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IIASA Greenhouse Gas Initiative (GGI)
Long-term Emissions and Climate Stabilization Scenarios

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Abstract

This paper presents an overview of the greenhouse-gas emissions scenarios developed as part of an institute-wide collaborative effort within IIASA's Greenhouse Gas Initiative (GGI). The interdisciplinary research effort within GGI links all major research programs of IIASA dealing with climate change related research areas including population, energy, technology, forestry, as well as land-use changes and agriculture. GGI's research includes both basic as well as applied, policy-relevant research, aiming to assess conditions, uncertainties, impacts as well as policy frameworks for addressing climate stabilization both from a near-term as well as long-term perspective.

We first describe the motivation behind this scenario exercise and introduce the main scenario features and characteristics in both qualitative as well as quantitative terms. Altogether we analyze three "baseline" scenarios of different socio-economic and technological developments which 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 feasibility, costs and uncertainties of meeting a range of different climate stabilization targets in accordance with the Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC, 1992). The scenarios were developed by the IIASA Integrated Assessment Modeling Framework that encompasses detailed representations of the principal greenhouse gas emitting (GHG) sectors — energy, industry, agriculture, and forestry. 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 emission 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 with the energy system that accounts for the largest share of emissions reductions, but is also the case in land use patterns where emissions reduction and sink enhancement measures are more modest.

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1 Introduction

Svante Arrhenius published his seminal classic “On the Influence of Carbonic Acid in the Air upon the Temperature on the Ground” more than a hundred 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 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 form of rock weathering, the likelihood of quickly reaching any of the levels of atmospheric CO_2 concentrations addressed in his calculation seemed rather slim from the perspective of the day.

Today’s situation is fundamentally different. Atmospheric CO_2 concentration have risen to some 380 ppmv and 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, i.e. 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 last century and vast potential for further changes in the next, there is thus a deep interest to better understand unfolding of future emissions paths. Such a look into the future is especially interesting because it can help:

a) anticipate magnitudes of possible climate changes;

b) assess economic, social and ecological consequences of such changes; and

c) 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.

Above considerations constitute the prime motivation for developing scenarios, i.e. stories and quantifications of how possible developments could unfold that can help in our desire to anticipate potential consequences and to plan to mitigate this large scale planetary geo-physical “experiment” which we are in the midst of performing.

Ironically, despite all progress in science and technology since the time of Arrhenius, one challenge remains as large as it was hundred 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, altering future climate, whose legacy, e.g. in 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 initiated policy changes will translate into a noticeable effect on emissions and hence avoidance of “dangerous interference in the climate system”, which is the stated objective of the UN Framework Convention on Climate Change (UNFCC, 1992), 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 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 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 like, perhaps filled with just more of the same of his time, geopolitically, socially, technologically. Would he have considered that 100 years later backward and colonially exploited China would be in the process of surpassing the United Kingdom’s economic output, eventually even that of all of Europe or the US?; the existence of a highly productive economy within a social welfare state in his home country Sweden elevating 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. We do know however that, like at the time of Arrhenius, a perspective of hundred years represents such a challenge that traditional (deterministic) forecasting is impossible. Instead our ability to anticipate, to imagine, to describe the deep uncertainties surrounding a hundred year future perspective is challenged, a challenge traditionally addressed through the development of alternative scenarios, or ranges of possible futures.

As a result, 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 (Ausubel and Nordhaus, 1983) and have been repeated periodically ever since (Alcamo et al., 1995, Nakicenovic et al., 1998). 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 4th IPCC assessment report will include altogether over 700 scenarios (Nakicenovic et al., 2006). A distinguishing feature of the climate change scenario literature (including the present study) is a customary distinction between “no controls” or “baseline” scenarios as well as 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." 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), as well as the 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 –even if ranging 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— aim to "stand on their own feet" 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 interaction, and resulting emission outcomes. Conversely, "control" (or "stabilization") scenarios are more controlled model experiments based (one is almost attempted to say "tacked on") given baseline scenarios for a range of climate stabilization targets, that while being technically feasible may not necessarily also meet the same criteria of scenario plausibility and consistency as applied to the corresponding original "baseline" scenarios.

The scenarios considered here are no exception to above described climate change scenario dichotomy. We also first proceed in developing and presenting a range of three "baseline" scenarios with the aim of elucidating the major salient uncertainties in drivers and resulting emission outcomes 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" imposed on the three baseline scenarios) in which exogenously pre-specified climate stabilization targets (represented by their equivalent CO_2 concentration levels or more precisely by stabilization of radiative forcing of all 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 greenhouse gases 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, Nakicenovic et al., 2000) 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, Metz et al., 2001) and within the model-intercomparison research performed under the auspices of the Energy Modeling Forum (EMF) (cf. e.g. Rao and Riahi, 2006). We have revised the original scenarios to reflect new information and to incorporate the results of scenario analyses performed with the help of the integrated modeling and assessment framework presented in more detail below with the aim to improve scenario consistency. One scenario (labeled as "revised SRES A2" scenario or "A2r"), while maintaining is main structural and qualitative characteristics, represents a major numerical revision, reflecting the most recent long-term demographic outlook with a corresponding lowering of future world population growth (O'Neill et al., 2005).

The main objective of our scenario exercise is to explore feasibility and costs of meeting alternative climate stabilization targets under a range of salient long-term uncertainties with a limited set of scenarios. In order to meet that objective we have developed two contrasting scenarios A2r and B1 that aim to bracket the upper and lower quadrants of emissions and hence magnitude of climate change and of possible vulnerability to climate change respectively. These two scenarios form also the backbone of the integration of the energy sector, agriculture and forest sector model linkages reported here. The more intermediary scenario B2 (whose revisions compared to its SRES variant are numerically minor) serves as a benchmark for comparison of the results presented here to earlier work in particular that of the IPCC SRES and TAR reports, as well as to earlier scenarios (in particular the scenario IIASA-WEC "B") developed in collaboration between IIASA and the World Energy Council (WEC), Nakicenovic et al., 1998, Grubler et al., 1996). In view of resource constraints we have not performed a detailed agricultural and forestry model analysis for this intermediary scenario B2 and will report results in due course.

It should be noted that the use of the term of upper 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/below the 75th and 25th percentile of the comparable scenario literature, without however necessarily always falling with all[1] their salient scenario parameters within this indicative range. Readers should also be alerted that above quantitative yardstick from a statistical analysis of the frequency distribution of the published scenario literature should not be confounded with the traditional concept of probability. Given the large number of variables and their interdependence, we continue to be of the opinion that it is impossible to assign subjective statements on likelihood of occurrence to emission scenarios. Likelihoods or probabilities are therefore not assigned to any of the scenarios reported here, which does not mean that we consider all scenarios equally likely. In fact we do not consider the three scenarios reported here equally likely, but simply cannot offer any scientifically rigorous way of differentiating 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 including alternative demographic, economic, as well as technological developments that lead alternatively to high (A2r), intermediary (B2), or low (B1) emissions of greenhouse gases (GHGs) and hence magnitude of future climate change.

