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Scenarios of long-term socio-economic and environmental development under climate stabilization

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Abstract

This paper presents an overview of the greenhouse gas (GHG) emissions scenarios that form the analytical backbone for other contributions to this Special Issue. We first describe the motivation behind this scenario exercise and introduce the main scenario features and characteristics, in both qualitative and quantitative terms. Altogether, we analyze three 'baseline' scenarios of different socio-economic and technological developments that are assumed not to include any explicit climate policies. We then impose a range of climate stabilization targets on these baseline scenarios and analyze in detail the feasibility, costs and uncertainties of meeting a range of different climate stabilization targets in accordance with Article 2 of the United Nations Framework Convention on Climate Change. The scenarios were developed by the IIASA Integrated Assessment Modeling Framework that encompasses detailed representations of the principal GHG-emitting sectors—energy, industry, agriculture, and forestry. The main analytical findings from our analysis focus on the implications of salient uncertainties (associated with scenario baselines and stabilization targets), on feasibility and costs of climate stabilization efforts, and on the choice of appropriate portfolios of emissions abatement measures. We further analyze individual technological options with regards to their aggregated cumulative contribution toward emissions mitigation during the 21st century as well as their deployment over time. Our results illustrate that the energy sector will remain by far the largest source of GHG emissions and hence remain the prime target of emissions reduction. Ultimately, this may lead to a complete restructuring of the global energy system. Climate mitigation could also significantly change the relative economics of traditional versus new, more climate friendly products and services. This is especially the case within the energy system, which accounts for the largest share of emissions reductions, but it is also the case

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in the agriculture and forestry sectors, where emissions reduction and sink enhancement measures are relatively more modest.

1. Introduction

Svante Arrhenius published his seminal classic *On the Influence of Carbonic Acid in the Air upon the Temperature on the Ground* [1] more than 100 years ago in 1896. This first, and today still surprisingly accurate, scientific quantification of the temperature effects of rising CO_2 concentrations included a sensitivity analysis to explore the effects of rising CO_2 concentrations by a factor between one to three above the then prevailing level of some 300 parts per million by volume (ppmv). While noting that the burning of some 500 million tons of coal was the anthropogenic source equivalent of a natural CO_2 sink in the form of rock weathering, the likelihood of quickly reaching any of the levels of atmospheric CO_2 concentrations addressed in his calculations seemed rather slim from the perspective of the day.

Today's situation is fundamentally different. Atmospheric CO_2 concentrations have risen to some 380 ppmv. By simply extrapolating historical growth rates (which is widely considered bad practice not only in climate science) it becomes apparent that over the next 100 years we could approach those levels of CO_2 concentrations that were considered in Arrhenius' calculations of temperature effects. That is, we could enter a regime of significant alterations of the Earth's climate characterized by the proverbial 'doubling' of atmospheric CO_2 concentrations over pre-industrial times. Given the enormous changes over the past century and vast potential for further changes in the next, there is thus a deep interest to better understand the unfolding of future emissions paths. Such a look into the future is especially interesting because it can help:

- anticipate magnitudes of possible climate changes;
- assess economic, social, and ecological consequences of such changes;
- determine if and by how much undesirable consequences can be mitigated, either in better adapting to a changing climate or in avoiding unfolding climate change as much as possible (i.e., through emissions reduction).

The above considerations constitute the prime motivation for developing scenarios, that is stories and quantifications of how possible developments could unfold that can help in our desire to anticipate the potential consequences and to plan to mitigate this large-scale planetary geophysical 'experiment' that we are in the midst of performing.

Ironically, despite all the progress in science and technology since the time of Arrhenius, one challenge remains as large as it was 100 years ago: the need to consider a time scale of a century (or even longer), which is dictated by the twin inertias of the coupled socio-economic and climate systems. Given our current understanding of the carbon cycle, CO_2 emitted today will remain in the atmosphere many decades to come and altering future climate, whose legacy (e.g., in the form of thermal expansion of oceans and resulting sea level rise) might even take a millennium to fully unfold. Likewise, given the longevity of infrastructures and the capital stock of our energy system, many decades will pass before any initiated policy changes translate into a noticeable effect on emissions and hence avoidance of "dangerous interference in the climate system". This is the stated objective of the UN Framework Convention on

Climate Change [2], a convention ratified by most of the planet (much different to the ensuing Kyoto Protocol that only applies to industrialized countries and which the USA and Australia have refused to ratify).

The task ahead of anticipating the possible developments over a time frame as ‘ridiculously’ long as a century is wrought with difficulties. Particularly, readers of this Journal will have sympathy for the difficulties in trying to capture social and technological changes over such a long time frame. One wonders how Arrhenius' scenario of the world in 1996 would have looked, perhaps filled with just more of the same of his time—geopolitically, socially, and technologically. Would he have considered that 100 years later:

- backward and colonially exploited China would be in the process of surpassing the UK's economic output, eventually even that of all of Europe or the USA?
- the existence of a highly productive economy within a social welfare state in his home country Sweden would elevate the rural and urban poor to unimaginable levels of personal affluence, consumption, and free time?
- the complete obsolescence of the dominant technology cluster of the day-coal-fired steam engines?

How he would have factored in the possibility of the emergence of new technologies, especially in view of Lord Kelvin's sobering ‘conclusion’ of 1895 that “heavier-than-air flying machines are impossible”?

We do not know, as Arrhenius, perhaps wisely, refrained from a look into the future to check over which time horizon his model calculations could become a reality. However, we do know that, as at the time of Arrhenius, a perspective of 100 years represents such a challenge that traditional (deterministic) forecasting is impossible. Instead, our ability to anticipate, to imagine, and to describe the deep uncertainties that surround a 100 year future perspective is challenged, a challenge traditionally addressed through the development of alternative scenarios, or ranges of possible futures.

As a result, the development of long-term scenarios in conjunction with climate change science and policy analysis has both a distinguished tradition and has grown almost into an industry of its own. First reviews of the resulting scenario literature date back to the early 1980s [3] and have been repeated periodically ever since [4,5]. The latter review surveyed altogether more than 400 scenarios, which required the use of data base management tools to handle the large number of scenarios published in the literature. An update of that review for the forthcoming Fourth IPCC assessment report will include altogether over 700 scenarios [6].[1] A distinguishing feature of the literature on climate change scenarios (including the present study) is a customary distinction between ‘no controls’ or ‘baseline’ scenarios and so-called ‘intervention’ or climate policy scenarios that analyze various target levels in response to the stated UNFCC objective of “stabilizing greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” [2]. In other words, it has become customary to distinguish between two major types of uncertainties of the future:

- uncertainties in emission drivers (population, income, technology, diets, etc.) and their resulting emissions outcomes (magnitude of projected climate change uncertainty);

[1] An update of this earlier analysis is presented in Figs. 2 and 9 herein.

- uncertainty surrounding levels, commitment, and effectiveness of globally coordinated policy efforts to slow or halt global warming (often referred to as ‘target uncertainty’).

Readers should be aware that the two types of scenarios serve different purposes and are not always to be judged with the same qualitative yardstick typically applied to a scenario (reproducibility, plausibility, internal consistency, etc.). ‘Baseline’ scenarios can range in degree of complexity and logic from ‘blind’ trend extrapolation to sophisticated blends of qualitative and quantitative scenario ‘storylines’ that attempt to check for plausibility and internal consistency of the scenario(s) under consideration with the help of sophisticated models. Across this range they aim to ‘stand alone’ in providing a ‘narrative’, or a sequence of carefully crafted conditional ‘when if, then’ statements that, when quantified with formal models, lead to quantifications of different emission drivers, their interactions, and the resulting emissions outcomes. Conversely, ‘control’ (or ‘stabilization’) scenarios are more controlled model experiments based on (one is almost attempted to say ‘tacked on to’) given baseline scenarios for a range of climate stabilization targets. While these are technically feasible, they may not necessarily meet the same criteria of scenario plausibility and consistency as applied to the corresponding original ‘baseline’ scenarios.

The scenarios considered in this Special Issue are no exception to the above dichotomy in climate change scenarios. We also first proceed in developing and presenting a range of three ‘baseline’ scenarios aimed to elucidate the major salient uncertainties in drivers and the resulting emissions outcomes that a century-long perspective necessarily entails. These three scenarios are then used as input to a number of controlled model experiments (altogether 11 ‘stabilization scenarios’ are imposed on the three baseline scenarios). In these exogenously pre-specified climate stabilization targets (represented by their equivalent CO_2 concentration levels, or more precisely by various levels of stabilization of radiative forcing of all greenhouse gases (GHGs)) are examined from a multi-gas and multi-sector perspective. In other words, the customary, almost exclusive, focus on energy-related CO_2 emissions in both baseline and ‘policy’ scenarios is replaced here by a much wider analytical framework that covers all relevant GHGs and all major emitting sectors.

The scenarios presented here also do not emerge *ex nihilo*. Instead, they are derivatives of (a subset of) scenarios developed by the authors for the IPCC *Special Report on Emissions Scenarios* (SRES) [7] that were also used for a subsequent analysis of the feasibility of meeting a range of climate stabilization targets analyzed in the IPCC Third Assessment Report (TAR) [8] and within the model intercomparison research performed under the auspices of the Energy Modeling Forum (EMF) [9]. We have revised the original scenarios to reflect new information that has become available with the aim to improve also scenario consistency. The new scenarios were developed with the help of the integrated modeling and assessment framework presented in more detail below. One scenario (labeled as ‘revised SRES A2’ scenario or ‘A2r’), while maintaining its main structural and qualitative characteristics, represents a major numerical revision that reflects the most recent long-term demographic outlook with a corresponding lowering of future world population growth [10].

Next to numerical scenario revisions (particularly pronounced in the demographic and economic developments described in the A2r scenario, and to a much lesser extent also in the other two scenarios B1 and B2, are described in more detail elsewhere in this Special Issue [11]), a number of novel methodological features also characterize the scenarios presented here. Foremost, the scenarios encompass a multi-sector and multi-GHG perspective in which the integrated assessment paradigm is extended from the traditional focus on the energy sector to all other salient sectors (in particular agriculture and forestry) that emit GHGs or potentially contribute to climate change mitigation efforts through either emissions

reductions or enhancements of GHG sinks [12]. By a full coupling of the corresponding models that represent the energy, agriculture, and forestry sectors, we are not only able to account consistently for all GHGs and their respective mitigation potentials across the sectors,[2] but also account for important feedbacks and interdependencies (e.g., competition for land-use) between sectors. Likewise, impacts of climate change are also endogenously considered in the scenarios reported here, for example, in terms of changes in agricultural production and gross domestic product (GDP) [13] or in the corresponding changing water needs for agricultural production [14]. Finally, the scenarios also incorporate previously unexplored mitigation options, such as the use of biomass in conjunction with carbon sequestration and storage (CSS), that could result in an artificial 'sink' for anthropogenic CO_2 emissions, in addition to traditionally considered forest sinks.

The main objective of our scenario exercise is to *explore the feasibility and costs of meeting alternative climate stabilization targets under a range of salient long-term uncertainties* with a limited set of scenarios. To meet this objective we have developed two contrasting scenarios, A2r and B1, that aim to *bracket the upper and lower quadrants of emissions* and hence magnitudes of climate change and of the possible *vulnerability to climate change*, respectively. These two scenarios also form the backbone of the model linkages to integrate the energy, agriculture, and forestry sectors reported in this Special Issue. The more intermediary scenario B2 (with numerically minor revisions compared to its SRES variant) serves as a benchmark from which to compare the results presented here with those of earlier work, in particular that of the IPCC SRES and TAR reports, as well the earlier scenarios (in particular the scenario IIASA–WEC 'B') developed in collaboration between the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC) [5,11].

The use of the terms of 'upper quadrant' and 'lower quadrants' to position the scenarios reported here in comparison to the entire scenario literature is indicative only. The scenarios developed aim to be positioned above and below the 75th and 25th percentile, respectively, of the comparable scenario literature, but without all[3] their salient scenario parameters necessarily always falling within this indicative range. It is also important that the above quantitative yardstick produced from a statistical analysis of the frequency distribution of the published scenario literature is not confounded with the traditional concept of probability. Given the large number of variables and their interdependencies, we are of the opinion that it is impossible to assign objective likelihoods or probabilities to emissions scenarios. We have also not attempted to assign any *subjective* likelihoods to the scenarios either. The purpose of the scenarios presented in this Special Issue is, rather, to span the range of uncertainty without an assessment of likely, preferable, or desirable future developments. A subjective assessment

[2] In many multi-sector, multi-gas climate change scenarios these non-energy sector sources and mitigation measures are treated as exogenous scenario inputs. Conversely, in our scenarios we use a modeling framework that explicitly considers all sectors and their interdependencies in a consistent fashion. For instance, instead of using biomass energy potentials as exogenously given, we assess those in relation to agricultural production and land-use availability [14]. Similarly, the forest sector model considers both constraints from agricultural land availability and carbon prices as derived from the energy sector model calculations in its assessment of forestry mitigation and sink enhancement options, which are fed back to the energy sector model [12] in an iterative modeling process.

[3] Given the variable interdependence this would be a mathematical impossibility. A scenario in which all the salient input parameters would, for example, be positioned at the 90th percentile of the corresponding scenario literature not only would not yield a logical and plausible scenario, but also it would not fall on the 90th percentile of the resulting emissions.

Table 1
Taxonomy of scenarios

Uncertainty type	Factors affecting uncertainty	A2r	B2	B1
		Classification of scenarios: high (H), medium (M), low (L) relative to each other		
Emission(magnitude cumulative carbon)	Population size	H	M	L
	Income	L	M	H
	Resource use efficiency	L	M	H
	Technology dynamics, fossil	M	M	L
	Technology dynamics, non-fossil	L	M	H
	Emission	H	M	L
Vulnerability	Population size	H	M	L
	Urbanization	H	M	L
	Income	L	M	H
	Vulnerability	H	M	L
Target (for stabilization)	Exogeneous input			
	Scale of required reduction	H	M	L

of scenario likelihoods goes well beyond the scope of this paper and those presented in this Special Issue. Likelihoods or probabilities are therefore not assigned to any of the scenarios reported here, which does not mean that we consider all the scenarios equally likely. Indeed, we do *not* consider the three scenarios reported here equally likely, but simply cannot offer any scientifically rigorous way to differentiate the likelihoods across the scenarios and therefore refrain from any necessarily arbitrary, subjective ranking.

Table 1 summarizes the positioning of the three scenarios with respect to the most important uncertainties examined in this study. These include, in particular:

- *Development pathway uncertainty*, which includes alternative demographic, economic, and technological developments that lead to high (A2r), intermediary (B2), or low (B1) emissions of GHGs and hence magnitude of future climate change. A more detailed discussion of the scenario's that underlie the demographic and economic trends at alternative spatial scales (regional, national, and grid-cell level) is given elsewhere in this Special Issue [11].
- *Climate impacts vulnerability uncertainty*, the multiple dimensions of which include, in particular, 'soft' institutional and technological variables, is treated here in a simplified manner framed by the variables population density, population concentration, and per capita income, which exercise amplifying and dampening effects on climate vulnerability.[4] Vulnerability ranges from high (A2r),

[4] To illustrate the concept of climate vulnerability, consider the impacts of Katrina on New Orleans. Impacts were a function of magnitude of the event (Katrina), location (areas of New Orleans located below sea level), and socio-economic variables that define risk exposure. These are population density and concentration (New Orleans being a city, as opposed to other low population density coastal areas also affected by Katrina) and income per head, with poor residents of the city being particularly vulnerable.

through intermediary (B2), to low (B1) in the scenarios presented here. Discussions of the impacts and vulnerability that focuses on the implications of the scenarios for the agriculture sector, people at risk and irrigation needs induced by climate change are given elsewhere in this Special Issue [13,14].

- *Climate stabilization target uncertainty*, as mentioned above, is addressed by systematic model simulations for a range of alternative climate stabilization targets imposed on the no-policy baseline scenarios. Altogether, we performed calculations for 11 stabilization scenarios for eight comparable stabilization levels that ranged from 480 to 1390 ppmv (CO_2-equivalent concentration for all GHGs taken together) by 2100. The number of stabilization scenarios analyzed is highest (five) for the high emissions scenario A2r, followed by scenario B1 (four stabilization levels analyzed) and scenario B2 (two stabilization levels). The higher the baseline emissions, such as in scenario A2r, the higher, therefore, is the range of stabilization targets and resulting emissions reduction needs (and costs) examined to fully represent target uncertainties (see Table 4 below).[5,6] Finally, the lower bound of the stabilization targets analyzed is also a function of the scenario baseline emissions—with higher baseline emissions the lowest stabilization targets achievable are also higher compared to the scenarios with lower baseline emissions.[7]

For reasons of scenario parsimony, our set of three scenarios does not include a scenario that combines high emissions (and hence high climate change) with low vulnerability (e.g., as reflected in high per capita incomes). These were the characteristics of the scenarios within the A1 scenario family in the SRES report [7,8], which also explored the impacts of alternative directions of technological change on future emission levels. This group of scenarios, while of considerable interest, especially for technology uncertainty analysis, is not analyzed further here.

In addition to addressing the uncertainties summarized above, the scenarios also have an additional methodological purpose. They serve as an integrative tool to link a variety of sectorial models (energy, agriculture, and forestry) under continued development at IIASA, and so help to quantify interlinkages and feedbacks between various sectors that are at the core of comprehensive (multi-gas) climate stabilization efforts. The scenarios also help to put additional sensitivity and uncertainty analyses performed within sectorial models into perspective. Therefore, all articles in this Special Issue make use of comparable common scenarios in their analysis. The significance of this feature can only be fully appreciated when we consider that the climate policy analysis literature

[5] In our model simulations, stabilization below some 500 ppmv CO_2 only (670 ppmv CO_2-equivalent concentration considering all GHGs) in the A2r scenario was technically not feasible with the range of scenario assumptions deemed congruent with the A2r scenario storyline.

[6] For B2 we examined a limited set of two stabilization targets below 500 ppmv CO_2-equivalent only, based on Rao and Riahi [9].

