow price			Global demand ↓ 9%	√
MiniCAM	All	Price induced demand ↓			Adv. power gen. tech.	Higher efficiency
PETRO	A1 550	$65/tC	1995	2025		
	A1 650	$41/tC	1995	2025		
	A1 750	$27/tC	1995	2025		
	A2 550	$81/tC	1995	2035		
	A2 650	$27/tC	1995	2035		
WORLD SCAN	A1 450 EA(DR)	$475 (500)/tC	1995	2025 (2035)	(Note) Average annual growth rate of carbon tax 2040–2100 is as follows: 3.5 (3.2)%	
	A1 550	$90 (115)/tC	1995	2025 (2035)	2.5 (3.5)%	
	A2 450	$950/tC	1995	2025	3.2%	
	A2 550	$425 (550)/tC	1995	2025 (2035)	4.4 (5.3)%	
	B1 450 EA	$90 (95)/tC	1995	2025 (2035)	0.2 (0.1)%	
	B1 550 DR	$0 (0)/tC	1995	2025 (2035)	3.7 (3.3)%	
	B2 450 EA	$225 (240)/tC	1995	2025 (2035)	2.3 (2.7)%	
	B2 550 EA	$60/tC	1995	2025 (2035)	1.6%	

SEI, social efficiency improvement; TEI, transport efficiency improvement; OEI, other end-use technology efficiency improvement; ↑ Higher than baseline; ↓ Reduction/Lower; + Additional; DC, developing countries; √ Included; EA, early action; DR, delayed response

stabilization. Each modeling team found several robust options based on their simulations. The following list summarizes some of the findings of specific analyses:

(a) Technological efficiency improvements for both energy use technology and energy supply technology, social efficiency improvements, renewable energy incentives, and the introduction of energy price incentives such as a carbon tax can be regarded as robust policies (AIM)

(b) Robust options across the SRES worlds are natural gas and promoting biomass resources (MARIA)

Policy options					
Energy					Carbon sequestration/ absorption
Renewable	Nuclear	Nat. gas	Syn-oil	Syn-gas	
CO_2 scrubbing and removal 860, 460, and 170 GtC cum. 1990–2100 respectively					
CO_2 scrubbing and removal 73 and 26 GtC cum. 1990–2100					
CO_2 scrubbing and removal 3 GtC in 2100	Nuc. power gen.				CO_2 scrubbing technology
New renewable technology		Enhanced prod.			

(c) Innovative "transitional" strategies of using natural gas as a "bridge" toward a carbon-free hydrogen economy (including CO_2 sequestration) are at a premium in a possible future world with low emissions (MESSAGE-MACRO)

(d) In all mitigation scenarios, gas combined-cycle technology bridges the transition to more advanced fossil and zero-carbon technologies (MESSAGE-MACRO)

(e) The future electricity sector is not dominated by any single dominant technology; however, hydrogen fuel cells are the most robust technology among all stabilization cases (MESSAGE-MACRO)

(f) Climatic stabilization requires the introduction of natural gas and biomass energy in the first half of the 21st century, and either plutonium recycling or carbon sequestration in the latter half of the century as the cost effective pathways (MARIA)

(g) Carbon sequestration has a role to play in this scenario, especially for the moderate targets (MiniCAM)

(h) It would be reasonable to start with energy conservation and reforestation to cope with global warming. However, innovative supply-side technologies will be required eventually to achieve the stabilization of atmospheric CO_2 concentration (LDNE)

(i) Even in a sustainable world there are very difficult decisions to be made and these may well imply the need to really significantly further redirect the energy system (MiniCAM)

(j) Energy systems would still be dependent on fossil fuels over the next century, even with the regulation of CO_2 concentration (LDNE)

These conclusion were reached not only by the single teams listed above, but also similarly by other modeling teams.

The Post-SRES analyses supplied several other suggestive findings from individual model simulations: The AIM team found that technological progress plays a very important role in stabilization, and that knowledge transfer to developing countries is a key issue in facilitating developing countries' participation in early CO_2 emission reduction. From the viewpoint of policy integration, the AIM team found that integration between climatic policies and domestic policies could effectively reduce GHGs in developing regions from their baselines for the next two or three decades. On the other hand, the MESSAGE-MACRO team estimated that controls of sulfur emissions could amplify possible climate change in the medium-term perspective. Therefore, tradeoffs are likely to persist for environmental policies throughout the 21st century. The MiniCAM team concluded that agriculture and land use and the energy system controls need to be linked, and that failure to do this can lead to much larger than necessary costs.

6 Concluding remarks

The major findings of the Post-SRES program can be summarized in brief as follows: First, different development paths require different technology/policy measures and show different costs of mitigation to stabilize atmospheric CO_2 concentrations at the same level. Second, no single type of measure will be sufficient for the timely development, adoption and diffusion of mitigation options for CO_2 stabilization. Rather, a portfolio based on technological change, economic incentives, and institutional frameworks should be adopted. Therefore third, policy integration across an array of technologies, sectors and regions is the key to the successful promotion of climate policies. Fourth, the level of technology/policy measures in the beginning of the 21st century will be significantly affected by the choice of development path over next one hundred years.

And finally, several "robust policy options" across the different worlds are identified for stabilization. Large and continuous energy efficiency improvements and afforestation are common features of mitigation scenarios in all the different SRES worlds. Introduction of low-carbon energy is also a common feature of all scenarios, especially biomass energy introduction over the next one hundred years as well as natural gas introduction in the first half of the 21st century. In an A1 or A2 world, either nuclear or carbon sequestration would become increasingly important for GHG concentration stabilization. Furthermore, other robust technologies, such as gas combined-cycle technology and hydrogen fuel cells, have to be considered for future innovations.

The Post-SRES process is only a starting point for systematic studies on the relationships between development path and climatic policy/technology measures. Much work still remain to be done. First, mitigation scenarios in developing countries, as well as burden sharing with regard to emission reduction between North and South, should be examined in relation to the choice of future development paths. Second, mitigation scenarios for non-energy and non-CO_2 gases should be quantified based on the SRES baselines. Third, the relative costs of different mitigation scenarios have to be estimated using common definitions among modeling teams for the precise comparison. Fourth, more technology/policy options, such as dematerialization and land use management, should be analyzed for climate stabilization. And fifth, the feasibility and/or applicability of various technology/policy options have to be examined in a more systematic way with relation to the socio-political assumptions underlying the different SRES baseline worlds. For example, the future development path will clearly heavily influence or even determine some aspects of future social structures, and, in turn, these social structures will influence or determine whether the technology/policy options would be accepted or rejected. There is much work to be done in addressing these more qualitative issues. In this connection, the SRES approach of combining narrative storylines and model quantifications points the way to some new and exciting possibilities.

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