Climate impacts vulnerability uncertainty whose multiple dimensions that in particular include also "soft" institutional and technological variables are treated here in a

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[1] Given variable interdependence this would in fact be a mathematical impossibility. A scenario in which all salient input parameters would e.g. be positioned at the 90th percentile of the corresponding scenario literature not only would not yield a logical and plausible scenario it also would not fall on the 90th percentile of 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 reach other*		
emissions (magnitude of CC)	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
	emissions	**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**

simplified manner framed by the variables population density, population concentration, as well as per capita income, which exercise an amplifying and dampening effect on climate vulnerability respectively.[2] Vulnerability ranges from high (A2r), to intermediary (B2), to low (B1) in the scenarios presented here.

<u>Climate stabilization target uncertainty</u>: As mentioned above this uncertainty is addressed by systematic model simulation for a range of alternative climate stabilization targets imposed on the no-policy baseline scenarios. Altogether we perform calculations for 11 stabilization scenarios for 8 comparable stabilization levels ranging from 480 to 1390 ppmv (CO_2-equivalent concentration for all greenhouse gases taken together) by 2100. The number of stabilization scenarios analyzed is highest (5) for the high emissions scenario A2r, followed by scenario B1 (4 stabilization levels analyzed) and scenario B2 (2 stabilization levels). The higher the baseline emissions such as in scenario A2r, the higher therefore is also the number and range of stabilization targets

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[2] 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 being located below sea level) as well as socio-economic variables defining risk exposure: population density and concentration (New Orleans being a city, as opposed to other low population density coastal areas also affected by Katrina), as well as income per head, with poor residents of the city being particularly vulnerable.

and resulting emission reduction needs (and costs) examined to fully represent target uncertainties.[3]

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 (for details see Nakicenovic et al., 2000, and Metz et al., 2001) that 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 of addressing the uncertainties summarized above the scenarios also have an additional methodological purpose: they serve as integrative tool to link a variety of sectorial models (energy, agriculture, forestry) under continued development at IIASA, helping 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 (e.g., Rokityanskiy et al., forthcoming; Fischer et al., forthcoming). The significance of this feature can only be fully appreciated when considering that the climate policy analysis literature has to date been “plagued” by significant problems of incomparability of results as 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. Before however proceeding to the customary presentation of numerous input assumptions and their resulting outcomes in terms of greenhouse gas emissions and resulting climate consequences, it might be useful to provide some context in form of qualitative scenario “narratives” or “storylines” (Box 1). In fact, the blending of both qualitative as well as 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) that to date 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 Nakicenovic et al., 2000).

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[3] Note that in our model simulations, stabilization below some 500 ppmv CO2 only (670 ppmv CO2 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.

2.1 Scenario “storylines”

BOX 1 Scenario Storylines

(italics are quotations from the original SRES storylines as presented in the SRES Summary for Policy Makers (SPM), Nakicenovic et al., 2000)

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), reflecting the most recent consensus of demographic projections towards lower future population levels as a result of a more rapid recent decline in fertility levels of developing countries. 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 of a reorientation to traditional family values in light of disappointed modernization expectations in this world of “fragmented regions” or be result of economic pressures from 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), fertility levels are assumed to converge slowly but 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 of economic catch-up are only opened, 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 as well as regionally. The combination of high population with limited per capita income growth yields large internal and international migratory pressures for the poor seeking economic opportunities. Given the regionally fragmented characteristic of the A2 world, international migration is assumed to be 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 (e.g. between affluent districts and destitute “favelas”) cities as well as between urban-rural areas. Given persistent heterogeneity in income levels and the large pressures exercised on supplying enough materials, energy, and food for a rapidly growing population, supply structures and prices of commodities as well as of services remain different across and within regions, reflecting differences in resource endowments, productivities as well as regulatory priorities (e.g. for energy and food security). The more limited rates of technological change that result both from the slower rates of productivity and economic growth (reducing R&D as well capital turnover rates) translates into lower improvements of resource efficiency across all sectors leading to high energy, food, and natural resources demands, and 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. Resulting energy use and emission are consequently highest among the scenarios with carbon emissions approaching 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 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 towards sub-replacement levels, leading 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 patters is also mirrored in the economic growth outlook of the scenario where the core characteristic is one of a conditional convergence to the prevailing economic productivity frontier. Hence per capita GDP growth is assumed to be the highest of the scenarios analyzed and incomes are assumed to converge both internationally as well as 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, however only conditionally as a result of investments into human capital and a general trend towards pushing the productivity frontier to ever higher service and information-intensive economic activities, assumed extant in this scenario. Distributive policies both domestically as well as internationally (along the 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 as well as domestically, ultimately blurring the traditional distinction between urban wealth and rural poverty that lead to a substantial reduction in economic incentives for rural-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 pushing 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" not necessarily acts any longer 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, as well as manufacturing, differences in resource and environmental productivities are reduced significantly, leading to comparatively low levels of GHG emissions even in absence of dedicated climate policies. Carbon emission for instance peak at some 10 Gt by 2050 in order 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 ITC activities and technologies). World population growth is assumed to reach some 10 billion by 2100, based on the UN central projection underlying the original SRES scenario and retained also here. The UN scenario assumes strong convergence in fertility levels towards 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 respectively, largely reflecting 20th century historical experiences, without however assuming large discontinuities such as economic decline or "lost decades" of economic development for any particular region. The dynamics of income growth are assumed to be 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, also per capita productivity (income) growth is assumed to higher (e.g. China). In lagging regions (e.g. Africa) economic catch-up is assumed to be delayed until the time the demographic transition accelerates. Peak of per capita income growth therefore is 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 that would continue pushing the energy productivity frontier along their historical "high efficiency" trajectory. 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 as a twin result of technological progress in alternatives and increasing scarcity of easy access fossil resources.

Readers are advised to exercise their own judgment on the plausibility of above scenario "storylines" 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 possible developments that could result in either high or low emission futures. From that perspective, scenario B1 that 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, needs to be assessed in terms of its plausibility not as a "business as usual" scenario (which it is definitively not), but rather in terms of a plausible narrative of how a low emissions future could unfold even in absence of vigorous, dedicated climate policies. From that perspective, the scenario aims at illustrating a plausible "best case" within the context of both magnitude of future climate change (low emissions) as well as (low) vulnerability to climate change (as for instance represented in its high per capita income projections), which we feel as of high importance in a comprehensive assessment of uncertainties surrounding climate change.

From that perspective, 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 yielding both low emissions as well as low vulnerability to climate change in a comprehensive assessment of uncertainties. Thus even if challenging, we maintain the legitimacy of the "convergence" theme underlying 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 and economic theory and the evidence put forward by the economic convergence literature once inherent data, measurement, and modeling uncertainties are taken into account.