[7] For instance, in terms of radiative forcing (by 2100) the highest emissions scenario A2r results in an estimated 9.3 W/m^2, and the lowest stabilization level analyzed is 4.5 W/m^2, which gives a range of radiative forcing difference between A2r scenarios of 4.8 (9.3–4.5) W/m^2. For the intermediary scenario B2, the baseline radiative forcing is 6.6 and the lowest stabilization level is 3.2, so the B2 scenario radiative forcing range is 3.4 W/m^2. For B1, the baseline radiative forcing is 5.5 and lowest stabilization level 2.8, so the B1 scenario range for radiative forcing change is 2.7 W/m^2.

has, to date, been 'plagued' by significant problems of incomparability of results because different models and analyses continue to use widely different projections and scenarios as their analytical basis.

2. An overview of scenarios

This section provides a quantitative overview of the scenarios that underlie the articles of this Special Issue. Before, however, proceeding to the customary presentation of numerous input assumptions and their resulting outcomes in terms of GHG emissions and climate consequences, it might be useful to provide some context in the form of qualitative scenario 'narratives' or 'storylines' (*Box 1*). Indeed, the blending of both qualitative and quantitative scenario characteristics is a comparatively recent methodological improvement in the scenario literature (most prominently developed for the SRES scenario exercise on which we draw heavily here). To date, this literature has been characterized by the (largely separated) co-existence of qualitative scenario 'narratives' with quantitative model-based 'number crunching' scenario descriptions (for a review of these two scenario streams see [7]).

2.1. Scenario 'storylines'

Readers should exercise their own judgment on the plausibility of above scenario 'storylines' (Box 1) that contain, particularly in the two more extreme scenarios A2r and B1, a number of normative scenario elements. However, the plausibility of these scenarios also needs to be put in context with the objectives of the scenario exercise reported here, namely to explore the possible developments that could result in either high or low emission futures. From this perspective, scenario B1 might look at first glance very normative ('desirable' under the sustainable development paradigm, and definitively less 'desirable' in terms of a perpetuation of the current geopolitical and economic status quo) with its paradigmatic theme of (conditional) convergence. However, it needs to be assessed in terms of its plausibility not as a 'business as usual' scenario (which it is definitively not), but rather as a plausible narrative of how a low emissions future could unfold even in the absence of vigorous, dedicated climate policies. From this perspective, the scenario aims to illustrate a plausible 'best case' within the context of both the magnitude of future climate change (low emissions) and the (low) vulnerability to climate change (as, for instance, represented in its high per capita income projections). We feel this is highly important in a comprehensive assessment of the uncertainties that surround climate change.

In this approach, while we certainly do not consider the B1 scenario 'likely' in view of current trends, we claim that it is perhaps the most likely scenario to yield both low emissions and low vulnerability to climate change in a comprehensive assessment of uncertainties. Thus, even if challenging, we maintain the legitimacy of the 'convergence' theme that underlies the B1 scenario as a 'best case' scenario for climate policy assessment. We also maintain that the scenario, while being 'extreme' in the unfolding of existing trends, is not counterfactual (hence not implausible) with respect to historical experience, economic theory and the evidence put forward by the economic convergence literature once inherent data, measurement, and modeling uncertainties are taken into account.

Box 1

Scenario storylines

Italics are quotations from the original SRES storylines as presented in the SRES Summary for Policy Makers (SPM) [7].

A2 (A2r)

The A2 storyline describes a very heterogeneous world. Fertility patterns across regions converge only slowly, which results in continuously increasing global population. The resulting 'high population growth' scenario adopted here is with 12 billion by 2100, lower than the original 'high population' SRES scenario A2 (15 billion). This reflects the most recent consensus of demographic projections toward lower future population levels as a result of a more rapid recent decline in the fertility levels of developing countries. As in the A2 scenario, fertility patterns in our A2r scenario initially diverge as a result of an assumed delay in the demographic transition from high to low fertility levels in many developing countries. This delay could result both from a reorientation to traditional family values in the light of disappointed modernization expectations in this world of 'fragmented regions' and from economic pressures caused by low income per capita, in which large family size provides the only way of economic sustenance on the farm as well as in the city. Only after an initial period of delay (to 2030) are fertility levels assumed to converge slowly, but they show persistent patterns of heterogeneity from high (some developing regions, such as Africa) to low (such as in Europe). *Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other* [scenarios]. Per capita GDP growth in our A2r scenario mirrors the theme of a 'delayed fertility transition' in terms that potentials for economic catch-up only become available once the demographic transition is re-assumed and a 'demographic window of opportunity' (favorable dependency ratios) opens (i.e., post-2030). As a result, in this scenario, 'the poor stay poor' (at least initially) and per capita income growth is the lowest among the scenarios explored and converges only extremely slowly, both internationally and regionally. The combination of high population with limited per capita income growth yields large internal and international migratory pressures for the poor who seek economic opportunities. Given the regionally fragmented characteristic of the A2 world, it is assumed that international migration is tightly controlled through cultural, legal, and economic barriers. Therefore, migratory pressures are primarily expressed through internal migration into cities. Consequently, this scenario assumes the highest levels of urbanization rates and largest income disparities, both within cities (e.g., between affluent districts and destitute 'favelas') and between urban and rural areas. Given the persistent heterogeneity in income levels and the large pressures to supply enough materials, energy, and food for a rapidly growing population, supply structures and prices of both commodities and services remain different across and within regions. This reflects differences in resource endowments, productivities, and regulatory

priorities (e.g., for energy and food security). The more limited rates of technological change that result from the slower rates of both productivity and economic growth (reducing R&D as well as capital turnover rates) translates into lower improvements in resource efficiency across all sectors. This leads to high energy, food, and natural resources demands, and a corresponding expansion of agricultural lands and deforestation. The fragmented geopolitical nature of the scenario also results in a significant bottleneck for technology spillover effects and the international diffusion of advanced technologies. Energy supply is increasingly focused on low grade, regionally available resources (i.e., primarily coal), with post-fossil technologies (e.g., nuclear) only introduced in regions poorly endowed with resources. The resulting energy use and emissions are consequently highest among the scenarios with carbon emissions that approach 20 Gt by 2050 and close to 30 Gt by 2100 (compared to 8 Gt in 2000).

B1

The B1 storyline … describes a convergent world with [a low global population growth] *that peaks in mid-century and declines thereafter* [to some 7 billion by 2100], *but with rapid changes in economic structures towards a service and information economy, with 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* …. Given that the latest demographic projections confirm a level of 7 billion by 2100 as a qualified lower bound of the uncertainty of future population growth, we retain the original SRES population scenario here. Fertility levels are converging toward sub-replacement levels, which leads to a decline in global population in the second half of the 21st century. However, regional differences in fertility patterns are not assumed to disappear entirely in this scenario. The theme of converging demographic patterns is also mirrored in the economic growth outlook of the scenario, for which the core characteristic is one of a conditional convergence to the prevailing economic productivity frontier. Hence, it is assumed that per capita GDP growth is the highest of the scenarios analyzed. Also, incomes are assumed to converge both internationally and domestically given a favorable institutional environment domestically (e.g., stable institutional and efficient regulatory settings) as well as internationally (international development cooperation, and free flow of knowledge and technologies, enhanced by dedicated transfer mechanisms). The concept of *conditional convergence* is key in this scenario. As economic growth increasingly accrues from service and information-intensive activities, traditional industrial and locational comparative advantages are reduced and high human capital (education) moves to the forefront providing a 'level playing field' for initially poorly endowed regions to catch up to the productivity frontier. Per capita incomes are thus converging, but only conditionally as the result of investments into human capital and a general trend toward pushing the productivity frontier to ever-higher service- and information-intensive economic activities, assumed extant in this scenario. Distributive policies, both domestically and

internationally (along the European Union (EU) regional cohesion fund model), also play a major role. As a result, the scenario assumes policy-driven comparatively high convergence rates in per capita income differences, both internationally and domestically. This ultimately blurs the traditional distinction between urban wealth and rural poverty and leads to a substantial reduction in economic incentives for rural-to-urban migration (and hence the lowest urbanization rates in the scenarios analyzed). While developing regions thus may reach, even surpass, *current* productivity (and income) levels of the most advanced regions, their growth nonetheless still remains conditional on the growth rate of the overall productivity frontier and thus on the absolute productivity (and income) levels achieved in the leading regions. Hence, international differences in productivity levels also prevail in this scenario, even if at much lower levels than in the other scenarios explored. No systematic 'economic overtake' is assumed in the scenario. The emphasis on information-intensive and 'dematerialization of' economic growth also implies that, given an assumed continued development of modern communication infrastructures (such as the Internet), the importance of 'space' (locational advantages, especially of urban agglomerations) diminishes significantly. 'Distance' no longer necessarily acts as a defining characteristic of economic transaction costs, access to knowledge, and availability of technology. Combined with the assumed global availability of clean and high-efficiency production technologies for food, raw materials, energy, and manufacturing, differences in resource and environmental productivities are reduced significantly, which leads to comparatively low levels of GHG emissions even in the absence of dedicated climate policies. Carbon emissions, for instance, peak at some 10 Gt by 2050 to fall below current levels thereafter (5 Gt by 2100), with the progressive international diffusion of rapidly improving post-fossil technologies.

B2

The B2 storyline … describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing population at a rate lower than in A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 … storyline. By design, the B2 scenario is an intermediary scenario, characterized by 'dynamics as usual' rates of change, inspired by historical analogies where appropriate (e.g., shifts in food preferences), but also departing from historical contingencies (e.g., growth in information technology and communication (ITC) activities and other technologies). World population growth is assumed to reach some 10 billion by 2100, based on the United Nations (UN) central projection that underlies the original SRES scenario and is also retained here. The UN scenario assumes strong convergence in fertility levels toward replacement levels, ultimately yielding a stabilization of world population levels. Like total population size, urbanization rates in this scenario are assumed to be intermediary as well, bridging the more extreme scenarios A2r (high) and B1 (low). The economic growth outlook in B2 is regionally more heterogeneous, with per capita income growth and convergence assumed to be intermediary between

the two more extreme scenarios A2r and B1. This largely reflects 20th century historical experiences, without assuming large discontinuities, such as economic decline or 'lost decades' of economic development for any particular region. It is assumed that the dynamics of income growth are tightly correlated with rates of social modernization, as reflected, for instance, in the dynamics of the demographic transition. In low-income regions where this transition has progressed further and more dynamically, per capita productivity (income) growth is also assumed to be higher (e.g., China). In lagging regions (e.g., Africa), it is assumed that economic catch-up is delayed until the demographic transition accelerates. Peaks of per capita income growth are therefore assumed to coincide with the fertility transition metric (second derivative of population growth). Given a more modest technology outlook, resource endowments and differences in income levels result in only slowly converging differences between domestic and international demands, productivities, and prices. For instance, regions endowed with large energy resources (such as the Middle East) would experience continued low energy prices and thus more lavish energy-use patterns compared to import-dependent regions such as Japan or Western Europe. These would continue to push the energy productivity frontier along their historical 'high efficiency' trajectory. The resulting food, energy, and resource demands and corresponding GHG emissions are consequently also intermediary between the two more extreme scenarios A2r and B1. Global carbon emissions, for instance, could rise initially along historical rates (to some 13 Gt by 2050), but growth would eventually slow down (14 Gt by 2100) as progressively more regions shift away from their reliance on fossil fuels, a twin result of technological progress in alternatives and increasing scarcity of easy-access fossil resources.

2.2. Scenario quantifications

2.2.1. Demographic and economic development

A distinguishing feature of the scenarios reported here is that they consider demographic and economic development not as autonomous processes, but instead as (partly) interlinked. These linkages, however, do not operate in a deterministic or one-directional sense, such that, for example, a given rate of demographic transition and its resulting demographic opportunity window[8] would automatically translate into a particular rate and pattern of economic growth, or vice versa. Instead, these linkages operate at a conditional level, that is, are subject to variations in accordance with a given scenario feature as described in its respective 'storyline'. Scenarios B1 and A2r describe the more extreme manifestations of the demographic–economic development nexus, whereas scenario B2 displays less pronounced linkages. In B1, a rapid demographic transition from high to low fertility leads to a low total population projection. This combined with the assumed high levels of education and free access to knowledge, capital, and technology enables especially developing countries to make full use of their demographic opportunity

[8] A period characterized by low dependency ratios, that is a high ratio of (potentially) economically active population (typically in the age group 15–65 years) to non-active population (younger and older age groups outside the range 15–65 years).

Table 2
Scenario baselines: population and GDP

		Population, million			GDP (mer) billion $(1990)		
		North	South	World	North	South	World
1990		1271	3990	5262	17437	3430	20866
	A2r	1430	6384	7814	32512	13258	45770
2020	B1	1440	6177	7617	34124	18017	52140
	B2	1404	6268	7672	31420	17981	49401
	A2r	1536	8708	10245	52422	47703	100125
2050	B1	1504	7200	8704	56074	79569	135644
	B2	1370	7997	9367	46227	63153	109380
	A2r	1663	10724	12386	84971	104256	189227
2100	B1	1448	5608	7056	100418	227932	328350
	B2	1316	9105	10421	75698	163494	239192

window. Rates of economic growth accelerate with the progress of demographic transition and are assumed to peak at the demographic opportunity window (maximum of the second derivative of population growth). In turn, accelerated rates of modernization, as reflected in economic development catch-up, also feed back into demographic development, which maintains the rapid mortality and fertility transitions characteristic of the B1 scenario. Conversely, scenario A2r, with its delayed demographic transition, intends to illustrate the 'downside' of the demographic–economic development linkages explored in the scenarios. The assumed delayed demographic transition in A2r not only leads to a high population projection, but also to a delay in the potential to fully use the demographic opportunity window for development catch-up. This combined with the more fragmented geopolitical outlook that limits free access to knowledge and technology, the corresponding economic growth rates are much lower in an A2r world, which results initially in an even further divergence of income differences between the 'North' and 'South'.

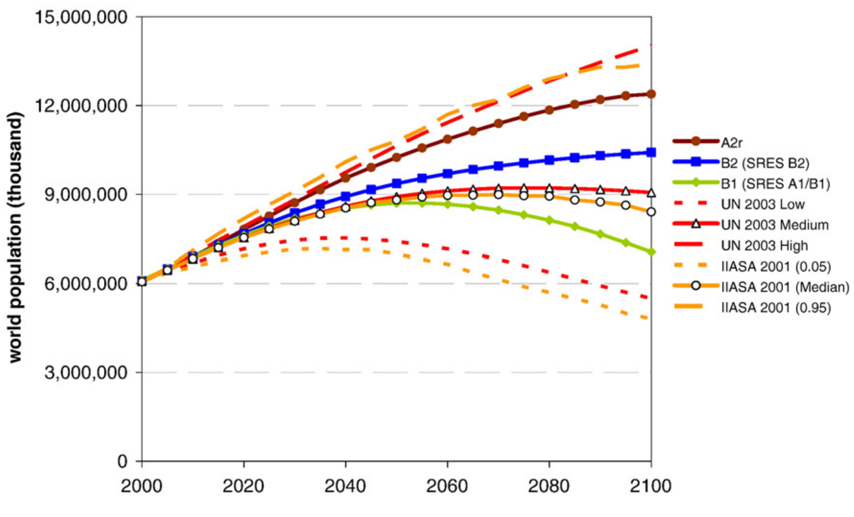

Fig. 1. World population: scenarios presented here in comparison to the recent demographic literature.

In terms of adopting numerical scenario values (summarized in Table 2), we analyzed in detail the corresponding scenario literature [6], updating earlier analyses [7]. For population, we retained the original SRES low (B1) and medium (B2) scenarios, as they are in good agreement with the most recent demographic projections from the UN [15] and IIASA [16,17]. Global population grows from some 6 billion in 2000 to some 9 billion by 2050 (8.7 and 9.3 billion in B1 and B2, respectively) and to between 7 (B1) and 10.4 (B2) billion by 2100. The original SRES A2 scenario, with its projected population of some 15 billion by 2100, appears high in comparison with most recent projections that have generally shifted levels of future population downwards[9] (for a review see [17]). Therefore in our revised A2r scenario we use a modified IIASA projection for the 'high population' growth quantification. The scenario is characterized by an assumed delay in the demographic transition of some two to three decades, which leads to a world population of some 10 billion by 2050 and 12.4 billion by 2100. A comparison of the world population scenarios reported here with the original SRES study and the most recent population projections from IIASA and the UN is shown in Fig. 1.

In terms of economic growth, all the scenarios describe a world becoming more affluent, albeit at different rates and with different regional patterns.

Global economic output (GEO) is estimated at 27 trillion US$(1990) at market exchange rates (MERs) in the year 2000. By 2050, GEO ranges between 106 (A2r), 119 (B2), and 150 (B1) trillion US$. By 2100 the corresponding scenario range is between 204 (A2r), 270 (B2) and 392 (B1) trillion US$, corresponding to an increase between a factor of 7 to 14 over a time period of 100 years. This compares with an estimated factor of 18 growth in GEO over the past 100 years (1900–2000) according to the estimates of Angus Maddison.[10] From this perspective, all our scenarios are squarely within historical experience and also not particularly bullish when compared to a more recent update of a review of the scenario literature ([6], see Fig. 2).

Conversely, per capita GDP growth patterns portray a somewhat different pattern, in which scenario B1, by design, describes an extremely affluent world in which income disparities also decline substantially, although absolute differences in per capita GDP continue to persist across regions over the entire 21st century (also discussed in this Special Issue [11]). Thus, even in a scenario of assumed gradual conditional convergence in per capita income, there is no convergence in absolute income differences. Per capita income (at some 4560 US$(1990) and calculated with MERs) in B1 could approach a challenging 55,000 US$ by 2100, which represents a 12-fold increase over the 21st century. Scenario B2 is more conservative, with a projected per capita income of some 25,000 US$ by 2100 (or an increase by a factor of 5.8). Scenario A2r, finally, represents the lower side of the economic growth outlook of our scenarios: per capita GDP would grow to some 16,000 US$ by 2100, or by a factor of 3.7 over a period of 100 years.[11] To put these numbers into perspective: Maddison's estimate of world

[9] The original A2 population scenarios are, for instance, higher than the most recent UN 'high' projection and also above the 95th percentile of the IIASA probabilistic population projections.