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: e.g. that a given rate of demographic transition and its resulting demographic opportunity window[4] would automatically translate to a particular rate and pattern of economic growth, or vice versa. Instead these linkages operate at a conditional level, i.e. are subject to variations in accordance to 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 low total population projection. Combined with 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 window. Rates of economic growth accelerate with progress of the demographic transition and are assumed to peak at the demographic opportunity window (maximum of second derivative of population growth). In turn, accelerated rates of modernization as reflected in economic development catch up feed back onto demographic development as well, maintaining 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. Combined with the more fragmented geopolitical outlook that limits free access to knowledge and technology, corresponding economic growth rates are much lower in an A2r world resulting initially even in a further divergence of income differences between "North" and "South."

In terms of adopting numerical scenario values (summarized in Table 2), we have analyzed in detail the corresponding scenario literature. For population we have retained the original SRES low (B1) and medium (B2) scenarios respectively as in good agreement with the most recent demographic projections from the UN (2005) and IIASA (Lutz and Sanderson, 2001; O'Neill, 2005). Global population grows from some 6 billion in 2000 to some 9 billion (8.7-9.3 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[5] (for a review see O'Neill et al., 2005). Therefore in our revised A2r scenario we use a

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[4] A period characterized by low dependency ratios, i.e. a high ratio of (potentially) economic active population (typically in the age group 15-65 years) to non-active population (younger and older age groups beyond 15-65 years).

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

		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

Table 2. Scenario Baselines: Population and GDP.

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, leading to a world population of some 10 billion by 2050 and of 12.4 billion by 2100. A comparison of the world population scenarios reported here with the original SRES study as well as most recent population projections from IIASA and the United Nations is shown in Figure 1.

In terms of economic growth all 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, MER) in the year 2000. By 2050, GEO would range between 106 (A2r), 119 (B2) to 150 (B1) trillion Dollars. By 2100 the corresponding scenario range is between 204 (A2r), 270 (B2) and 392 (B1) trillion Dollars, 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 last 100 years (1900-2000) according to the estimates of Angus Maddison.[6] From this perspective all our scenarios are squarely within historical experience and also not particularly bullish when compared to the scenario literature (see Figure 2).

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[6] Source: Maddison, 2001. Data are in principle not directly comparable as Maddison statistics refer to purchasing power GDP estimates. However, comparable long-range GDP estimates in market exchange rates exist only since 1960 (based on World Bank statistics discussed in Nakicenovic et al., 2003) and indicate a factor increase of 4.3 in GEO over the 1960-2000 period, compared to also a factor 4.3 increase in GEO estimated at purchasing power parities by Maddison over the 1960-2000 period.

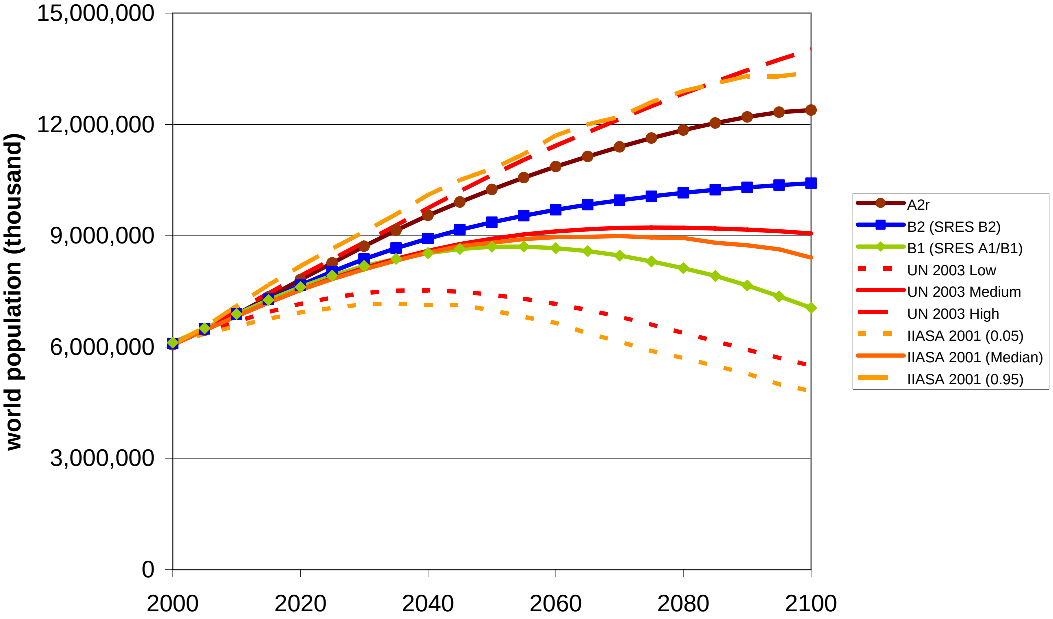

Figure 1. World Population: Scenarios presented here in comparison to the recent demographic literature

Conversely, per capita GDP growth patterns portray a somewhat different pattern, in which scenario B1 by design describes an extremely affluent world in which also income disparities decline substantially, although absolute differences in per capita GDP continue to persist across all countries over the entire 21st century (see also Grubler et al. forthcoming). 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 4,560 $US1990 and calculated with market exchange rates) in B1 could approach a challenging 55,000 $US by 2100, representing a 12-fold increase over the 21st century. Scenario B2 is more conservative: a projected per capita income of some 25,000 $US by 2100 (or an increase of a factor of 5.8). Scenario A2r finally represents the lower side of 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 time period of 100 years. To put these numbers into perspective: Maddison's estimate of world 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 the historical experience, a categorization that also applies when the scenarios are compared to the future scenarios literature (see Figure 2).

In comparison to our earlier published scenarios (Grubler et al., 1996, Nakicenovic et al., 2000) that reported economic output using two alternative measures for converting national currencies into a common denominator (market exchange rates, MER, and purchasing power parities, PPP), the present study only considers GDP calculated with 1990 market exchange rates (MER). There are two reasons for this. First, our study objective of assessing feasibility and costs of climate stabilization under full consideration of inter-sectorial linkages and feedbacks requires an economic conversion metric commensurate with international comparative advantage (e.g. in assessing the relative economics of land-based biomass or forestry product production) and requires an endogenous representation of international trade in energy, food, forestry products, biofuels, and carbon and other greenhouse gases (in case of the stabilization scenarios examined), which dictates the use of market exchange rates. (The use of PPP conversion rates in determining international comparative advantage and trade would simply be methodologically flawed.) A second reason for refraining to report 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 PPP entails intricate index number and aggregation problems across countries/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 (see Grubler et al., forthcoming). 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 considering the size of the task involved (solving 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.