[10] Data are in principle not directly comparable as Maddison [18] statistics refer to purchasing power GDP estimates. However, comparable long-range GDP estimates in MERs exist only from 1960 (based on World Bank statistics discussed elsewhere [19]) and indicate a factor increase of 4.3 in GEO over the 1960–2000 period, compared to a 4.3 factor increase in GEO estimated at purchasing power parities (PPPs) by Maddison over the 1960–2000 period.

[11] In comparison to earlier variants of the A2 scenario (e.g., [7]), regional income disparities are more pronounced in our revised A2r scenario, which reflects our aim to explore a wide range of vulnerability to climate change.

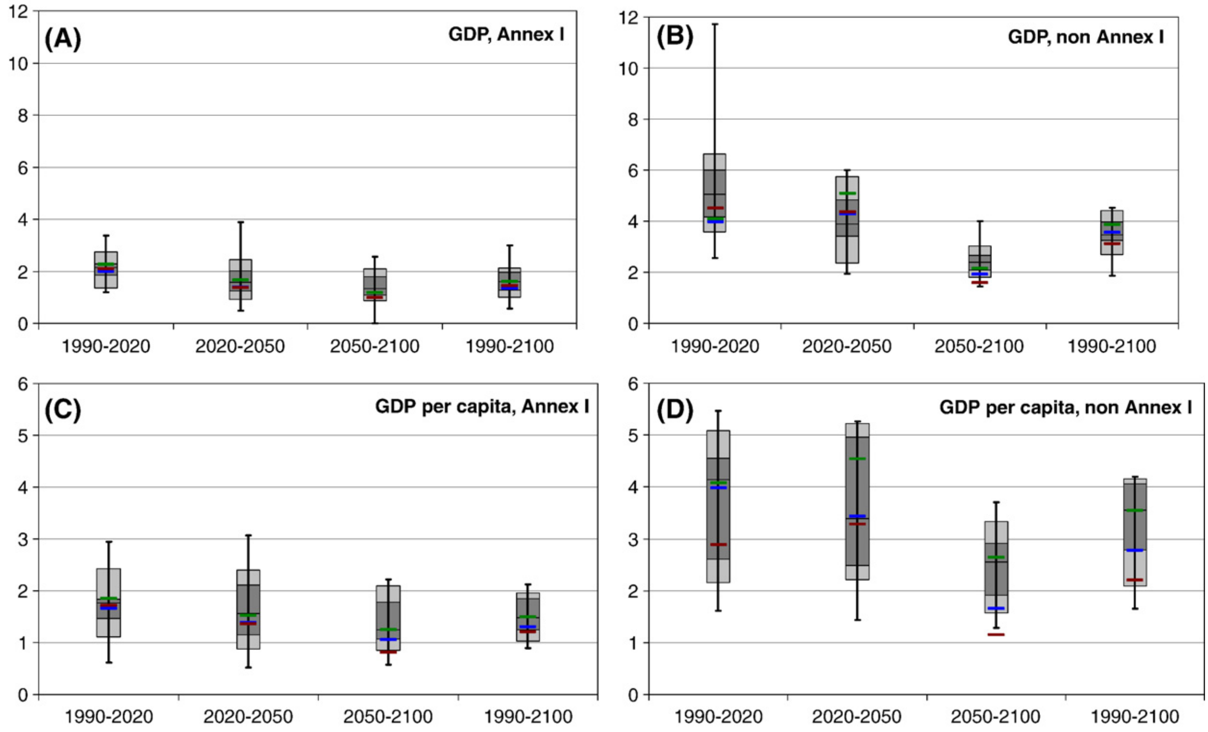

Fig. 2. Economic growth rates (percent per year) for total GDP (top panels) and GDP per capita (bottom panels) and for UNFCC Annex-1 (i.e., industrialized, left panels) and non-Annex-1 (i.e., developing, right panels) countries. Scenarios presented here (A2 brown, B2 blue, and B1 green) in comparison with statistics derived from the scenario literature [6]. See the electronic version of this paper for colored figures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

per capita GDP growth between 1900 and 2000 is a factor of 4.8. Scenarios B1 and A2r are, therefore, again squarely within historical experience, with B1 being above and A2r being below historical experience, a categorization that also applies when the scenarios are compared to the future scenarios literature (see Fig. 2).

In comparison to our earlier published scenarios [7,20] that reported economic output using two alternative measures to convert national currencies into a common denominator (MERs and purchasing power parities (PPPs)), the present study only considers GDP calculated with 1990 MERs. There are two reasons for this. First, our study objective to assess the feasibility and costs of climate stabilization taking into consideration all inter-sectorial linkages and feedbacks requires an economic conversion metric commensurate with international comparative advantage (e.g., to assess the relative economics of land-based biomass or forestry product production). It also requires an endogenous representation of international trade in energy, food, forestry products, biofuels, and carbon and other GHGs (for the stabilization scenarios examined), which dictates the use of MERs. (The use of PPP conversion rates to determine international comparative advantage and trade is simply methodologically flawed.) A second reason to refrain from reporting PPP estimates of GDP is methodological. Given that the models used in our analysis are formulated at the level of regional aggregates (e.g., all of Latin America is considered as a single region), the use of PPPs entails intricate index number and aggregation problems across countries

and/or regions and over time. These are best addressed by detailed bottom-up aggregations of scenarios formulated at the national level, which we have developed for this study (reported in this Special Issue [11]). A reformulated and recalibrated model to calculate PPP scenarios 'bottom-up' is under development and will be reported subsequently. In the meantime we ask readers for their patience and understanding given the size of the task involved (to solve simultaneously equations for 185 countries and for three scenarios). PPP as comparison metric, even if valuable for other purposes, such as climate impact assessments, is neither appropriate nor necessary for the analysis presented here and therefore we leave its publication to a later paper.[12]

2.2.2. *Technology, resource efficiency, and energy and land-use*

In the previous sections, we formulated the basic drivers of demand in the scenarios, including population and income. Now we address the interlinked issues of resource availability, efficiency, and the corresponding technologies that 'intermediate' between demand and supply.

To represent their salient uncertainties, we again follow the basic scenario taxonomy introduced above, which ranges from conservative (A2r), through intermediary (B2), to optimistic (B1).

A general feature of our scenarios, consistent with our interpretation of economic and technology history, is that rates of productivity growth and technology growth are interrelated. In other words, in scenarios of high macroeconomic productivity growth as reflected in per capita incomes (B1), the productivity of resource use (e.g., energy, agricultural land) and rates of technological innovation are also high. In turn, the rapid capital turnover rate that results from high economic growth enables a rapid diffusion of new technology vintages, which renders the high productivity and efficiency scenario storyline internally consistent. Scenario A2r maintains the same scenario logic, which represents, with its lower productivity, efficiency, and innovation rates, the 'slow progress' mirror image of the B1 scenario. It is important to emphasize the two-way linkages and interdependencies of these variables, which lead to complex patterns in the scenarios that defy simplistic linear scaling perceptions. In our view, it is precisely the nature of these complex, non-linear relationships that makes a scenario analysis with formal models a necessity, both to achieve internally consistency and to provide an informed basis for policy debates.

For instance, the scenarios illustrate that higher economic growth does not necessarily translate into a proportional growth in energy demand and resulting emissions. The growth of the latter is moderated by higher rates of technological change and efficiency improvements that counterbalance the demand and emissions growth of an increase in economic activity. This is illustrated best, for instance, by comparing the energy intensity (energy use per unit of GDP) across our scenarios (Fig. 3). *Ceteris paribus*, energy intensities are lowest in the B1 scenario, precisely because of its high productivity, technology, and capital turnover rates, with the economic structural change that results from rapid economic development also playing an important role. Conversely, energy intensities are highest in the A2r scenario, which illustrates the resource efficiency implications of limited productivity and technological innovation growth. Only through massive (and costly) efforts, as illustrated in the A2r stabilization scenarios, do intensities approach those of the much more efficient B1 scenario, which, because of the high efficiency already achieved in the baseline, needs comparatively little further adjustments under the climate stabilization targets imposed on the scenario.

The different demands for energy, as well as for food and forest products, of the scenarios determine their respective levels of resource utilization. For agriculture and forestry, to assess resource availability is a

[12] In terms of emissions outcomes the use of PPP versus MER does not yield any significant differences given an appropriate model recalibration of all the inter-related parameters, as shown in another scenario analysis reported [21].

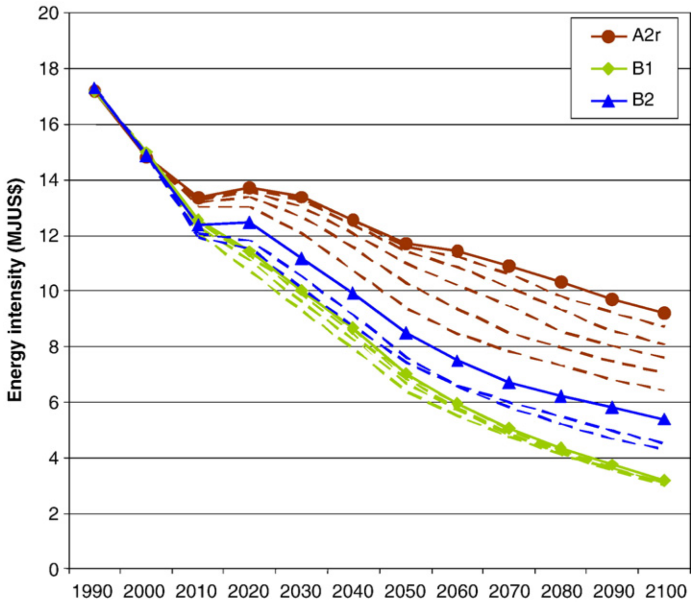

Fig. 3. Energy use per unit of GDP (energy intensity) for the three baseline scenarios and their climate stabilization scenarios. See the electronic version of this paper for colored figures.

straightforward matter, as land availability is fixed and land-use patterns are endogenous to the scenarios as a function of current uses and projected future demand–supply interactions (also reported in this Special Issue [12,14]). For energy, the situation is more complex. First, the amount of fossil fuels that might become available in the future is inherently uncertain as a function of both degree of explorative efforts that lead to new discoveries and the evolution of technology (exogenous input to our scenarios) as well as prices (endogenous in our scenarios). By and large we follow the quantitative assumptions adopted for the corresponding scenarios in the SRES report [7]. For renewable energies, the scenario literature (including our earlier work) has, to date, relied on exogenously determined upper bounds for physical supply potentials derived from the literature [22], without explicit treatments of technology or economics (prices). Taking advantage of our integrated modeling framework, we replace this traditional approach by a new one that explicitly considers competing land-uses for food, fiber, and forest products and the resulting economics of supply. This methodological refinement has also led to a significant numerical revision of our earlier estimates as a result of the endogenization of the economics of land-based bioenergy and carbon sequestration options, which we consider a major methodological advance in the modeling state-of-the-art [12].

Fossil fuel resource availability is differentiated in our study by major fuel (coal, oil, and gas) as well as by resource category (especially conventional versus unconventional resources). Fig. 4 summarizes our assumptions at the global level, giving both exogenously defined upper bounds on resource availability and endogenously determined actual use (or 'call on resources'). All of our scenarios reflect the well-known dichotomy of the inverse relationship between availability and quality of fossil energy resources. Easily accessible and clean resources (e.g., conventional gas) are relatively scarce in comparison to 'dirty' (coal) or difficult-to-harvest 'dirty' fossil fuels (unconventional oil, such as tar sands or oil shale). Nonetheless, even in considering uncertainty, the scenarios indicate that the frequently voiced fear of

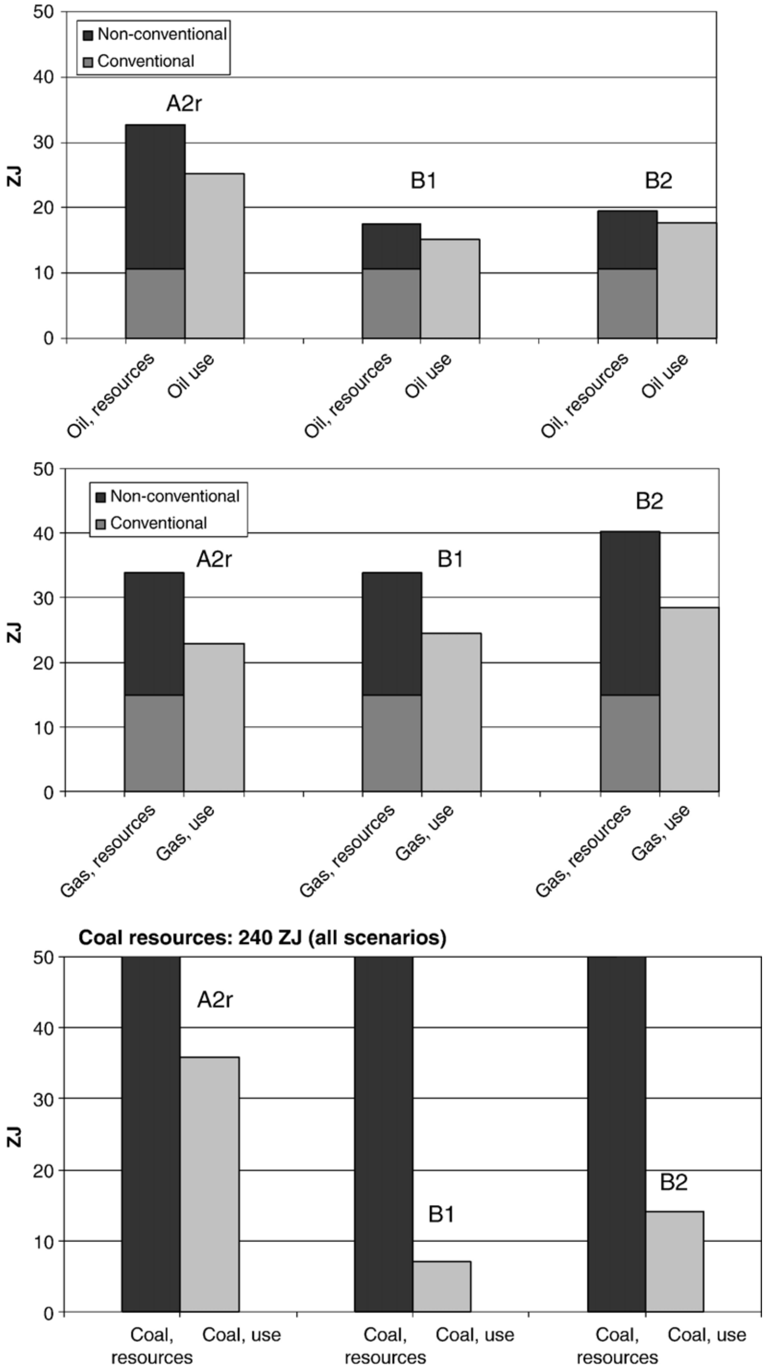

Fig. 4. Fossil energy resources: assumed availability (left bars) and actual use (right bars) for oil (top panel), natural gas (middle panel), and coal (bottom panel) in the scenarios.

'running out' of energy resources needs to be differentiated into a graduation from easy-access 'clean', to more-difficult-to-access 'dirty' fossil fuels.

Actual resource use in the scenarios, in turn, result from the interplay between exogenously defined upper bounds on resource availability ('potentials'), assumed rates of technological progress, and the relative economics between different fossil fuel resources and their non-fossil substitutes that play out under the different demand scenarios examined, ranging from 'high' (A2r) to low (B1). The 'call on resources' for coal in our scenarios provides a good illustration. In the A2r scenario demand is high (high population growth combined with slower productivity growth and, thus, less progress on the efficiency front), international trade in energy and technology is limited, and overall rates of technological progress are assumed to be more modest, which limits the contribution from (expensive) alternatives to fossil fuels. As a result, the scenario relies heavily on coal (including for synfuels production), which results in high emissions.

Conversely, scenario B1, with its lower energy demand (as a twin result of lower population combined with high productivity growth) and an assumed rapid progress in post-fossil technologies (that diffuse rapidly because of the high capital turnover rates of this 'high growth' scenario), relies little on coal (even with an assumed physical availability similar to that in the A2r scenario). Instead, in a B1 world natural gas serves as the 'transition fuel' to a post-fossil energy system, which results in comparatively low emissions. Scenario B2 is between scenarios A2r and B1. Therefore, invariably the traditional deterministic perspective on resource availability ('how much to dig out, when') is replaced in the scenarios reported here by a view that considers resource availability not geologically, but rather socially and technologically. This is reflected by different scenario tendencies in the evolution of demand, exploration efforts, technological change (in fossil as well as post-fossil alternatives) and the resulting comparative economic interplay of different energy supply options.[13]

For renewable resources we have adopted a new methodology to translate theoretical potentials (the renewable equivalent to fossil fuel 'resources') into supply potentials consistent with competitive land-uses and prices from non-energy sectors (agriculture and forestry). Our new approach improves on a traditional drawback of sectorial energy models, which have, to date, only considered the availability and costs of biofuels in a competitive context within the energy sector proper, but not in relation to other sectors.

To this end, we perform model iterations between the forest, agriculture, and energy sector models until a consistent picture with respect to land availability and prices is derived (also see Section 3 below). That is, the estimated biomass potentials account for most salient constraints on land-use availability through food-production and land price changes (e.g., driven by urbanization and increasing regional affluence). A detailed discussion of biomass potentials and prices at spatially explicit levels is also given in this issue [12]. In addition, the implications of selected scenarios for food security, agricultural production and land-use change, as well as implications for agricultural-related irrigation are also discussed in this Special Issue [13,14]. However, the integrated scenarios presented here do not yet explicitly consider the possible water availability constraints or ecological impacts that might result from vastly expanded biomass use and

[13] This scenario characteristic also emerges from our scenario design, which ignored the possibility that high demand for clean fossil fuels might induce technological change in a direction that would render these resources more widely available and at competitive prices, for example, in the form of cheap, unconventional gas (e.g., methane hydrates). Such a scenario, while not examined here, is nonetheless consistent with our interpretation of the history of fossil resource availability and use. A quantification is provided in the 'A1G' scenarios of the SRES report [7].

enhancement of carbon sinks. Related in-depth analyses (for biomass as well as other synfuel options, which would equally require vast amounts of water) remain an important area of future research.