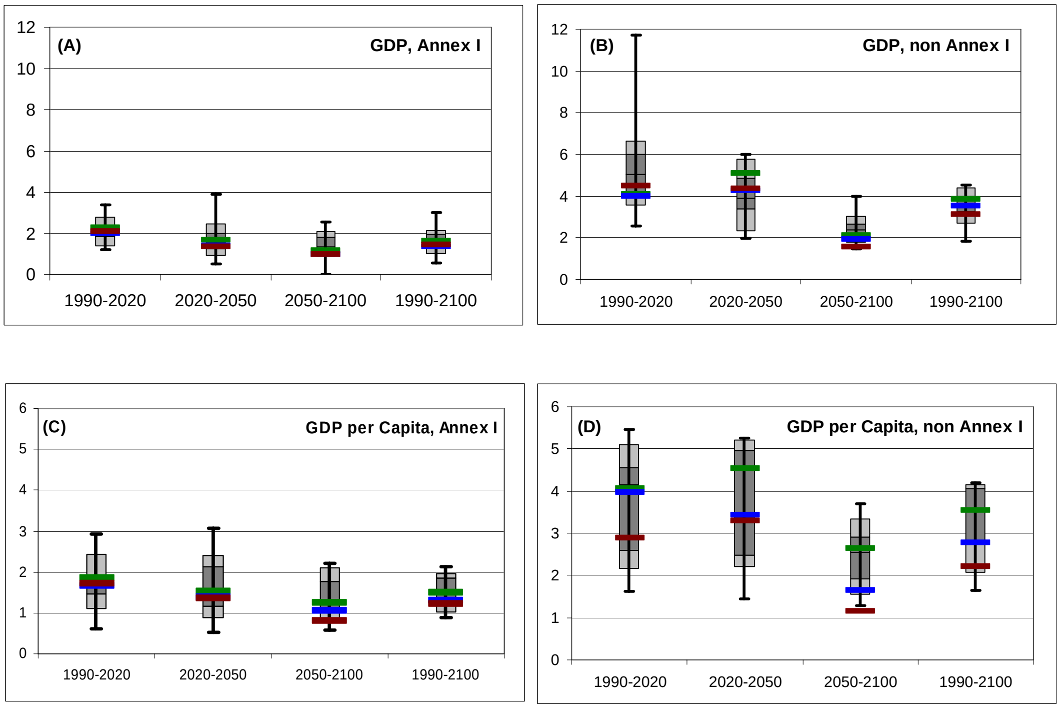

Figure 2. Economic growth rates (percent per year) for total GDP (top panels) and GDP per capita (bottom panels) and for UNFCC Annex-I (i.e. industrialized, left panels)and non-Annex-I (i.e. developing, right panels) countries. Scenarios presented here in camparison with statistics derived from the scenario literature.

2.2.2 Technology, Resource Efficiency, and Energy and Land use

In the previous sections, we have 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, ranging from conservative (A2r), intermediary (B2) to optimistic (B1).

A general feature of our scenarios, consistent with our interpretation of economic and technology history is that productivity growth and technology growth rates are interrelated. In other words, in scenarios of high macroeconomic productivity growth as reflected in per capita incomes (B1), also the productivity of resource use (e.g. energy, agricultural land) and rates of technological innovation are high. In turn, the rapid capital turnover rate resulting from high economic growth, enables a rapid diffusion of new technology vintages, rendering the high productivity and efficiency scenario storyline internally consistent. Scenario A2r maintains the same scenario logic, representing 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 that 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 make a scenario analysis with formal models both a necessity for achieving internally consistency as well as providing an informed basis for policy debates.

For instance, the scenarios illustrate that higher economic growth not necessarily translates 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 in comparing the energy intensity (energy use per unit of GDP) across our scenarios (Figure 3). *Ceteris paribus,* intensities are lowest in the B1 scenario, precisely because of its high productivity, technology, and capital turnover rates, with economic structural change resulting from rapid economic development also playing an important role. Conversely energy intensities are highest in the A2r scenario illustrating 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 its high efficiency achieved already 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 food and forest products of the scenarios determine their respective levels of resource utilization. For agriculture and forests assessments of resource availability are a straightforward matter, as land availability is fixed and land-use patterns are endogenized in the scenarios as a function of current uses and projected future demand/supply interactions (see Fischer et al., and Rokityanskiy et al. forthcoming). For energy, the situation is more complex. First, the amount of fossil fuels that might become available in the future is inherently uncertain as both a function of degree of explorative efforts, leading to new discoveries, as well as 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 (and detailed in Nakicenovic et al., 2000). 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 (see e.g. WEA, 2000) without explicit treatment of technology or of 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 has led to a revision of our earlier estimates as a result of the endogenization of the economics of land-based bio-energy and carbon sequestration options, which we consider a major methodological advance over the modeling state-of-art.

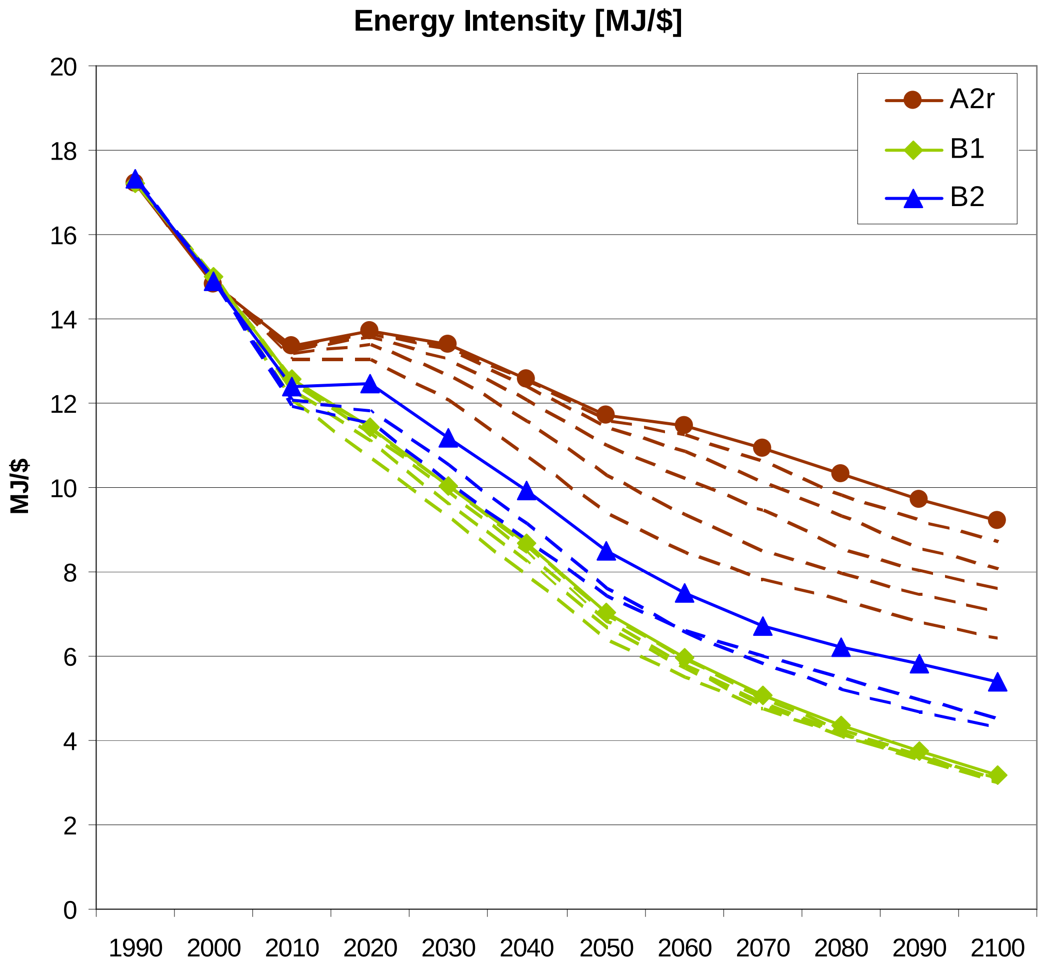

Figure 3 Energy Use per Unit of GDP (energy intensity) for the three baseline scenarios and their climate stabilization scenarios.

Fossil fuel resource availability is differentiated in our study by major fuel (coal, oil, and gas) as well as by resource category (esp. conventional versus unconventional resources). Figure 4 summarizes our assumptions at the global level giving both exogenously defined upper bounds on resource availability as well as 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 "running out" of energy resources needs to be contrasted by 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, as well as 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, limiting the contribution from (expensive) alternatives to fossil fuels. As a result, the scenario relies heavily on coal (including for synfuels production) resulting 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 due to the high capital turnover rates of this "high growth" scenario) relies little on coal (even with an assumed similar physical availability as in the A2r scenario). Instead, in a B1 world, natural gas serves as "transition fuel" to a post-fossil energy system, resulting in comparatively low emissions. Scenario B2 is situated in-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 as geologically, but rather as socially and technologically "constructed". This is reflected in different scenario tendencies of the evolution of demand, exploration efforts, technological change (in fossils as well as post-fossil alternatives) and the resulting comparative economic interplay of different energy supply options.[7]

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[7] It should be noted that this scenario characteristic emerges also out of our scenario design that 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, e.g. in form of cheap, unconventional gas (e.g. methane hydrates). Such as 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 (Nakicenvic et al., 2000).

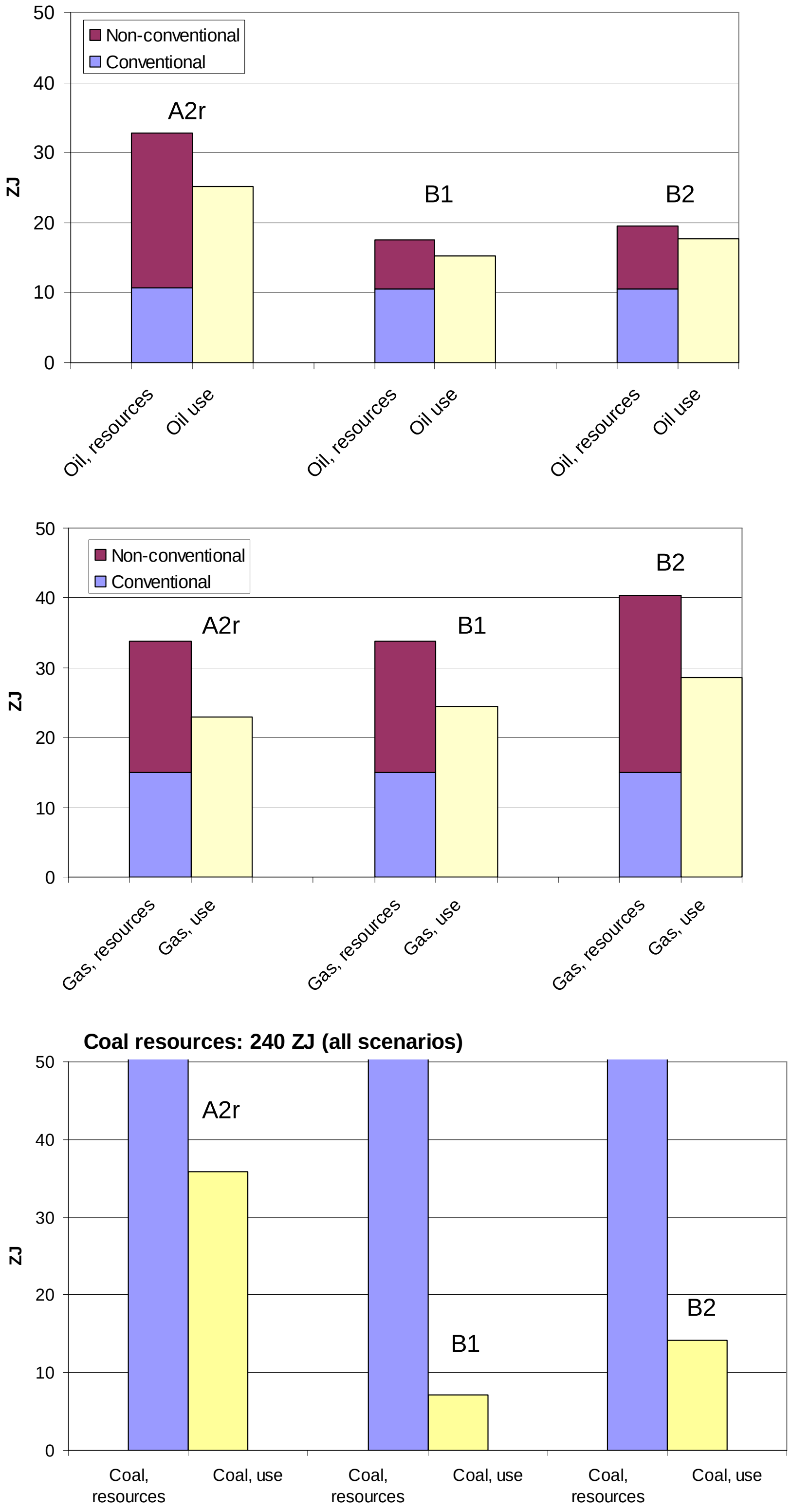

Figure 4. Fossil energy resources: Assumed availability (left bars) and actual use (right bars) for oil (top panel), natural gas (middle panel), and coal (bottom panel) in the scenarios.

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 that have to date only considered availability and costs of biofuels in a competitive context within the energy sector proper, but not in relation to other sectors.

To that 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 (see also Section 3 below). Compared to earlier published results, we were therefore able to improve upon scenario consistency. Figure 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 thus limiting the economic availability of land resources for biofuels in comparison to alternative land uses (settlements, agriculture, and forests), resulting in a corresponding reduction in the resource potential for biomass in the B1 scenario.

Equally visible in Figure 5, is that the baseline scenarios only use a fraction of the (revised) production potentials. With increasing climate constraints and emission 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 we consider a major methodological and scenario advance for energy and climate policy models that have to date not been able to consider these interdependencies.