Fig. 5 compares our revised estimates of biomass potentials and use with those used in the SRES scenario exercise. Revisions at the global level are minor for the A2r and B2 scenarios, but significant in the case of the B1 scenario. The high economic growth projection of that scenario results in an inflationary trend on land prices, which thus limits the economic availability of land-resources for biofuels compared to alternative land-uses (settlements, agriculture, and forests). This results in a corresponding reduction in the resource potential for biomass in the B1 scenario.

Equally visible in Fig. 5 is that the baseline scenarios only use a fraction of the (revised) production potentials. With increasing climate constraints and emissions reduction efforts, however, increasingly larger fractions of the biomass resource potentials are exploited. Respective levels are again determined within a consistent economic framework, always considering alternative land-uses, which energy and climate policy models have, to date, not been able to consider. Also, as shown in Fig. 3, the actual biomass use levels are significantly lower in our revised scenarios compared to earlier results. This reflects the impact of a comprehensive and consistent treatment of land availability and production of alternative goods and services in both forestry and agriculture (and hence energy–biomass production opportunity costs).

Table 3 summarizes our scenarios in terms of major resource use category: energy, and agricultural and forestry land-use. As indicated above, the energy sector scenarios were calculated for all three baseline scenarios and their stabilization counterparts, whereas for the agriculture sector resource constraints only allowed the analysis of the two “extreme” scenarios A2r and B1. Global energy use in the scenarios is projected to increase up to four-fold over the next century (A2r). Only in the scenario with highest productivity, efficiency, and technological change (B1) is this growth reduced to an increase by a factor of two over the next century. Given the range of uncertainties

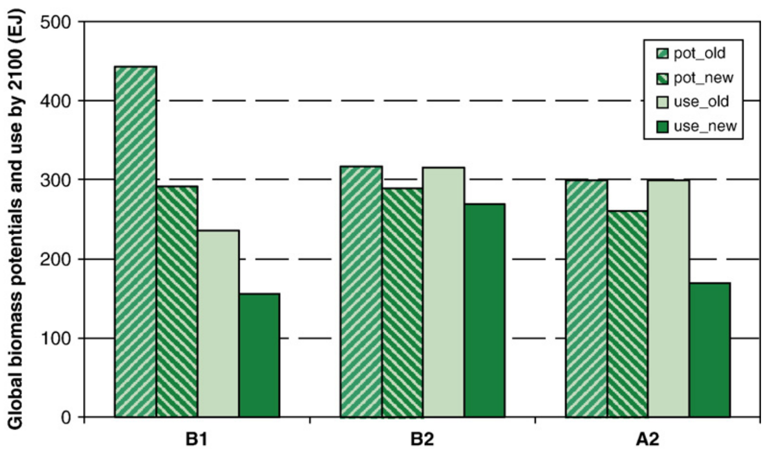

Fig. 5. Biomass energy potentials (pot., left bars) and actual use (right bars) in the scenarios (in EJ): Comparison of previous estimates (left bars) with this study (right bars).

Table 3
Main resource use in the scenarios: energy (EJ), and forest and agricultural land (in hectares)

	2000	2020	2050	2100
Primary energy (EJ)				
A2r	402	628	1173	1742
A2r-stab.[a]	402	595–628	926–1162	1162–1644
B1	402	596	953	1041
B1-stab.[a]	402	554–594	857–945	986–1012
B2	402	616	930	1288
B2-stab.[a]	402	567–584	798–829	1017–1046
Forest land (Mha)[b]				
A2r	4217	4242	4244	4234
A2r-stab.	4217	4251	4284	4438
B1	4217	4300	4410	4636
B1-stab.	4217	4302	4419	4679
B2	4217	4273	4358	4517
B2-stab.	4217	4287	4381	4620
Agricultural land (Mha)[b]				
A2r	1540	1719	1617	1780
A2r-stab.	1540	1722	1616	1779
B1	1540	1609	1651	1601
B1-stab.	1540	1609	1651	1601
B2	1540	1615	1677	1682
B2-stab.	1540	1612	1676	1680

Note that the different sectorial models analyzed do not always include the full range of the three baseline and 11 mitigation scenarios explored altogether with the MESSAGE–MACRO model.
[a] Range across all stabilization levels.
[b] Values refer to the intermediate stabilization level of 4.5 W/m^2; model calculation for agricultural land-use extent to 2080 (and are kept constant thereafter).

explored in our scenarios, further energy demand growth above the levels projected here appears unlikely as more vigorous demand growth would be counterbalanced by increasing pressures on resource availability. This would result in rising energy prices that, in turn, would further induce energy conservation measures and bias technological change in the direction of factor substitution.[14]

Contrary to many earlier scenarios published in the literature (for a review see [4]), in which forest cover almost invariably declined substantially through continued deforestation, our scenarios indicate a somewhat different pattern. Despite continued short-to-medium term deforestation in the tropics (especially in scenario A2r), global forest cover remains initially stable because of substantial afforestation in industrialized countries as a result of continued agricultural productivity increases (discussed in this Special Issue [12]).[15] Our alternative scenarios suggest, instead, the possibility of a stabilization of forest cover and preservation of forest resources over the next

[14] For a contrasting scenario, see the A1 scenario family developed for the SRES report [7].
[15] This scenario feature requires further in-depth analysis with respect to its short-term feasibility and congruence with current and near-term trends.

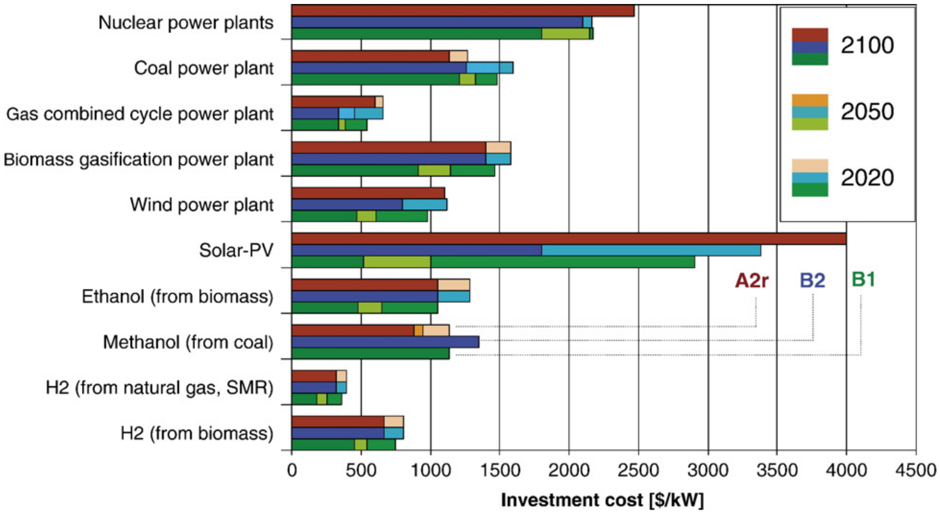

Fig. 6. Representing technology dynamics in the scenarios. Example of investment costs (US$(1990) per kW) assumed here for selected (groups of) energy technologies over time (2020, 2050, and 2100) and across three scenarios (A2r, B2, and B1). The technology cost assumptions are varied in the three baseline scenarios only. The imposition of alternative climate stabilization targets is not assumed to affect the availability and costs of technologies beyond those assumed for the respective scenario baseline. See the electronic version of this paper for colored figures.

century, a feature already foreshadowed in some previously published land-use scenarios [7]. This holds especially for the environmental 'preservationist' scenario B1, as well as for the stabilization scenarios in which forest cover increases through the enhanced utilization of forests as carbon sinks.

Last but not least, we consider technology as an important driver for our scenarios. Rates of technological change are critical across all sectors, as well as for both demand and supply aspects that together determine future GHG emission levels. Assumptions about pace and direction of technological change are scenario dependent, ranging from high (B1) through intermediate (B2) to low (A2r). The scenarios equally assume that technological change, which by its nature is cumulative, builds upon clusters of interrelated technologies that result in path-dependent behavior in the scenarios. Scenario A2r, for instance, continues to rely on derivatives of current fossil fuel technologies to match the growing demand for liquid fuels and electricity from conventional sources, such as coal, which results in high emissions. Conversely, in scenario B1, technological change favors the development of fossil fuel alternatives that branch out to ultimately pave the way for a transition away from the current reliance on fossil fuel technologies and resources, which leads to low emissions.

Technological change assumptions in the scenarios operate both at the level of aggregate trends, such as macroeconomic productivity growth or resource efficiency, and at the sectorial level (e.g., crop yields in agriculture). The detailed, 'bottom-up' energy sector model MESSAGE deploys technology-specific assumptions on availability, performance, and costs of energy conversion technologies whose dynamics unfold over time (for an example see Fig. 6). All technology-specific assumptions relate to the aggregate characteristics chosen to describe the three scenarios and thus provide a consistent

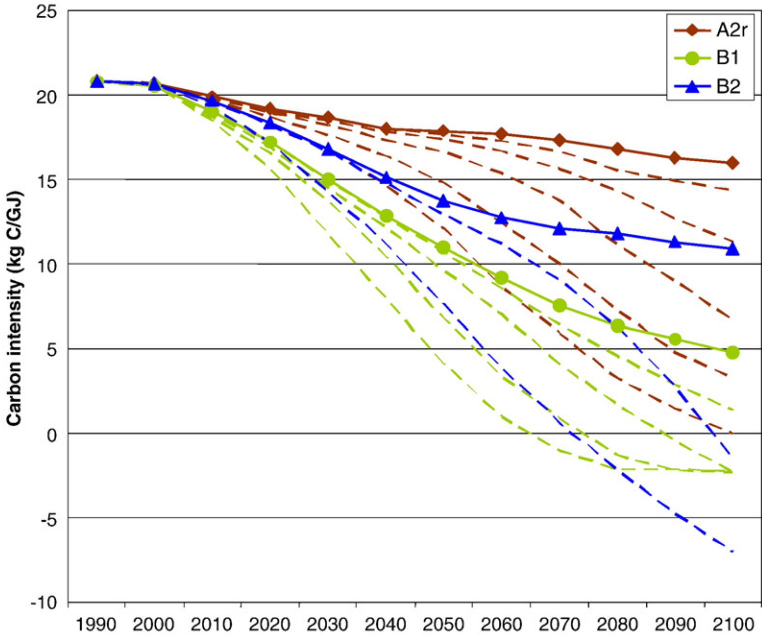

Fig. 7. Carbon emissions (net) per unit energy used (carbon intensity) across the three baseline scenarios and their stabilization counterparts. That negative values indicate exceedance of carbon sinks (natural and via CSS) over emissions. See the electronic version of this paper for colored figures.

picture that ranges from rapid change and improvements (B1) to a straightforward conservative technology outlook (A2r).[16]

Fig. 7 provides an aggregate illustration of the resulting dynamics of technological change across the scenarios and analyzes the resulting carbon emissions intensity per unit of GDP. The resulting trends for the three baseline scenarios are indicative of their respective positioning concerning the dynamics of technological change: rapid, leading to a pronounced ‘decarbonization’ trend in B1, and more slowly

[16] In our analysis we consider also a variety of different technological add-on options for carbon capture and storage (CCS) during energy conversion processes. For fossil-based CCS systems in the power sector we adopt published cost assumptions [23,24] with an average efficiency of 90% of the removal process. Capital requirements for CCS range from 940 US$/kWh for coal-based pre-combustion CCS systems to less than 510 US$/kWh for post-combustion (gasification) processes. The associated energy penalties (conversion losses) range from 13 to 25%. In addition, for biomass-based CCS systems (BECS) we assume limited initial up-scaling potential for energy conversion plants during the next three decades. Thereafter, plant sizes of 100–200 MW_e are assumed to become available. The costs of BECS are assumed to be about 30–70% higher than those of equivalent large-scale coal-based CCS systems [24]. The cost for CO_2 transportation and storage are based on published estimates [25], which report a range for the costs of storing CO_2 in deep saline aquifers or depleted oil or gas fields between 3.7 and 11 US$/tC. For our calculations we adopted the mean value of this range, which corresponds to 7.3 US$/tC. For transportation of captured CO_2 from the sources to the reservoirs, we used a cost range of 3.7–11 US$/tC/100 km [25]. For our scenario calculations, we retained the mean value of these estimates and assumed an average pipeline length of 250 km, assuming that CO_2 is transported in the liquid state, which corresponds to 18.3 US$/tC/250 km. We consider also that a large share of biomass power plants will be located in relative closer proximity to the biomass supply than the prospective storage sites. Thus, CO_2 from BECS has to be transported over larger distances than CO_2 from fossil power plants. Costs of CO_2 transportation are assumed to be higher than those from coal by a factor of more than two.

(with less decarbonization) in scenario A2r. The technological challenge ahead for climate stabilization scenarios is equally well illustrated in Fig. 7. To achieve climate stabilization, rates of decarbonization would have to be accelerated significantly, surpassing, for instance, in the stabilization scenarios of the otherwise conservative A2r scenario those assumed for the optimistic B1 scenario baseline. Perhaps even more importantly is to consider the lowest stabilization scenarios in which emissions would have to be reduced below zero levels. This implies in the most stringent stabilization scenarios that, in addition to low emissions, massive carbon management is also required in the form of carbon sequestration and disposal, as reflected in the negative values for carbon intensities toward the end of the 21st century.

2.2.3. GHG emissions and climate impacts

Fig. 8 summarizes the scenario outcomes in terms of the three most important GHGs, CO_2 (carbon dioxide expressed as tons elemental carbon), CH_4 (methane), and N_2O (nitrous oxide). The emission patterns reflect the overall scenario taxonomy adopted for this study, ranging from high (A2r) to low (B1) with the B2 scenario taking a more intermediary position. This relative ranking of emissions should, however, not be interpreted as being simply a result of linear scaling of the relationships. The

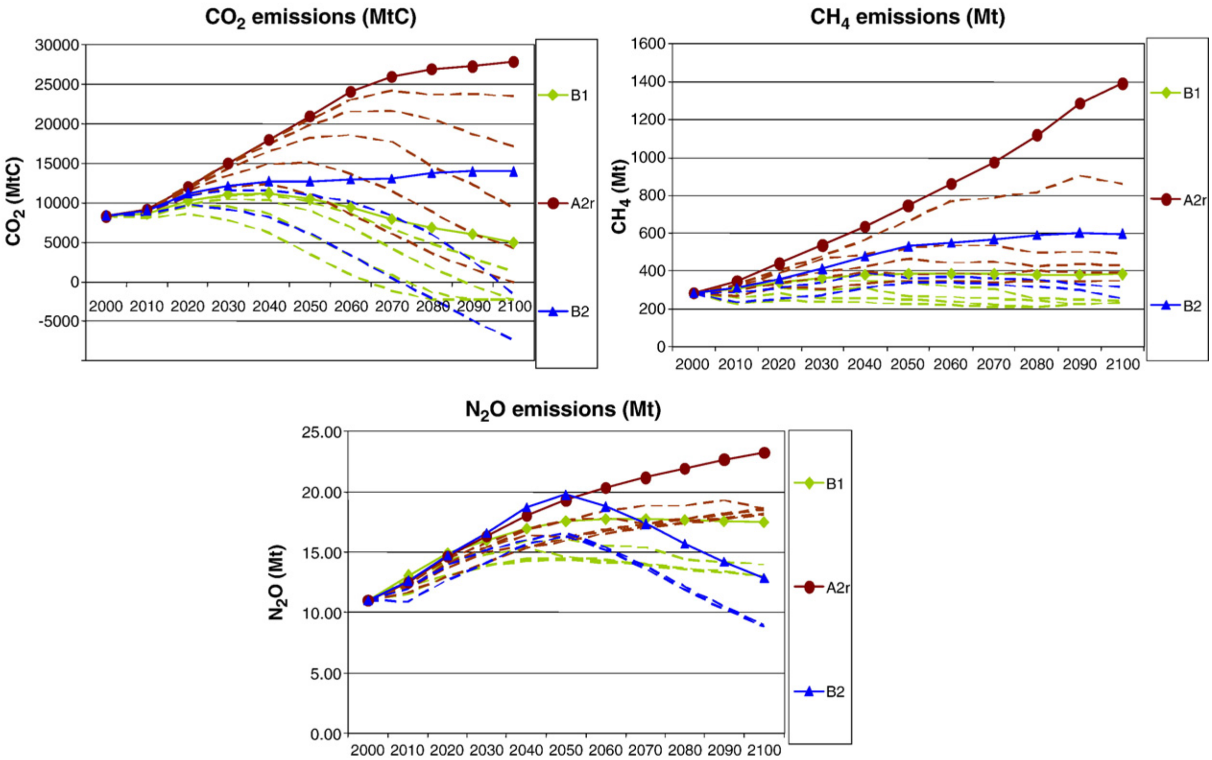

Fig. 8. GHG emissions in the scenarios (CO_2, in million tons elemental carbon), methane (million tons CH_4), and nitrous oxides (million tons N_2O). Straight lines denote baseline scenarios and dashed lines stabilization scenarios respectively. Negative emission numbers for CO_2 indicate exceedance of natural and artificial sinks over emissions. See the electronic version of this paper for colored figures.