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 forestry and agricultural sector resource constraints allowed only 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 a factor two increase over the next century. Given the range of uncertainties 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 resulting in rising energy prices that in turn would further induce energy conservation measures and bias technological change in direction of factor substitution.[8]

Contrary to earlier scenarios published in the literature (cf. the review in Alcamo et al., 1995), in which forest cover almost invariably declined substantially due to 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 due to substantial afforestation in industrialized

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[8] For a contrasting scenario see the A1 scenario family developed for the SRES report (Nakicenovic et al., 2000).

countries (for a discussion see Rokityanskiy et al., forthcoming[9]). Our alternative scenarios suggest instead the possibility of a stabilization of forest cover and preservation of forest resources over the next century. This hold especially for the environmental “preservationist” scenario B1 as well as in the stabilization scenarios where forest cover increases due to enhanced utilization of forests as carbon sinks.

Last but not least, we consider technology as important diver for our scenarios. Rates of technological change are critical across all sectors and for both demand as well as supply aspects that together determine future GHG emission levels. Assumptions about pace and direction of technological change are scenario dependent, ranging from high (B1) to intermediate (B2), to low (A2r). The scenarios equally assume that technological change that 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, resulting in high emissions. Conversely, in scenario B1, technological change favors the development of fossil-fuel alternatives that branch out in order to ultimately pave the way for a transition away from the current reliance on fossil fuel technologies and resources, leading to low emissions.

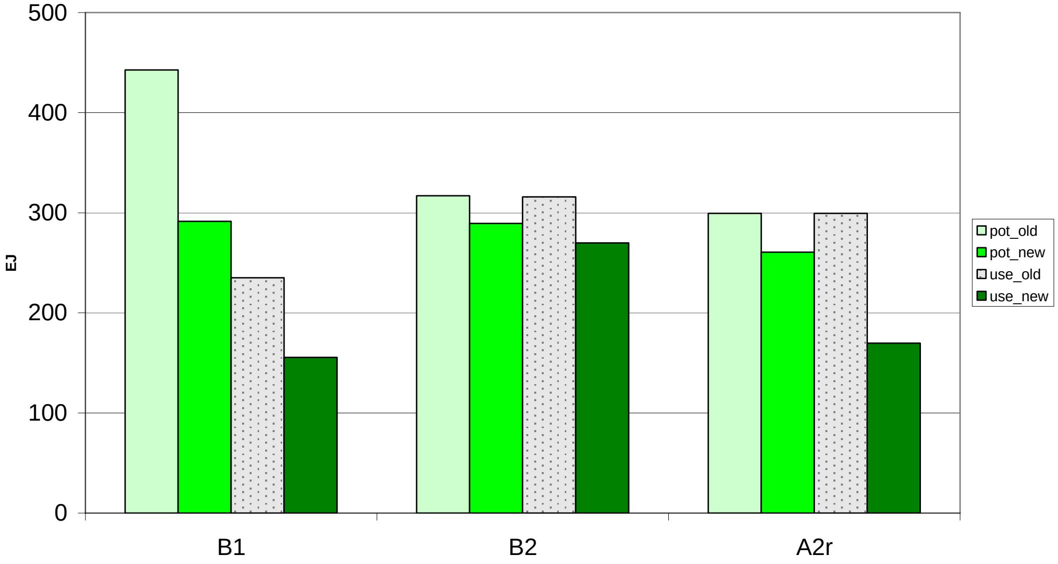

Figure 5. Biomass energy potentials (left bars) and actual use (right bars) in the scenarios (in EJ): Comparison of previous estimates (left bars) with this study (right bars).

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[9] This scenario feature requires further in-depth analysis with respect to its short-term feasibility and congruence with current and near-term trends.

Table 3 Main resource use in the scenarios: Energy (EJ), forest, and agricultural land (in hectares). Note that the different sectorial models analyzed not always the full range of the altogether three baseline and 11 mitigation scenarios explored with the MESSAGE-MACRO model.

	2000	2020	2050	2100
Primary Energy (EJ)				
A2r A A2r	402	628	1173	1742
A2r-stab.*	402	595 - 628	926 - 1162	1162 - 1644
B1	402	596	953	1041
B1-stab.*	402	554 - 594	857 - 945	986 - 1012
B2	402	616	930	1288
B2-stab.	402	567 - 584	798 - 829	1017 - 1046
Forest land (mil. ha)				
A2r	4217	4242	4244	4234
A2r-stab.**	4217	4251	4284	4438
B1	4217	4300	4410	4636
B1-stab.**	4217	4302	4419	4679
B2	4217	n.a.	n.a.	n.a.
B2-stab.	4217	n.a.	n.a.	n.a.
Agricultural land (mil. ha)				
A2r	1576 [+]	1606	1693	1741
A2r-stab.	n.a.	n.a.	n.a.	n.a.
B1	1575 [+]	1599	1634	1591
B1-stab.	n.a.	n.a.	n.a.	n.a.
B2	n.a.	n.a.	n.a.	n.a.
B2-stab.	n.a.	n.a.	n.a.	n.a.

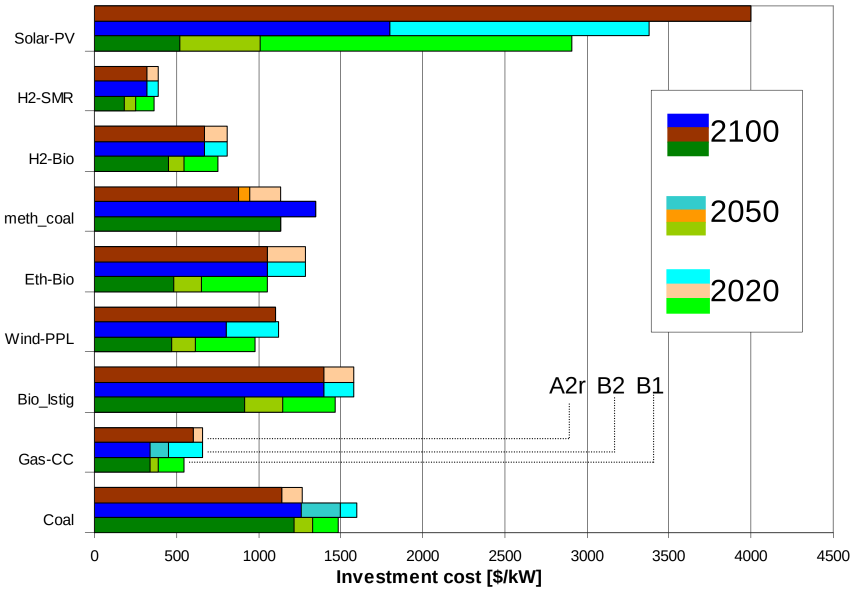
* Range across all stabilization levels

** Values refer to the intermediate stabilization level of 670 ppmv (CO2-eq.)

[+] Values for year 2010.

Figure 6. Representing technology dynamics in the scenarios: Example of Investment costs (US$(1990) per kilo-Watt) for selected energy technologies over time and across scenarios. Note that technology assumptions are varied in the three baseline scenarios only. The imposition of alternative climate stabilization targets is not assumed to affect availability and costs of technologies beyond those assumed for the respective scenario baseline.