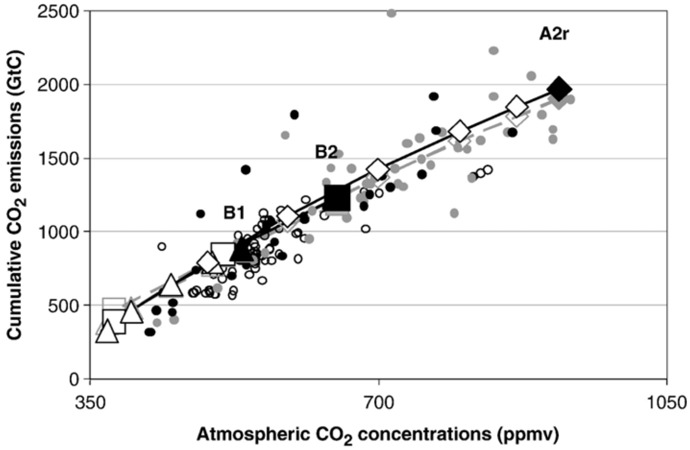

Fig. 9. The scenarios analyzed in this Special Issue (baseline scenarios denoted by black symbols, corresponding stabilization scenarios by white symbols, A2r by diamonds, B2 by squares, and B1 by triangles) compared to an update of the climate change and mitigation scenario literature [6] in terms of two important climate change precursor indicators (cumulative carbon emissions 1990–2100, in GtC, and corresponding atmospheric CO_2 concentrations, in ppmv, small circles). The scenarios presented here and the scenario literature reviewed are represented by comparing both CO_2-only (gray color shading) and multi-GHG scenarios (black and white shadings).

drivers for high and low emissions across the scenarios are both scenario and sector specific. For instance, the high carbon emissions in the A2r scenario are dominated by energy sector emissions that are a result of high growth in demand because of the combined effects of high population growth and more limited efficiency improvements. These are coupled with slower rates of technology improvements that result from lower economic productivity growth. Conversely, the high emissions for CH_4 and N_2O in A2r result primarily from the demand growth for agricultural products, which reflects the dominance of this sector for these two GHGs.

Fig. 8 also shows illustrative emissions trajectories that result from imposing ever-more stringent *ex ante* pre-specified climate stabilization constraints onto the three baseline scenarios. In the most stringent stabilization scenarios, emissions can even be negative as a result of sink enhancement activities and large-scale carbon sequestration (e.g., from biofuels). [17]We emphasize that these emissions trajectories result from an intertemporal least-cost optimization framework with perfect foresight that, in addition, assumes full intertemporal, spatial, and sectorial flexibility (see also Section 3 below). In other words, the model calculations illustrate pathways toward climate stabilization assuming that emissions reductions happen in a ‘perfect’ economic environment in absence of uncertainty, free riding, and all other possible market imperfections. In the stabilization scenarios reductions are performed when, where (in space or across sectors), and by what measure it is cheapest to do so. These assumptions result from applying an optimization framework to the analysis of stabilization scenarios, which is customary state-of-the-art in climate policy analysis, evidently are highly stylized. The resulting model calculations should therefore not be interpreted as

[17] In such scenarios, carbon uptake from the atmosphere by vegetation that is subsequently sequestered and disposed in permanent formations yields negative emissions.

Table 4
Main climate change outcomes of the scenarios analyzed

		B1					A2r						B2		
		B1	B1-670	B1-590	B1-520	B1-480	A2r	A2r-1390	A2r-1090	A2r-970	A2r-820	A2r-670	B2	B2-670	B2-520
Carbon equivalent	2000	368	368	368	368	368	368	368	368	368	368	368	368	368	368
concentrations	2050	623	612	584	561	537	621	607	580	576	590	578	645	588	566
(ppmv)	2100	792	673	591	522	482	1630	1388	1088	971	819	668	983	673	561
Radiative forcing	2000	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
(W/m^2)	2050	4.2	4.1	3.8	3.6	3.4	4.2	4.0	3.8	3.8	3.9	3.8	4.4	3.9	3.7
	2100	5.4	4.6	3.9	3.2	2.8	9.3	8.4	7.1	6.5	5.6	4.5	6.6	4.7	3.2
Temperature	2000	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
change (°C)	2050	1.7	1.7	1.6	1.6	1.5	1.4	1.4	1.3	1.3	1.4	1.4	1.7	1.5	1.5
	2100	2.7	2.4	2.1	1.8	1.6	4.0	3.8	3.3	3.1	2.7	2.3	3.1	2.4	1.9
Sea level rise	2000	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
(cm)	2050	28.4	28.2	27.6	27.0	26.2	25.9	25.3	24.6	24.6	25.0	25.1	29.0	26.9	26.7
	2100	57.0	53.9	50.2	46.3	43.0	69.6	66.6	61.0	58.6	56.0	51.5	61.2	53.4	47.3

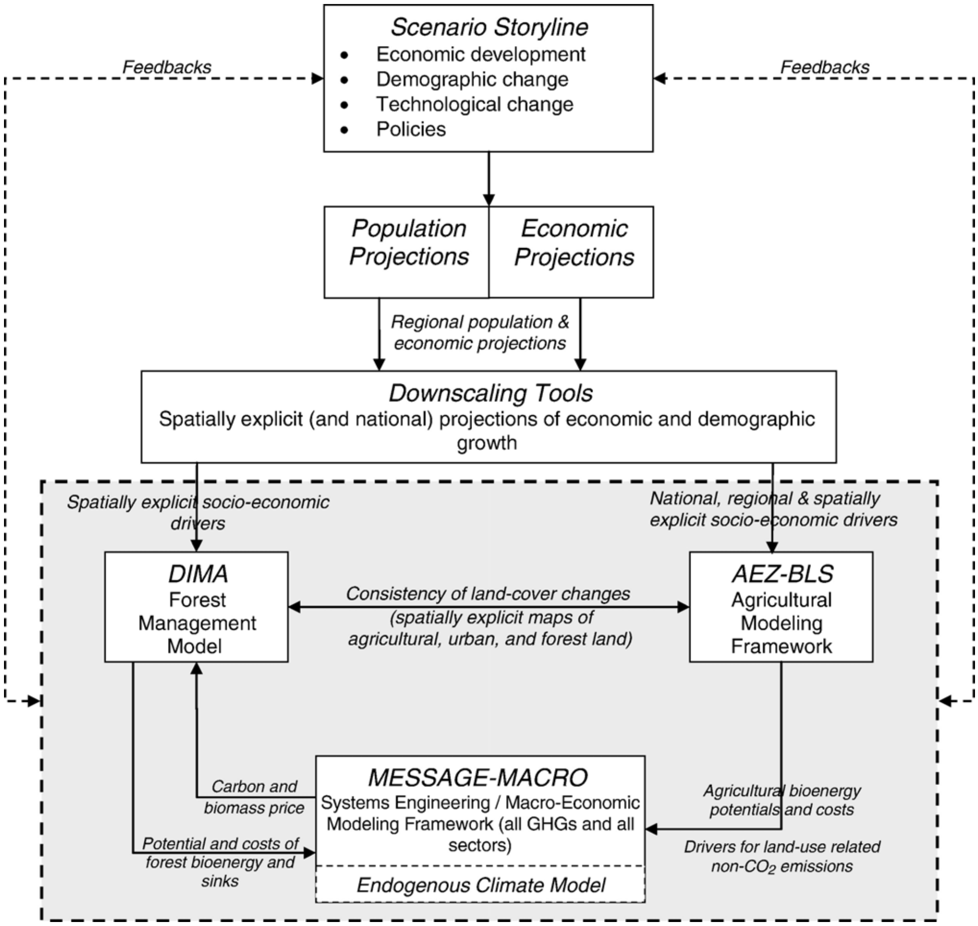

Fig. 10. IIASA Integrated Assessment Modeling Framework.

prescriptive, but simple as 'best case' illustrative scenarios of the possible globally least-cost pathways toward climate stabilization.

Fig. 9 positions our scenarios within the entire climate change scenario literature using two important precursor indicators for their potential for climate change: cumulative carbon emissions and atmospheric CO_2 concentrations. We have drawn on an updated analysis of the climate change scenario literature [6] that extends the analysis reported earlier [7].[18] Through our scenario design, we are able to represent, with a very limited number of baseline scenarios and corresponding ranges in stabilization targets, the entire scenario space spanned by the climate change scenario literature. Thus, the scenarios presented here are, indeed, parsimonious as well as comprehensive in providing input to climate models.

[18] The statistical relationship between cumulative carbon emissions and atmospheric CO_2 concentrations that emerge from Fig. 9 might represent a useful approximation for reduced-form models that lack a more detailed carbon cycle component (but this is not necessary for the scenario analysis reported here).

Using a simplified climate model (see discussion in Section 3 below) we also can provide first estimates on the climate change implications of our scenarios (Table 4). In the baseline scenarios global mean temperature could increase by between 2.7 (B1) and 4°C (A2r) toward the end of the 21st century, which leads to a sea level rise of between some 60 and 70 cm. Even in the lowest, most ambitious climate policy scenario (a 480 ppmv CO2-eq. stabilization target imposed on the lowest baseline scenario B1), climate change remains inevitable: global mean temperature would still rise by some 1.6° and sea level by some 40 cm. This most 'climate benign' scenario is also an excellent illustration that some climate change (and resulting impacts) will be inevitable, independently of how the future unfolds. Future generations will have to adapt to a changing climate as a result of past emissions, the resulting committed global warming signal, and the twin inertias of the climate and socio-economic systems that make instantaneous emissions reductions impossible and result in a long-lasting 'imprint' of emissions on the climate system.

3. Scenario methodology and model linkages

To develop the scenarios presented in this Special Issue paper we used a set of interlinked disciplinary and sectorial models referred to as the Integrated Assessment (IA) Modeling Framework (illustrated in Fig. 10). The framework combines a careful blend of rich disciplinary models that operate at different spatial resolutions that are interlinked and integrated into an overall assessment framework. The framework covers all GHG-emitting sectors, including agriculture, forestry, energy, and industrial sources for a full basket of GHGs, including CO_2, CH_4, N_2O, hydrofluorocarbons (HFCs), CF_4, and SF_6. In contrast to the traditional model integration through a simplified 'black box' representation of individual components, our modeling approach encompasses a detailed representation of each of the individual sectors. Integration is achieved through a series of hard and soft linkages between the individual components, to ensure internal scenario consistency and plausibility.

At the origin of our scenario formulation is a scenario storyline, a textual description or narrative of how the world might unfold. The storyline describes the evolution of the main driving forces, such as socio-economic, demographic, and technological change, as well as related policies, in a qualitative way (see Section 2 above). The storyline serves as the basis for the quantification of global and regional GDP as well as regional population trajectories. Through a combination of decomposition and optimization methods, world regional scenario results are first disaggregated to the level of countries. In a subsequent second step, national results are further disaggregated to the grid-cell level, which provides spatially explicit patterns of population and economic activities (reported in this Special Issue [11]). The latter indicators are particularly important for the spatially explicit modeling of land-cover changes in the forestry and agriculture sectors, as they provide the basis for the estimation of consistent, internationally comparable indicators (such as relative land prices) that define the relative comparative advantages of agriculture- and forestry-based GHG mitigation options.

The regional, national, and spatially explicit demographic and economic projections serve as exogenous inputs for the three principal models of the IA framework (Fig. 10): DIMA [12], AEZ–BLS [14], and MESSAGE–MACRO [7,9,26].

The DIMA model is used to estimate forest-related land-use changes, including reforestation, afforestation, and deforestation (RAD) and forest management as triggered by carbon sink and bioenergy incentives. It operates on a half-degree grid basis on the global scale. Its main outputs are spatially explicit

biomass energy supply schedules and sink enhancement activities consistent with the scenario's prices for CO_2 and bioenergy (reported this Special Issue [12]). Model outputs are 'soft linked' to the energy model MESSAGE (i.e., are used as exogenous inputs to successive MESSAGE runs to incorporate price-quantity trajectories calculated with the DIMA model).

The AEZ–BLS modeling framework provides a detailed account of the evolution of the agriculture sector. AEZ (agro-ecological zones) uses agronomic-based knowledge to simulate land-resource availability and use, farm-level management options, and crop production potentials as a function of climate. At the same time, it employs detailed spatial biophysical and socio-economic datasets to distribute its computations at fine-grid intervals over the entire globe [27]. In addition to land-resource assessment and computation of potentially attainable yield, this analysis included an agro-economic model to estimate actual regional production and consumption, using the Basic Linked System (BLS) developed at IIASA. BLS provides a framework for analyzing the world food system, viewing national agricultural components as embedded in national economies, which in turn interact with each other at the international trade level [28]. The BLS model consists of 34 national and regional geographical components that cover the globe. In this study the AEZ–BLS framework was used to:

- estimate agricultural impacts of climate change and adaptation needs in terms of water supply;
- assess potential conflict of bioenergy and forest activities with food security;
- estimate changes in agricultural demand and commodities, the principal drivers of non-CO_2 GHGs.

The BLS model results are again 'soft linked' to the MESSAGE and DIMA models, where they serve as inputs to calculate constraints on land availability (DIMA) as well as for the calculations of non-energy sector GHG emissions (MESSAGE).

The MESSAGE–MACRO modeling framework comprises the systems engineering optimization model MESSAGE [29] and the top-down macroeconomic equilibrium model MACRO [30]. MESSAGE and MACRO are linked iteratively, which permits the estimation of internally consistent scenarios of energy prices and energy systems costs-derived from a detailed systems engineering model (MESSAGE)—with economic growth and energy demand projections obtained from a macroeconomic model (MACRO). The framework operates at the level of 11 world regions, and maps the entire energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport and distribution to end-use services. Integration of agriculture and forestry sectors in the MESSAGE–MACRO framework has been achieved through linkages to the DIMA and AEZ–BLS models. While, potentials for bioenergy supply and CO_2 mitigation via forest-sink enhancement are based on sensitivity analysis of the DIMA model, the AEZ–BLS framework provides important inputs with respect to agricultural drivers of GHG emissions, such as changes in rice cultivation, animal stock, and fertilizer use. In that sense, the MESSAGE–MACRO stands at the heart of the fully integrated assessment framework. Its principal results comprise the estimation of technologically specific multi-sector response strategies for a range of alternative climate stabilization targets.

A set of linkages between the models guarantees scenario consistency for a number of physical and financial scenario indicators. In particular, competition for land between food security, bioenergy, and afforestation or reforestation activities are geographically explicit. Consistency of land-cover changes is achieved through exchange of spatially explicit information between the agricultural framework (AEZ–BLS) and the forest management model (DIMA) for urban land, primary agricultural cropland, and forest areas. In addition, DIMA and AEZ–BLS are linked to MESSAGE. The data exchange includes costs,

prices, and quantities for forest-sink enhancement, bioenergy supply, and the primary agricultural drivers of non-CO_2 emissions.

A typical scenario development cycle comprises four main steps:

1) development of spatially explicit economic and demographic projections;
2) estimation of spatially explicit national and regional (dynamic) supply curves for forest sinks and bioenergy supply, and agriculture-related drivers of GHG emissions;
3) incorporation of this information into the MESSAGE–MACRO model at the level of 11 world regions;
4) development of multi-gas mitigation scenarios with MESSAGE–MACRO.

The latter model identifies the appropriate portfolio of mitigation technologies, given a specific long-term climate target. The choice of the individual mitigation options across gases and sectors is driven by the relative economics of the abatement measures, assuming full temporal and spatial flexibility (i.e., emissions reduction measures are assumed to occur when and where they are cheapest to implement).[19] For intertemporal optimization, we use a discount rate of 5% throughout all of the calculations reported here.

4. Summary of scenario results

This section summarizes the main scenario results with respect to the portfolio of mitigation measures and the contribution of individual options to achieve various levels of stabilization of atmospheric GHG concentrations. Our scenario set considers two principal dimensions of uncertainty —that with respect to the development path (baseline uncertainty) and that of the appropriate level of mitigation (stabilization level uncertainty). Each of these two dimensions has important implications for the absolute level and the timing of emissions abatement, as well as for the choice of individual mitigation options.

Our analysis aims to identify measures that appear as robust choices given these uncertainties. For this purpose, we first explore the implications of the baseline assumptions for achieving stabilization. Next, we illustrate the contribution of various economic sectors as a function of the stringency of the stabilization level, and highlight important feedbacks in the forestry and agriculture sectors as responses to mitigation. Finally, we look more deeply into the technological options within individual sectors, and their potential and deployment over time. By doing so we address the following main questions:

- Which economic sectors are central to achieving stabilization of atmospheric concentrations, and which sectors gain importance at comparatively more stringent stabilization targets?
- Which technological options have the largest potential for emissions abatement and what technologies are robust against the baseline and target uncertainties?
- What options play an important role at higher marginal prices of carbon versus those that show significant contribution at modest carbon prices?

[19] The implications of relaxing this (optimistic) assumption of an economically efficient international climate policy regime and of perfectly functioning GHG abatement markets is examined in more detail in this Special Issue [31].

- What are the potential implication of stabilization for the forestry and agriculture sectors?
- Finally, what are the macroeconomic costs of stabilization given the wide range of alternative stabilization levels and baseline scenarios?

We give first a brief introduction of emissions abatement options considered in our scenarios analysis, and move thereafter to the implications of baseline and target uncertainty on emission abatement efforts and options deployed.

4.1. GHG mitigation options

The abatement of GHG emissions can be achieved through a wide portfolio of measures in the energy, industry, agriculture, and forestry sectors, the principal sources of emissions and thus global warming. Measures to reduce CO_2 emissions range from structural changes of the energy system and replacement of carbon-intensive fossil fuels by cleaner alternatives (such as a switch from coal to natural gas, or the enhanced use of nuclear and renewable energy) to demand-side measures geared toward energy conservation and efficiency improvements. In addition, the capturing of carbon during energy conversion processes with subsequent storage in geological formations or the ocean (carbon capture and sequestration, CCS) provide an ‘add-on’ ‘end-of-pipe’ approach for the decarbonization of fossil fuels, which enables their continued use with low CO_2 emissions to the atmosphere [32]. In addition, we consider in our analysis the novel concept of applying CCS to bioenergy-conversion processes (e.g., during electricity or hydrogen production). Bioenergy in combination with CCS (BECS) permits–if the biomass is grown sustainably–the supply of energy at negative CO_2 emissions [33]. The carbon removed by plant growth from the atmosphere is captured and permanently stored (e.g., in geological formations), which results in a net removal of carbon from the atmosphere (negative emissions). Another important option for CO_2 emissions reduction encompasses the enhancement of forest sinks through afforestation and reforestation activities (discussed in this Special Issue [12]).