Technological change assumptions in the scenarios operate both at the level of



aggregate trends such as macro-economic productivity growth or resource efficiency, as well as 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 Figure 6). All technology specific assumptions relate to the aggregate characteristics chosen for describing the three scenarios and thus provide a consistent picture ranging from rapid change and improvements (B1) to a straightforward conservative technology outlook (A2r). Figure 7 provides an aggregate illustration of the resulting dynamics of technological change across the scenarios analyzing 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 (with less decarbonization) in scenario A2r. The technological challenge ahead for climate stabilization scenarios is equally well illustrated in Figure 7. In order to achieve climate stabilization, rates of decarbonization would have to be accelerated significantly, surpassing for instance in the stabilization scenarios of the otherwise the conservative scenario A2r those assumed for the optimistic B1 scenario baseline. Perhaps even more noteworthy is to consider the lowest stabilization scenarios where emissions would have to be reduced below zero levels. This implies in the most stringent stabilization scenarios in addition to low emissions also massive carbon management in form of carbon sequestration and disposal as reflected in the negative values for carbon intensities towards the end of the 21st century.

2.2.3 GHG emissions and Climate Impacts

Figure 8 summarizes the scenario outcomes in terms of the three most important greenhouse gases CO_2 (carbon dioxide expressed as tons elemental carbon), CH_4 (methane) and N_20 (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 relationships. The drivers for high or low emissions respectively across the scenarios are both scenario as well as sector specific. For instance, the high carbon emissions in the A2r scenario are dominated by energy sector emissions that are high are a result of high growth in demand due to the combined effects of high population growth, and more limited efficiency improvements and that are coupled with slower rates of technology improvements that result from lower economic productivity growth. Conversely, the high emissions for CH_4 and N_20 in A2r result primarily from demand growth for agricultural products reflecting the dominance of this sector for these two greenhouse gases.

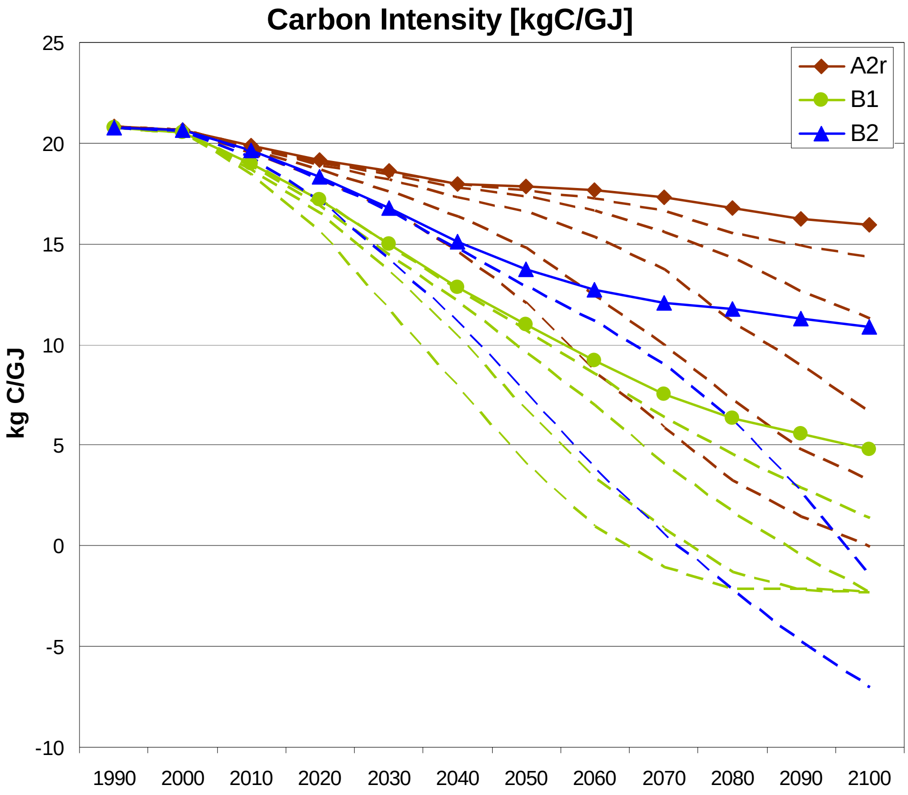


Figure 7. Carbon emissions per unit energy used (carbon intensity) across the three baseline scenarios and their stabilization counterparts. Note that negative values indicate exceedence of carbon sinks (natural and via carbon sequestration and storage) over emissions.

Figure 8 also shows the 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 even can turn negative as a result of very low emissions and large-scale carbon sequestration e.g. from biofuels.[10] It needs to be emphasized that these emission trajectories are the result from an intertemporal least-cost optimization framework with perfect foresight that in addition assumes full intertemporal, spatial, as well as sectorial flexibility (see also Section 3 below). In other words, the model calculations illustrate pathways towards climate stabilization assuming that emission 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 that 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