In addition to options to reduce CO_2 emissions, our analysis considers also the full basket of non-CO_2 gases. These gases comprise CH_4, N_2O, and F-gases, which account together for about 40% of the global warming since pre-industrial times [34]. Sources of CH_4 emissions include both energy-related ones, like the extraction and transport of coal, natural gas, and oil, and non-energy-related ones, like livestock, municipal solid waste, manure management, rice cultivation, wastewater, and crop residue burning. The major source of N_2O emissions is agricultural soils. To a smaller extent, N_2O emissions also stem from animal manure, sewage, industry, automobiles, and biomass burning. Finally, F-gases are emitted predominantly from industrial sources. We consider bottom-up, technology-based mitigation options for the majority of the above sources. For emissions sources with particularly large uncertainties, such as emissions from rice cultivation or agricultural soils, we use more aggregated information given by regionally specific marginal abatement cost curves. More details on mitigation technologies and the methodology used to derive cost estimates are given elsewhere [9].

4.2. Baseline implications

Assumptions concerning the future development path in the absence of climate policies, such as socio-economic, demographic, and technological developments, have important implications on emissions. The

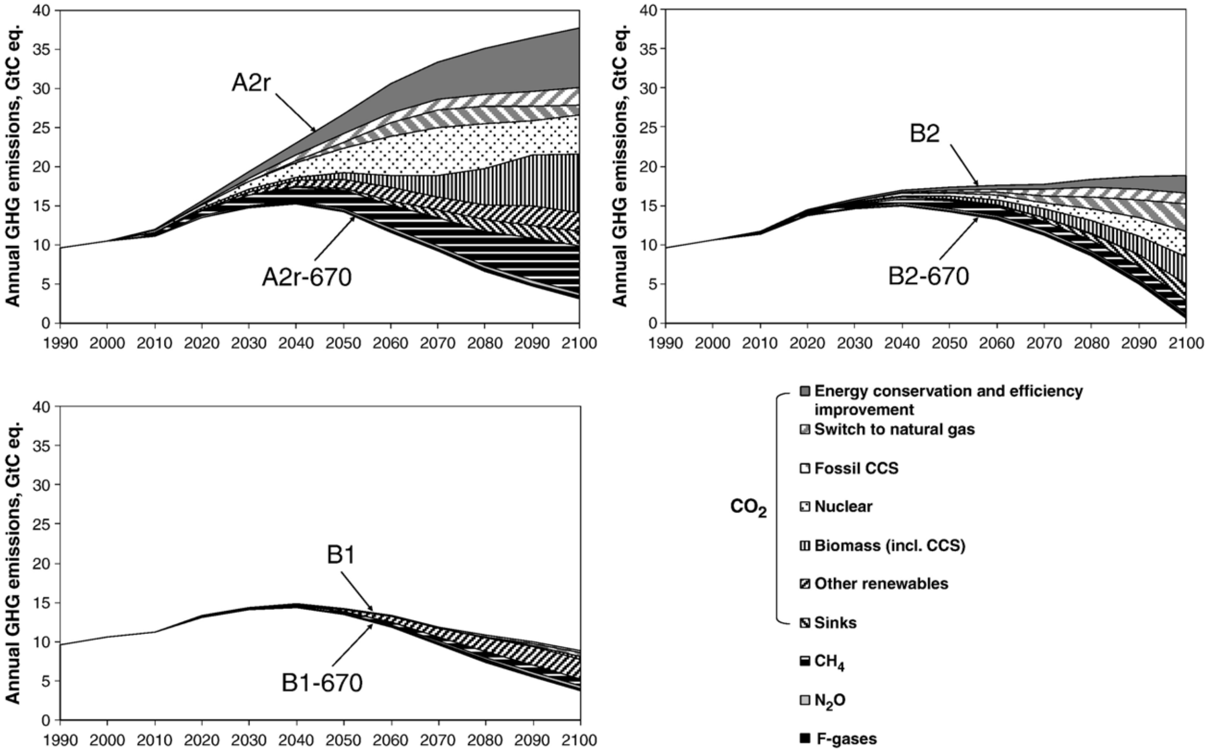

Fig. 11. Contribution of main mitigation measures for an illustrative, intermediary stabilization level at 670 ppmv CO_2-equivalent concentrations. The different panels show the portfolio of reduction measures deployed in the A2r, B2, and B1 scenarios.

resulting wide range in baseline emissions reflects these baseline uncertainties, which range from high emissions in A2r to more intermediate levels in B2, and relatively low levels in B1. The required emissions reductions for any given stabilization target strongly depends on the absolute level of the emissions in the baseline scenario. Similarly, the choice of the baseline scenario assumptions with respect to technology and productivity change also have major implications for the feasibility and costs of mitigation options for any given stabilization level.

The three panels of Fig. 11 illustrate the contribution of the main mitigation measures in the three different baseline scenarios to achieve stabilization of GHG concentrations at an illustrative level of 670 ppmv CO_2-equivalent. Fig. 11 clearly shows the difference in the required mitigation efforts across the baseline scenarios, which differs by about an order of magnitude, ranging from 160 GtC over the course of the 21st century in the B1 scenario to more than 1500 GtC in A2r. While the 670 ppmv stabilization is easily attainable in B1, and just modestly affects economic growth in B2 (see Fig. 18), it represents the most stringent target considered in our analysis for A2r. Yet lower stabilization targets appear - based on our modeling framework - technologically and economically unattainable in an A2r world.

Renewable energy, including electricity and hydrogen production from solar, are the primary sources of emissions reductions in the B1 scenario.[20] In that sense, in a B1 world the stabilization at 670 ppmv

[20] Details on the possible deployment of hydrogen technologies based on B1 are given elsewhere [35].

target is achieved primarily by adding 'a bit more of the same' technologies already included in the baseline. The main reason for this characteristic of the B1 stabilization scenario is the favorable technology assumptions that, by scenario design, were already incorporated into the B1 scenario baseline.

In contrast, in the A2r scenario emissions have not only to be reduced more severely, but also require a wider portfolio of emissions reduction measures. The bulk of the emissions reductions in A2r are achieved through four main measures: energy conservation and efficiency improvements, nuclear, biomass (including CCS), and CH_4 emissions reductions. High growth of the population and thus an increasing demand for agricultural products, together with a heavy reliance on coal, explains the high emissions in the A2r scenario baseline and the corresponding vast CO_2 and CH_4 emissions reductions in an A2r world. In addition, biomass and nuclear are seen as the main complementary technological building blocks of a future that predominantly relies on conventional technologies and the classic steam cycle. Demand-side measures also play a particularly important role, since the increase in energy prices caused by the stabilization constraint is most pronounced in A2r (see also the subsection on costs below).

The 'dynamics-as-usual' assumptions of the intermediate B2 baseline scenario result in the most diversified and balanced mitigation portfolio. Stabilization is achieved through a combination of measures with similar contributions across the full basket of possible mitigation options. An exception is the mitigation of N_2O and F-gases, which show comparatively small potentials for abatement across all three scenarios examined.

In the discussion thus far we have focused on a single stabilization level. Next we explore the implications for sectorial and gas-by-gas mitigation contributions across a wide range of stabilization targets.

4.3. Target implications

The ensemble of stabilization scenarios analyzed in this paper comprises a wide range of GHG concentration targets, from very high stabilization levels at about 1400 ppmv down to 480 ppmv CO_2-equivalent. The lowest stabilization target corresponds broadly to a stabilization of long-term 'CO_2 only' concentrations at slightly below present levels of 380 ppmv. Its temperature, radiative forcing, and concentration pathways depict a pattern of growth (short-term), 'overshoot' (mid-term), and eventual reduction in the long-term. Such ambitious, low stabilization targets–even if corresponding to the official climate target of the EU–have thus far been little analyzed in the literature (with some notable exceptions [9,36,37]).

Importantly, not all the stabilization levels are attainable for each baseline scenario. While the B1 and B2 scenarios can reach targets below 500 ppmv CO_2-equivalent, although at significantly different costs (see discussion below), the lowest attainable stabilization target for A2r is about 670 ppmv CO_2-equivalent. Unfavorable socio-economic conditions, including high population growth and the lack of economic and technological convergence between the industrialized and developing world, combined with relatively modest assumptions concerning technology improvements are the main factors that limit the feasibility of attaining very low stabilization targets in an A2r world. In contrast, the 670 ppmv CO_2-equivalent target is the least stringent one for the B1 scenario, which emphasizes again the importance of the baseline scenario uncertainty and the merits of a 'precautionary' development pathway of low emissions intensity that enlarges the flexibility and feasibility of attaining a wide range of climate stabilization targets.

We use the two extreme tails of the possible distribution of development paths, A2r and B1, to explore the implications of the target uncertainty for the portfolio of mitigation options. The stabilization scenario

counterparts of these two baselines cover the full range of climate targets. While A2r covers the upper part of the range from 1400 to 670 ppmv CO_2-equivalent, B1 explores the lower range of stabilization levels (670–480 ppmv CO_2-equivalent).

The contributions of individual sectors and gases as a function of the stabilization target and the baseline are illustrated in Fig. 12. A number of robust trends can be deduced from our analysis:

- First, Fig. 12 illustrates the dominant role of CO_2 as the major source of GHG emissions and as a target for emissions reductions across all baseline scenarios and stabilization targets. In both the A2r and B1 stabilization scenarios, the portfolio of measures to reduce CO_2 emissions accounts for between 55 and more than 80% of the total GHG emissions abatement. While the relative importance of CO_2 reductions for a specific stabilization level (e.g., see the overlapping 670 ppmv CO_2-equivalent stabilization scenarios in Fig. 12) is baseline dependent, there is nonetheless a distinct trend that the importance of CO_2 emissions reductions generally increases with the stringency of the stabilization level. By the same token, the importance of non-CO_2 gases is seen to be most significant at relatively modest stabilization targets. Our results confirm from a multiple baseline perspective similar findings to those of Hyman *et al*. [38] (which analyzed only a single baseline scenario), and also put into doubt claims [39] that non-CO_2 gases could solve the climate stabilization problem 'without sweat'.
- Second, our scenario results suggest that CH_4 is by far the most important non-CO_2 gas. Across all stabilization scenarios, CH_4 management contributes at least as much to total emissions reductions as all other remaining non-CO_2 gases combined. As for other non-CO_2 gases, the importance of CH_4 diminishes however, with the stringency of the target.
- Third, the most robust conclusion across all stabilization levels and baseline scenarios is the central role of emissions reductions in the energy and industry sectors. All stabilization scenarios concur that

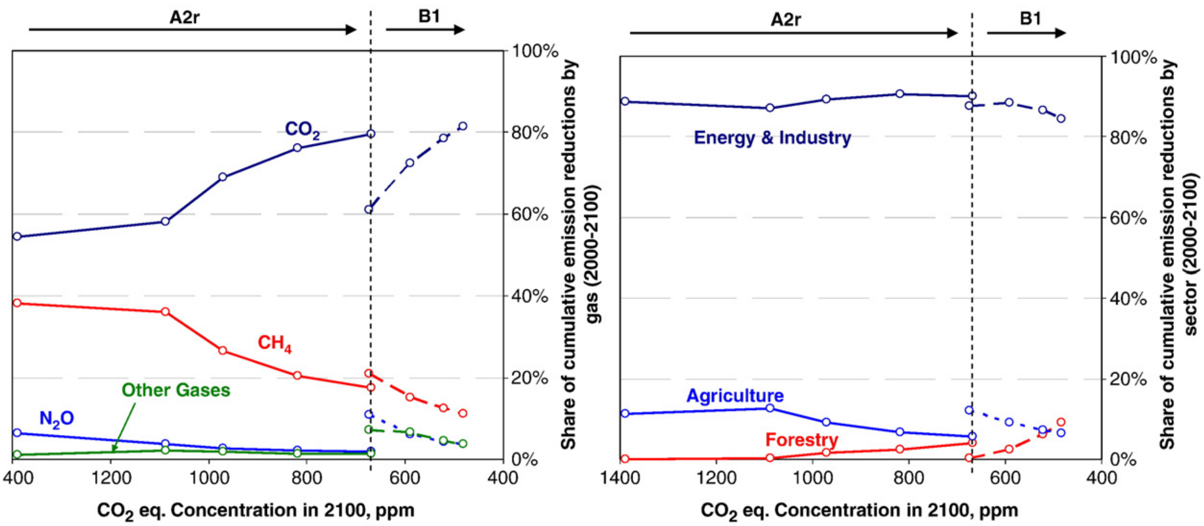

Fig. 12. Contribution of principal sectors and GHGs as a function of the stabilization target for the two extreme scenarios analyzed here (A2r scenarios from 1400 to 670 ppmv CO_2-equivalent, and B1 scenarios from 670 to 480 ppmv CO_2-equivalent.). See the electronic version of this paper for colored figures.

Table 5
Economic indicators for agricultural and forest activities in the A2r baseline and stabilization scenarios

(Billion 1990US$)	2000	2020	2050	2100
Bioenergy expenditures[a]				
A2r	48	78	140	294
A2r-stab.	48	78–78	141–243	369–755
Sink enhancement costs				
A2r	0	0	0	0
A2r-stab.	0	0–1	0–19	0–257
Timber market value				
A2r	200	334	723	1318
A2r-stab.[b]	200	337	743	1537
Agricultural GHG mitigation				
A2r	0	0	0	0
A2r-stab.	0	0–3	0–11	4–13
Agricultural GHG[c]				
A2r	1273	1684	2384	3217
A2r-stab.[b]	1273	1684–1684	2384–2386	3242–3254

[a] Including noncommerial energy accounted at 1 US$/EJ.
[b] Values refer to an intermediate target at 670 ppmv CO_2-equivalent.
[c] Exclusive bioenergy. Data for 2100 are based on extrapolations given in this Special Issue[13]. Ranges for different climate scenarios from alternative GCMs (ppmv CO_2 or approximately 670 ppmv CO_2-equivalent).

(independent of the baseline uncertainty) more than 80% of total emissions reduction could occur in these sectors. Thus, the primary focus of any cost-effective mitigation strategy has to target the full basket of energy-related and industrial sources of CO_2, CH_4, and F-gases.

- Fourth, the agriculture and forestry sectors are seen to contribute together from 10 to 17% of the total emissions reductions. The relative contribution of these sectors is strongly dependent on the scenario baseline. There are a number of cheap mitigation options in the agricultural sector (e.g., CH_4 reduction from rice cultivation and life-stock [40]) resulting in considerable emissions reductions particularly at relatively modest stabilization targets. In contrast, the forestry sector gains in relative importance at more stringent stabilization levels and thus higher marginal prices of carbon.

Although the relative mitigation potential of the agro-forestry sector is more limited when compared to the energy and industry sectors, *all* sectors play an important role in meeting the respective stabilization target cost effectively. Recent analysis using the MESSAGE–MACRO model [9] indicates potential cost savings in the order of 50% from the inclusion of non-CO_2 gases and forest sinks. Similarly, an international modeling comparison exercise (EMF 21 [41]) estimated ranges of cost savings of such a ‘multi-gas’ stabilization strategy across different models of between 25 and 70% when considering the marginal price of carbon and of between 40 and 70% for the macroeconomic costs (GDP losses) of climate stabilization.[21]

Results from our analysis also indicate that the implementation of climate policies may lead to fundamental changes in the economics of the agriculture and forestry sectors. This concerns, in particular,

[21] The studies explore costs for a central stabilization target of 4.5 W/m^2, comparable to our 670 ppmv CO_2-equivalent (or about 500 ppm CO_2 only) concentration target.

new markets and business opportunities through additional revenues from afforestation and bioenergy activities in these sectors (e.g., through GHG permits). Expenditures in the bioenergy sector alone are estimated to increase to about 300 billion US$ by 2100 (A2r baseline scenario, Table 5). The most stringent stabilization scenario yields additional bioenergy expenditures of up to 450 billion US$ and of up to 260 billion US$ for sink enhancement activities (by 2100). This corresponds, on aggregate, to monetary flows into these sectors larger than the present value of the global timber market or more than 50% of the present agricultural GDP. These additional revenues from agro-forestry climate mitigation efforts would also by far outweigh the costs of climate mitigation efforts in the agriculture sector (see Table 5, and a discussion is given in this Special Issue [14]).

4.4. Technology portfolios

Understanding the aggregated sectorial dynamics of emissions reductions requires to explore more deeply the underlying individual groups of mitigation technologies deployed. For this purpose we disaggregate our results into 10 selected technology clusters. We then compare the emissions reductions achieved by six principal measures to reduce CO_2 in the energy sector with abatement measures through forest sink enhancement, and CH_4, N_2O and F-gases reduction measures.

The cumulative contributions of these measures over the course of the century are illustrated in Fig. 13. The individual measures are ranked from top to bottom according to their average contribution across the alternative baseline and stabilization level scenarios. Some technology clusters show pronounced differences across baseline scenarios, while others do not. For example, while the contribution of nuclear energy is vast in the most stringent A2r stabilization scenario (equivalent to a reduction in cumulative carbon emissions of some 300 GtC), that of its deployment in the B1 is much more limited (35 GtC). A mere ranking of the importance of individual mitigation options (technology clusters) according to just the average contribution across scenarios is therefore insufficient to assess the robustness of a particular

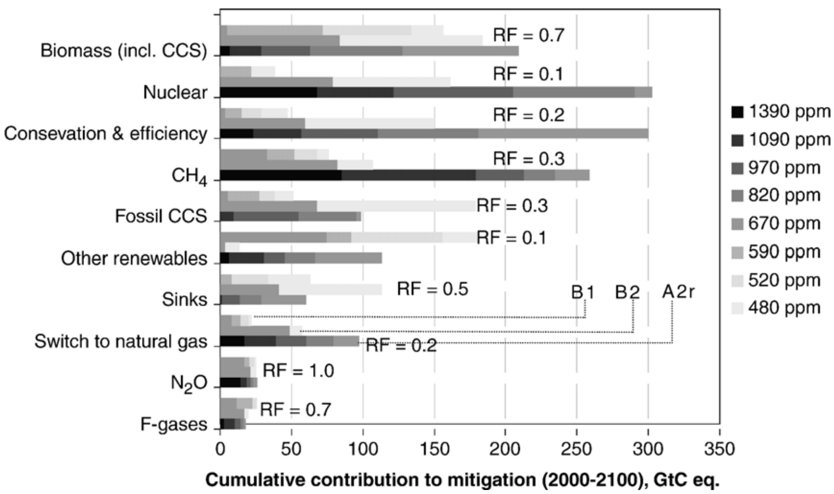

Fig. 13. Cumulative contribution to emissions reductions over the time horizon 2000–2100 by main mitigation measures (all stabilization levels and baseline scenarios) ranked according to their average contributions across all scenarios. RF denotes a calculated robustness factor for individual measures.

technological choice. We therefore introduce an additional indicator RF (robustness factor), which measures the ratio between the smallest and largest contribution for the most stringent stabilization scenario for each of the baselines (see Fig. 13). The combination of the two indicators, the average contribution across all the scenarios and the RF, is used to estimate the importance of any individual measure and/or technology within the overall mitigation portfolio. Nuclear, for example, combines a high ranking with respect to average contribution with a very low RF (=0.1). This implies that, although nuclear has a high potential for mitigation in some scenarios, it is not necessarily a robust choice if one takes into account all the salient uncertainties (baseline and target uncertainty).

An interesting finding from our analysis is that just one of the three top-ranked mitigation measures has a RF above 0.5. Nuclear and demand-side measures (energy conservation and efficiency) are seen as mitigation measures with high potential but limited robustness as calculated by our initial 'RF' calculations.[22] Biomass, in contrast, combines both a top ranking as well as a high calculated RF (0.7), which indicates its importance as part of the mitigation portfolio in the majority of the stabilization scenarios (irrespective of the baseline development path and the target uncertainty).

It is important to note that the relatively small RF (0.2) for energy conservation and efficiency improvements are, to some extent, caused by our scenario setup. Each of our baseline scenarios already assumes improvements in energy efficiency and intensity (see Fig. 3). These occur throughout the energy system, both as a result of technological change (e.g., learning or scale effects) and systems restructuring. In addition, there are also demand-side efficiency improvements and energy demand reductions. However, avoided carbon emissions from such a demand-side management in the baseline are not included in the above calculations. In the three baseline scenarios the improvements in energy intensity account for cumulative emissions reductions of between 1000 and 1400 GtC over the course of the 21st century.[23] Clearly, not all of these avoided emissions are through efficiency improvements, but to a large extent occur through structural changes of the economy and shifts toward less energy-intensive economic sectors, such as services. Taking these demand-side changes of the baseline development path into account would, nevertheless, increase the RF of demand-side measures to 0.9. This is a clear indication of the paramount importance and robustness of the energy efficiency option in both reducing the risks of climate change independent of climate policies and in lowering emissions yet further in climate policy scenarios.

The importance of biomass in the mitigation portfolio across different scenarios is primarily because of its flexibility as a fuel. It can be used in combination with fossil fuels (co-firing with coal [42] as in the A2r scenario, as well as stand alone to produce electricity, hydrogen [43], or liquid fuels (e.g., ethanol) as a substitute for oil products in the transport sector in the B1 scenario. In addition to being a low emissions alternative to fossil energy, biomass can also be combined with CCS [33]. In the latter case the use of biomass leads to net removal of CO_2 from the atmosphere, or negative emissions. Thus, biomass combined with CSS plays the part of a classic "backstop" technology in our scenarios, which explains its

[22] For energy efficiency and conservation this conclusion reflects our scenario design and does not suggest that this option is not a 'robust' one. As much of the potential energy-conservation measures are already included in the B1 scenario baseline, little additional conservation is feasible in the respective mitigation scenarios, which makes this option seemingly less 'robust'. When baseline efficiency improvements are included in the analysis, the relative ranking of options with respect to their RFs changes significantly in favor of energy efficiency. See the text for a more detailed discussion.

[23] Avoided emissions through energy intensity improvements in the baselines were calculated based on a hypothetical scenario in which energy demand would rise proportionally with economic growth (i.e., at zero energy intensity improvements).

comparatively robust deployment across all the stringent mitigation scenarios. Its robustness in the mitigation portfolio is therefore also a function of the availability of alternative 'backstops' that portray similar features (e.g., direct capturing of CO2 from air), but which were not examined in the present study.

Fig. 14 shows the contribution of the three top-ranked mitigation measures as a function of the stabilization level in the A2r and B1 scenarios. The share of biomass-based CCS technologies (BECS) in total biomass-related emissions reductions is shown in the upper panels. BECS contributes up to 100 GtC to the total cumulative emissions reduction in the most stringent stabilization scenarios (or, on average, 1 GtC per year over the course of the century). Also apparent from Fig. 14 is the more limited role of the two other top-ranked measures (nuclear and demand-side management) in the B1 scenario. As noted above, to some extent this conclusion results from our scenario design as the B1 baseline already

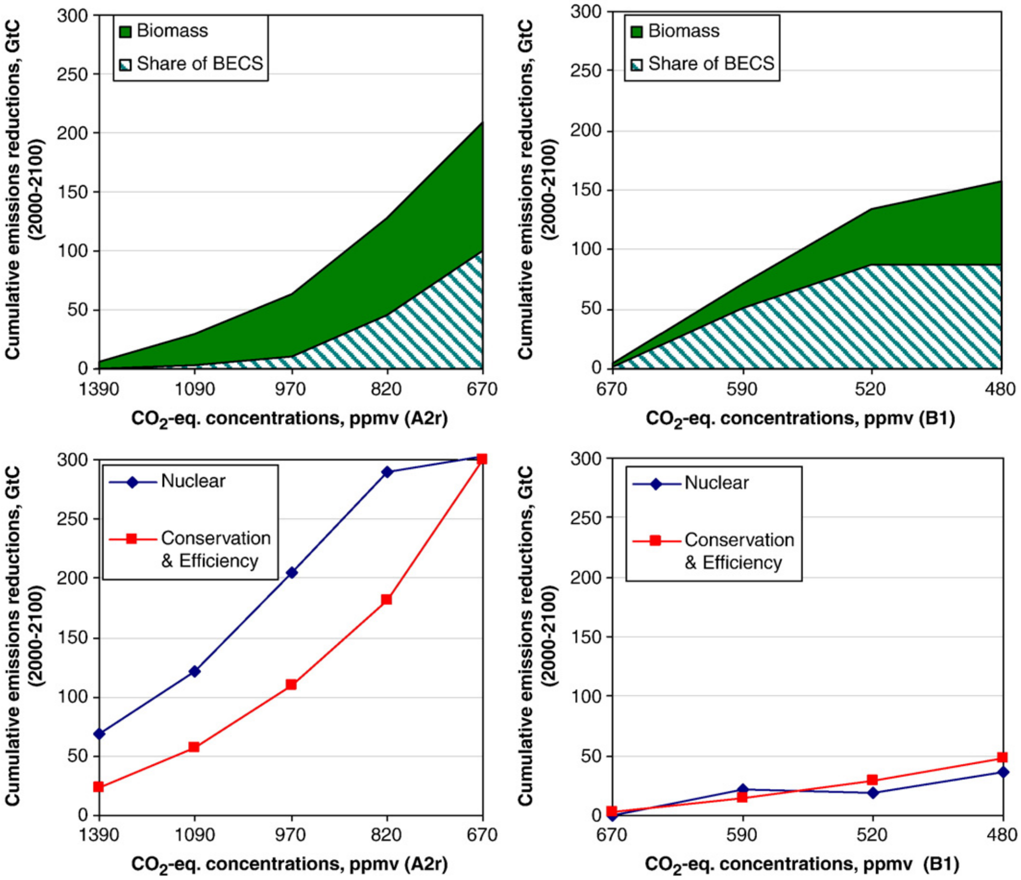

Fig. 14. Cumulative contribution of top-ranked mitigation options (2000–2100) as a function of the stabilization target. Upper panels show biomass-related mitigation measures including the share of biomass-based carbon capture and storage (BECS). Lower panels give the contribution of nuclear and demand-side measures. A2r scenarios are given in the left panels and B1 scenarios in the right ones. The low contribution of nuclear and conservation and efficiency measures in the B1 stabilization scenarios are, to a large degree, dependent on assumptions that define the B1 scenario baseline (which already incorporates large-scale deployment of these options even in absence of climate policies) and that limit, therefore, their potential further contribution in the stabilization scenario variants of the B1 baseline.

incorporates rapid energy intensity and efficiency improvements. The potential for additional mitigation induced by climate policy is therefore relatively limited because much of the efficiency and conservation potentials are already deployed in the B1 scenario baseline. Similarly, the relatively low contribution of nuclear is results from the technology cost assumptions in B1, which tend to favor renewable alternatives.[24]

A number of mitigation measures cluster in the mid-ranks of Fig. 13, which depicts average cumulative contributions well above 50 GtC over the course of the 21st century. These are, in particular, CH_4 emissions reductions, fossil CCS, non-biomass renewables (predominantly wind, solar, and hydro), and forest sink enhancement. Most of these options (with the exception of non-biomass renewables, which play a relatively minor role in the technologically cautious B2 scenario) generally also share relatively high calculated RFs above 0.3. These options are therefore important components of the mitigation portfolio explored in our scenario analysis.

The smallest average contributions across the mitigation options are given for measures that addressing N_2O, F-gases and the substitution among fossil fuels (in particular, the shift toward less carbon-intensive natural gas). For N_2O and F-gases, though, the RF values are the highest among all options. The result illustrates the pervasive use of these options in all mitigation cases, even with a comparatively very limited potential.

Given the diversity of the results and, in particular, the baseline scenario uncertainty, it is not possible to pick technological winners in a world constrained by climate change. It is obvious from our analysis, though, that the prime target of mitigation measures is the energy and industry sectors. There is, however, less agreement as to which technologies will be the largest contributors to future mitigation efforts.

4.5. Timing of mitigation

So far we have discussed the cumulative contribution of individual mitigation measures over the course of the 21st century as an indicator for their aggregated emissions reduction potential. We now address issues related to timing.

Structural change of the economy, such as the replacement of the fossil-based energy infrastructure by less carbon-intensive alternatives is a slow process. Even in our most stringent stabilization scenarios it requires decades of forceful policy efforts before global CO_2 emissions stop rising and eventually begin their declining trend to meet the respective stabilization target. Reasons for this inertia are manifold. First is the long-lived infrastructure of the energy system, with lifetimes in the order of 30–50 years, which makes replacement of the existing capital stock a lengthy process as accelerated rates of change would require a (costly) premature retiring of capital stock. Second, the diffusion process of new and advanced technologies itself, from the early stages of innovation to niche market applications and large-scale commercial use, requires a considerable amount of time. Other intangible factors, such as economic, institutional, and technological barriers, add to this technology inertia. Most successful historical rates of energy technology diffusion are, for example, illustrated by the example of nuclear, which was heavily supported by government subsidies from its early onset. It

[24] A more complete scenario analysis on the respective uncertainty of the contribution of nuclear energy in a low demand, 'high efficiency' scenario is provided elsewhere [5]. (Its C1 scenario is similar to the B1 scenario presented here; an alternative development including a higher nuclear contribution from a new generation of smaller scale modular reactor designs is outlined in scenario C2 [5]).

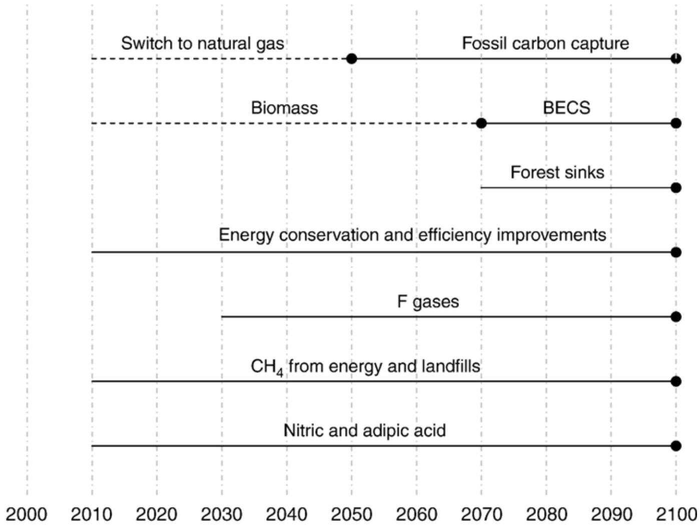

Fig. 15. Timing of selected mitigation technology clusters in the scenarios.

took about 25 years from the first nuclear power installations in the 1950s to the widespread use of the technology in the late 1970s. Empirical studies note considerably longer diffusion times for other successful energy technologies in the past [44].

Thus, many of today's most advanced technological options, such as the production of hydrogen through solar (or nuclear) processes or the combination of biomass with carbon capture and storage (BECS), are considered in the majority of the scenarios as long-term options, with significant contributions in the latter half of the 21st century only. Conversely, mitigation in the first 50 years is dominated by 'conventional' technologies, which interact synergistically with existing infrastructures. Some notable examples are the switch to more efficient natural gas combined-cycle power plants, energy conservation, and efficiency improvements, as well as the recovery of landfill CH_4 with subsequent use for energy purposes.

Fig. 15 summarizes a number of selected technologies that show pronounced characteristics with respect to their timing. That is, they share the same characteristics with regards to their contribution over time across the majority of the stabilization targets and baseline development paths.[25] In the fossil sector the majority of the scenarios suggest early abatement through fuel switching to natural gas, and later during the course of the century to CCS from fossil fuels. A similar development can be observed for biomass, which is initially used as a substitute of fossil fuels and only in the latter half of the century does it emerge in combination with CCS as an active carbon management option. It is also important that fossil-based CCS is generally deployed earlier in our scenarios than are biomass-based CCS applications, which reflects their characteristic as an 'add-on' incremental technological innovation.

A number of mitigation options play out as important elements of climate stabilization efforts throughout the entire century-long period of our scenarios. These are, in particular, the above demand-side

[25] To identify whether a technology is contributing at a specific point in time, we use a threshold of 5% of the total annual mitigation or a share of 30% of the mitigation potential of the respective technology cluster. This threshold has to be reached in the majority of all stabilization scenarios (for different targets) and at least in one stabilization scenario of each baseline.

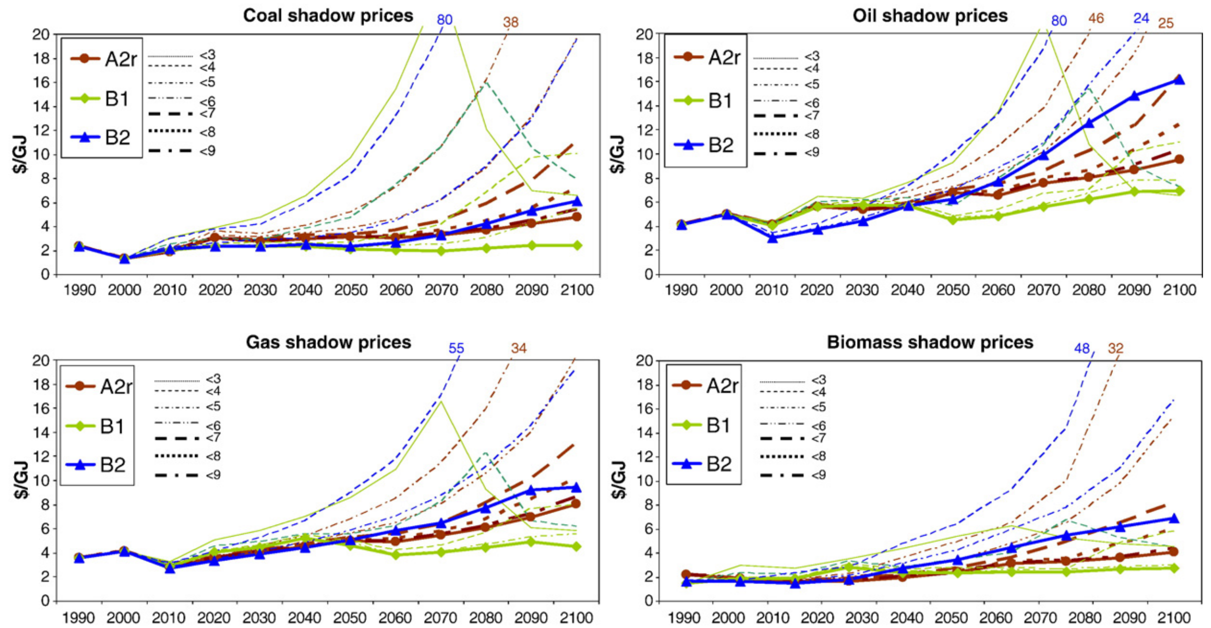

Fig. 16. Development of shadow prices for primary energy carriers coal, oil, natural gas, and biomass (US$/GJ, weighted global average calculated from 11 regions). Scenario projections from 2010 to 2100 (baseline scenarios, solid lines; stabilization scenarios from below 3 W/m^2 to more than 8 W/m^2, dotted lines). See the electronic version of this paper for colored figures.

measures and CH_4 reductions from energy and landfills. In addition, industrial sources with mitigation potentials that have low marginal costs, such as high efficiency catalytic reduction technologies in nitric acid production, also contribute to mitigation throughout the entire 21st century.

4.6. Energy shadow prices

The above relative contributions of technologies to the portfolios characteristic of different baseline and mitigation scenarios are primarily driven by two factors: the assumed relative economics of technologies across the entire energy sector spectrum, and the exogenously defined climate stabilization constraints. Given the complexity of current (not to mention future) energy systems, cost comparisons of individual technologies or technology clusters quickly become very complicated, particularly when considering interlinked energy chains, regional differences in resource availability and costs, transportation needs, etc. Nonetheless, the scenarios provide a convenient aggregate measure in terms of energy–economic scenario outcomes: energy shadow prices (see Figs. 16 and 17). Shadow prices represent the marginal costs of energy supply under a given set of cost assumptions and constraints,[26] and are determined endogenously in our modeling framework. In Figs. 16 and 17 we show shadow prices for energy carriers that are calculated as weighted global averages derived from the model results for 11 world

[26] Technically equaling the amount by which the objective function would increase if the binding constraint were relaxed by one unit.

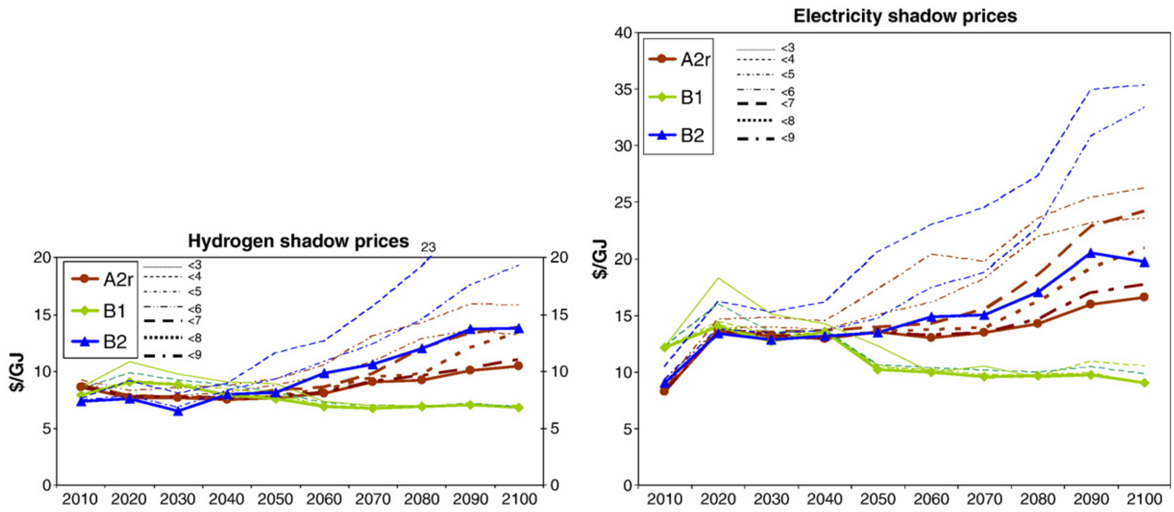

Fig. 17. Development of shadow prices for secondary energy carriers electricity and hydrogen (US$/GJ, weighted global average calculated from 11 regions). Scenario projections from 2010 to 2100 (baseline scenarios, solid lines; stabilization scenarios from below 3 W/m^2 to more than 8 W/m^2, dotted lines). See the electronic version of this paper for colored figures.

regions. Prices are given for primary or secondary energy carriers: coal, oil (including conventional and unconventional sources), natural gas, biomass (from dedicated energy plantations and agricultural residues), electricity, and hydrogen. Shadow prices are shown over time for the three baseline scenarios, as well as their corresponding climate stabilization scenarios. In the latter case shadow prices evidently include the effect of the carbon emission constraints (imputed carbon taxes needed to meet a range of climate stabilization targets and their resulting emission constraints).[27]

Given the nature of our modeling approach, which deploys a forward-looking optimization framework, it is not surprising that energy shadow prices increase[28] smoothly in the three baseline scenarios. Upward trends, such as for oil in the B2 and A2r scenarios, are primarily a function of the interplay between growth in energy demand and availability of low cost resources, as well as in cost improvements in alternatives to oil. Conversely, scenario B1 provides an optimistic lower bound on upward pressures for energy shadow prices because of its combination of vigorous efficiency improvements (lowering demand) and the rapid improvements in alternatives to conventional fuels and end-use technologies, which yielded almost constant shadow prices.

Shadow prices are, by definition, much higher in the climate-constrained scenarios. *Ceteris paribus* increases are more pronounced with higher initial price levels in the scenario baseline (e.g., B2 and A2r versus B1) and more stringent climate stabilization constraints. However, these upward pressures on shadow prices do not necessarily last forever. In some scenarios rising shadow prices induce innovation and accelerated diffusion of the clean and advanced technologies that ultimately lead to a trend reversal

[27] To provide a more intuitive comparison metric, an increase in shadow prices by one US$/GJ corresponds to a value of some 40 US$/ton elemental carbon for coal, 50 US$/tC for oil, and 65 US$/tC for natural gas (reflecting their different carbon intensities).

[28] Without major technological innovations and cost improvements, shadow prices tend to increase over the long-term, roughly with the discount rate (5%/year).

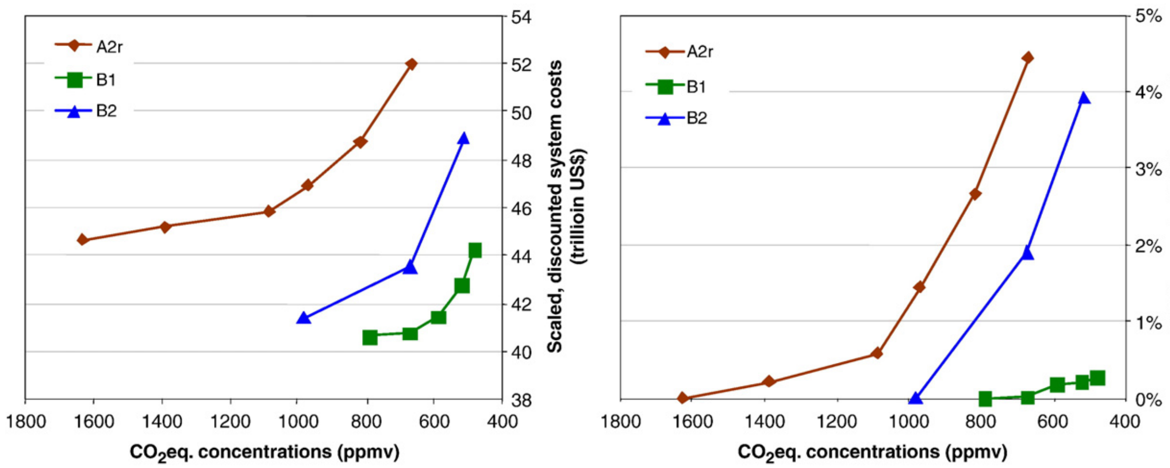

Fig. 18. Net present value of energy system costs (2000–2100, discounted at 5%/year) and GDP losses (by 2100) for the three baseline scenarios and as a function of stabilization targets.

and lowering of shadow prices in the second half of the 21st century (e.g., see the B1 stabilization scenarios in Figs. 16 and 17). In other words, rising prices appear inevitable with the progressive depletion of low cost fossil resources, especially in conjunction with ever-more stringent climate constraints. The only long-term remedy against these inflationary tendencies lies in technological innovation and niche market deployment, which ultimately could substantially lower the costs of the current costly alternatives. (Such an anticipatory innovation 'insurance' against ever-increasing energy prices might also be a politically more palatable argument than an exclusive focus on the potential threats of climate change.)

4.7. Mitigation costs

Fig. 18 presents the development of costs to meet alternative concentration stabilization targets based on the three scenario baselines (A2r, B1, and B2). We compute costs in terms of the loss of GDP by 2100 and the net present value of the differences in energy system costs over the entire period of our scenario simulations.[29] Both indicators are used widely in climate policy analysis and both convey important information. Energy system costs depict the increase in investments and other expenditures in response to climate constraints in the prime sectors of GHG emissions, while the loss in GDP accounts for the corresponding impacts of mitigation costs on the whole economy.

Costs generally increase non-linearly with the stringency of the concentration target. In our analysis, the costs of stabilization increase only modestly for intermediate targets (relative to the baseline), but increase further, almost exponentially, when moving to the lowest attainable stabilization targets.

Our analysis illustrates also the importance of baseline assumptions for future costs. The range of cumulative energy expenditures caused by uncertainties with respect to the socio-economic, demographic, and, in particular, technological change in the absence of climate policies is about 40.6 trillion US$ in the B1 scenario up to 44.6 trillion US$ in the most 'expensive' A2r baseline scenario. The cost

[29] For the net present value calculations we adopt a discount rate of 5% per year.

difference between the baseline scenarios (about 4 trillion US$) is thus of a similar magnitude to the cost impact of mitigation to attain the lowest possible stabilization level in the B1 scenario, in which costs increase from 40.6 trillion in the unabated baseline to 44.3 trillion in the 480 ppmv CO_2-equivalent concentration stabilization scenario. By the same token, the cost to meet a specific stabilization target is also highly baseline dependent—for example, the system costs for a 670 ppmv target correspond to 40.8 trillion US$ in B1, 43.5 in B2, and 52.0 in A2r. Similarly, GDP losses for the 670 ppmv target show a wide range between almost zero (0.01%) in B1 and more than 4% of GDP (by 2100) in A2r.

We emphasize that the macroeconomic costs of climate mitigation are relatively modest, particularly compared to the scenario's underlying economic growth assumptions. Even the highest losses of GDP by 2100 (between 4 and 4.5%, Fig. 18) translate into a loss of just about two years of economic output or, in other words, the stabilization scenarios would achieve similar levels of GDP as their corresponding baselines by 2102 instead of 2100.

5. Summary and conclusions

Through our scenario analysis we have illustrated the importance of considering the two most fundamental uncertainties that surround future efforts to mitigate against climate change:

- uncertainty of magnitude of future emission levels as described by alternative scenario baselines;
- uncertainty that surrounds the ultimate mitigation target (i.e., the stabilization levels).

Feasibility and costs, as well as the technological options needed to meet alternative climate stabilization goals all, depend critically on these two types of uncertainties.

Consistent with the vast majority of the scenario literature, our analysis confirms that the costs to achieve climate stabilization increase with the stringency of the stabilization target. However, the costs to meet a specific target are highly (baseline) scenario dependent. Long-term stabilization of GHG concentrations is orders of magnitude more costly under the relatively unfavorable socio-economic and technological development path that describes the 'non-cooperative' A2r world compared to a scenario like B1. Scenario B1 is characterized by rapid global technology diffusion and transfer, in which achieving climate stabilization can build upon a favorable environment created through demand management, rapid capital turnover, and sustained high innovation, especially in post-fossil technology alternatives. By the same token, stabilization targets significantly below the 670 CO_2-equivalent (500 ppmv 'CO_2 only') concentration are, according to our calculations, only attainable in the B1 and B2 scenarios (but not in A2r). We thus conclude that the uncertainty of the baseline development path has stronger implications for the feasibility and costs of mitigation than the choice of the long-term target itself. This suggests that policies that aim to influence scenario baselines in the direction of energy-efficient, low-carbon futures are a sensible hedging strategy given the continued uncertainty about the ultimate target of climate stabilization levels, i.e., the continued uncertainty as to what ultimately may constitute a "dangerous interference with the climate system", in the parlance of the UNFCCC.

From all the variables required to frame the fundamental uncertainties involved in the climate debate, technology emerges as a particularly important area worth further study. Not only is the influence of

technological change of similar importance to the demographic and economic development uncertainty (when analyzing its impacts on future emissions), it also represents a more 'malleable' variable for directed policy interventions and hence should be of interest to climate policy making. Foremost, improved technology on a broad front (efficiency, conservation, cleaner fossil technologies, renewables, nuclear) could not only alleviate the problem 'upfront' (through lower baseline emissions), but could also increase the available options for emissions reductions across a wide range of climate stabilization targets (as amply illustrated in the scenarios reported here). In addition, there is increasing evidence that the long-term costs of meeting various climate targets may, ultimately, be more a function of levels and types of climate policies and the resulting changes in economic incentives than be the inherent characteristics of potential mitigation technologies themselves. Such an 'induced innovation' perspective (reviewed elsewhere [45–47]) suggests that long-term costs to meet a wide range of climate stabilization targets are uncertain, but this uncertainty is rather technologically 'constructed' than given *ex ante* [48]. (Evidently, short-term costs are much less uncertain. Many short-term mitigation measures inevitably entail the deployment of more expensive alternatives to 'dirty' fossil fuels.) This opens a challenging, but potentially most fruitful area, of future research—to explore possible linkages and responses between environmental policies and the technological changes these may induce.

An important finding from our sectorial analysis is that the energy and industry sectors will play a central role in achieving the drastic reductions in GHG emissions required for climate stabilization. The robustness of this finding is highlighted by our full ensemble of stabilization scenarios, in each of which about 85% of total mitigation is to be achieved in the energy sector. These reductions are cost-effective independent of the choice of the baseline development path, technology assumptions, economic growth, or the ultimate stabilization target. It is therefore in the energy sector, where the question of induced technological change and an in-depth analysis of technological options, portfolios, and potential economic and environmental returns of improved technologies is of crucial importance.

Agriculture and forestry play a less important role in emissions reductions in absolute terms, but nonetheless are indispensable elements of a comprehensive and cost-effective mitigation portfolio. Emissions reductions from agricultural sources are comparatively important only at less stringent stabilization levels. Conversely, the forestry sector gains in importance with the stringency of the target (and thus higher marginal GHG reduction costs).

In our portfolio analysis we identified a limited number of technology clusters with particularly large cumulative potentials for emissions mitigation over the course of the 21st century. The three top-ranked mitigation options comprise reductions through the additional deployment of biomass, nuclear, and demand-side measures, such as enhanced energy conservation and efficiency improvements. The issue of end-use efficiency is of particular importance in framing both scenario baselines and mitigation potentials. There are also important linkages between end-use efficiency improvements that are accelerated in the mitigation scenarios, such as those that result from the deployment of advanced technologies (e.g., fuel cells) and the corresponding structural changes in energy supply (e.g., hydrogen production from a variety of sources). This suggests that a narrow focus on supply-side mitigation options alone is likely to fall short of harnessing the full synergistic mitigation potential of new technologies that could result from integrating both energy end-use and supply aspects.

From the perspective of energy supply options, those with the highest degrees of versatility in the production of a large variety of fuels suited for different end-use applications (gases, liquids, and electricity) generally emerge as the most robust technology options. These are natural gas in the short-

term (if available) and biomass in the long-term (but produced outside the traditional energy sector, i.e., in agriculture and forestry). Other renewables (solar, wind, and hydropower) and nuclear are important mitigation options, but not across all scenarios. Their potential contribution is checked by energy conservation efforts (that limit the potential 'demand' for these resources) as well by their integration into the overall energy systems architecture (that limits the potential for single-purpose resources and/or technologies, such as conventional 'electricity only' nuclear, hydropower, or intermittent renewables like solar PV or wind).

Large-scale CCS (beyond forest sink enhancements) portray the classic features of a 'backstop' technology. They are deployed on a massive scale only in unfavorable scenario baselines (e.g., the coal-intensive scenario A2r) or in combination with stringent stabilization targets. Nonetheless, even if these options appear less robust across the entire ensemble of scenarios analyzed, their potential contribution in the more extreme scenarios is so large as to justify continued research and development of these options as a hedging strategy against unfavorable developments.

We have also analyzed the timing of emissions abatement options and of the deployment of individual technologies and identified measures that appear robust across a wide range of stabilization scenarios for both the short-term and the long-term. The mitigation portfolios of our scenarios over the first 50 years are dominated by 'conventional' technologies, which interact synergistically with the existing infrastructures. For example, in the fossil sector the majority of the scenarios suggest early abatement through fuel switching to natural gas—and thus incremental changes of the present infrastructures. Later during the 21st century, CCS from fossil fuels becomes increasingly important, since it permits the continued use of these fuels at low emissions. A similar development can be observed for biomass, which is initially used as a substitute for fossil fuels and only in the latter half of the century does the combination with CCS emerge as an active carbon management option. It is also important that fossil-based CCS is generally deployed earlier in time in our scenarios than are biomass-based CCS applications. The deployment of CCS measures is primarily driven by the increasing price of GHG reduction over time and the need for deep emissions cuts in the latter half of the century. Another important finding from our analysis is the large mitigation potential of biomass-based CCS systems, particularly for very low stabilization target levels, which suggests a useful avenue for the further in-depth analysis of these technological options.

The short-term mitigation portfolios of the majority of the scenarios also comprises a number of cheap add-on options in the industry and non-CO_2 sectors, such as the reduction of CH_4 emissions from landfills and coal extraction, or emissions reductions in nitric and adipic acid production. These measures alone are, however, not sufficient to achieve climate stabilization, which requires, in the long-term, fundamental structural changes of the energy system to less carbon-intensive technologies. There is thus no 'silver bullet' that will successfully solve the climate change challenge outside the energy sector.

Finally, we conclude that the global macroeconomic costs of climate policies would be relatively modest, especially when compared to the scenario's underlying economic growth assumptions. We emphasize, though, that the implication for different sectors could be very diverse, ranging from boom (e.g., bioenergies) to bust (coal), but the effects can be moderated by the appropriate anticipatory strategies for technology development (e.g. CCS for coal). Climate policies may lead, in particular, to fundamental changes in the economics within the agriculture and forestry sectors. New markets and business opportunities, through revenues from afforestation and bioenergy activities, could emerge in these sectors (e.g., via GHG permits). The potential long-term market of these options could be of similar

magnitude to that of the present global timber market, or 50% of today's agricultural GDP. Addressing climate change thus changes significantly both the economic incentives and the 'the rules of the game' across all GHG-intensive sectors of the economy, which creates both opportunities and threats. This picture of potential losers and winners from climate mitigation within and across sectors adds to the well-known picture of winners and losers of climate change impacts across countries, sectors, and ecosystems. Reconciling these diverse perspectives and interests may, ultimately, be the greatest climate policy challenge.

A final postscript: The scenarios presented in this paper and the other contributions to this Special Issue contain a much richer set of information than was possible to describe here in detail. This, along with the need for documentation of the scenario data and input assumptions as well as requests put forward by potential users of the scenario data, has led us to the decision to make the numerical scenario data also available on the web (see www.iiasa.ac.at/Research/GGI/DB).

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