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

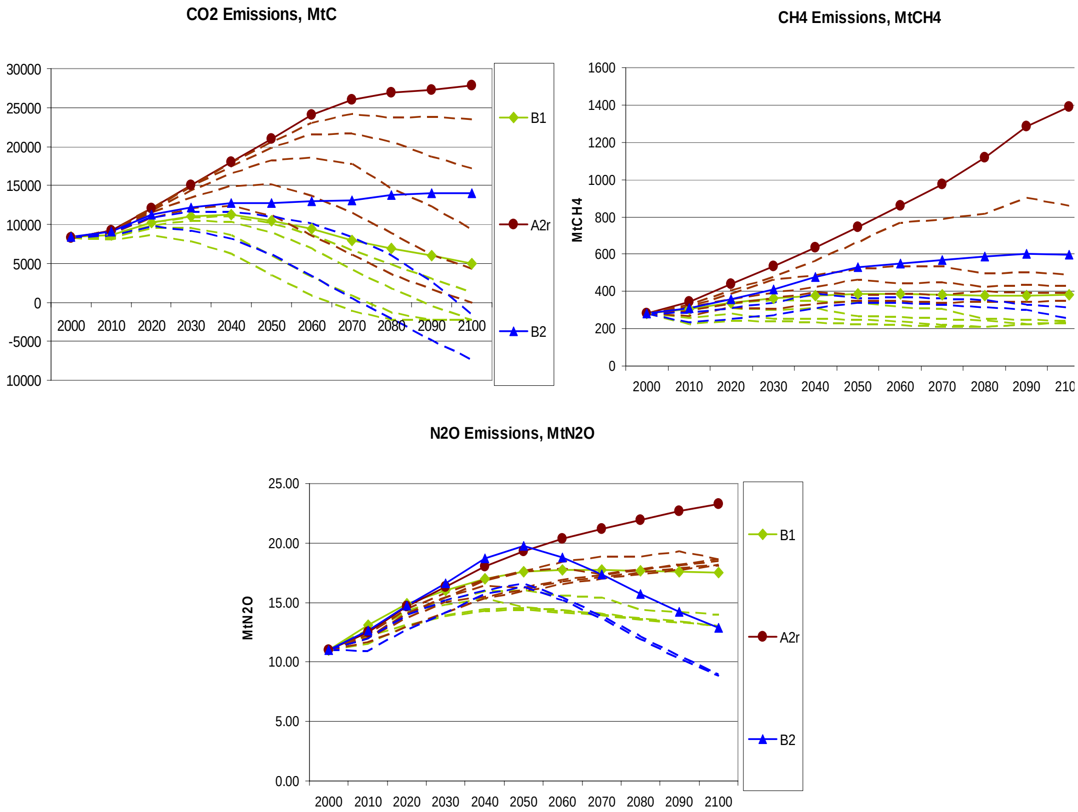

Figure 8. Greenhouse gas emissions in the scenarios (CO_2, in million tons elemental carbon), methane (million tons CH_4) and nitrous oxides (million tons N_20). Note that negative emission numbers for CO_2 indicate exceedence of natural and man-made sinks over emissions.

highly stylized. The resulting model calculations should there not be interpreted as prescripive but simple as "best case" illustrative scenarios of possible globally least-cost pathways towards climate stabilization.

Figure 9 positions our scenarios within the entire climate change scenario literature using two important pre-curser indicators for their potential for climate change: cumulative carbon emissions and atmospheric CO_2 concentrations. Through or 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 are indeed parsimonious as well as comprehensive in providing input to climate models.

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 between 2.7 (B1) to 4 degrees (A2r) towards the end of the 21st century, leading to sea level rise of between some 60-70 centimeters. Even in the lowest, most ambitious climate policy scenario (a 480 ppmv stabilization target imposed on the lowest baseline scenario B1), climate change remains inevitable: global mean temperature would still rise by some 1.6 degrees and sea level by some 40 centimeters. This most "climate benign" is also an excellent illustration that some climate change (and resulting impacts) will be inevitable, independently 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 as wella s the twin inertias of the climate and socio-economic systems that make instantaneous emission reductions impossible and result in a long-lasting "imprint" of emissions on the climate system.

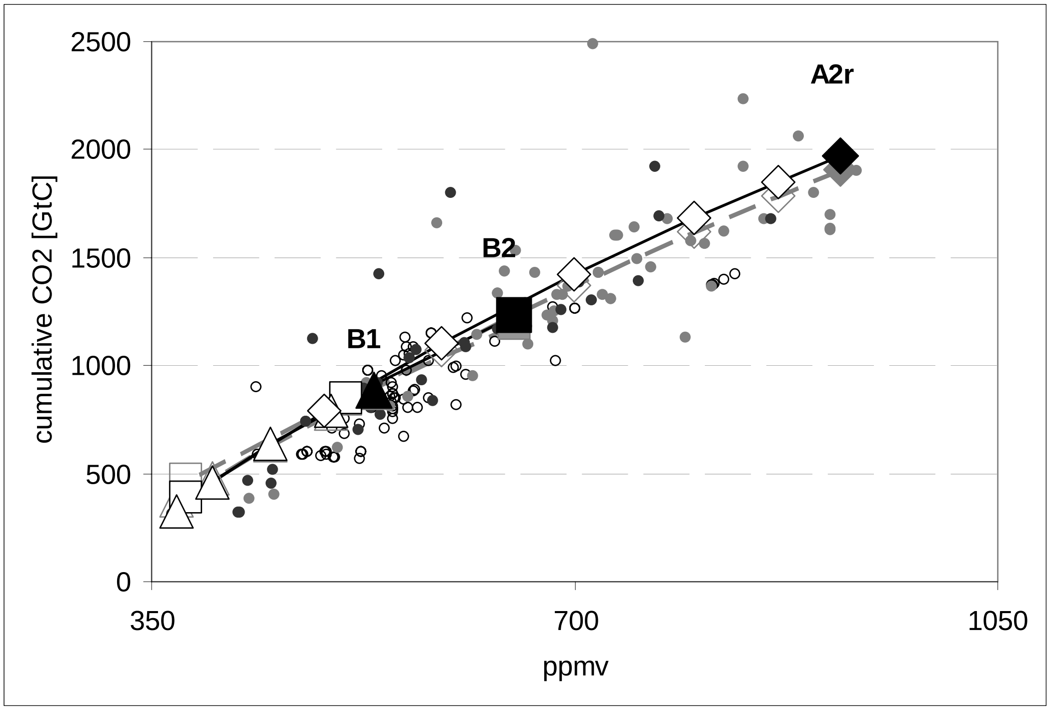

Figure 9. The scenarios in this paper compared to the climate change and mitigation scenario literature in terms of two important climate change precursor indicators (cumulative carbon emissions 1990-2100, in GtC, and corresponding atmospheric CO_2 concentrations, in ppmv).

	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 concentrations (ppmv)														
2000	368	368	368	368	368	368	368	368	368	368	368	368	368	368
2050	623	612	584	561	537	621	607	580	576	590	578	645	588	566
2100	792	673	591	522	482	1630	1388	1088	971	819	668	983	673	516
Radiative forcing (W/m2)														
2000	1.37	1.37	1.37	1.37	1.37	1.37	1.37	1.37	1.37	1.37	1.37	1.37	1.37	1.37
2050	4.17	4.08	3.83	3.61	3.38	4.16	4.03	3.79	3.75	3.89	3.77	4.36	3.87	3.67
2100	5.45	4.59	3.89	3.23	2.81	9.29	8.44	7.14	6.53	5.63	4.54	6.60	4.65	3.17
Temperature change (degrees C)														
2000	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
2050	1.70	1.68	1.61	1.56	1.49	1.44	1.40	1.33	1.33	1.40	1.41	1.72	1.55	1.53
2100	2.70	2.41	2.12	1.81	1.60	4.03	3.76	3.27	3.05	2.74	2.33	3.07	2.43	1.88
Sea level rise (cm)														
2000	7.58	7.58	7.58	7.58	7.58	7.58	7.58	7.58	7.58	7.58	7.58	7.58	7.58	7.58
2050	28.44	28.20	27.61	26.96	26.22	25.86	25.33	24.59	24.55	25.02	25.10	28.97	26.90	26.66
2100	57.00	53.94	50.18	46.31	42.97	69.64	66.62	61.03	58.58	55.95	51.53	61.17	53.42	47.30

Table 4. Main climate change outcomes of the scenarios analyzed.

3 Scenario Methodology and Model Linkages

For the development of the scenarios we use a set of interlinked disciplinary and sectorial models referred to as Integrated Assessment Modeling Framework (illustrated in Figure 10). The framework combines a careful blend of rich disciplinary models operating at alternative spatial resolution that are interlinked and integrated into an overall assessment framework. The framework covers all greenhouse-gas emitting sectors, including agriculture, forestry, energy and industrial sources for a full basket of greenhouse gases (GHGs), including CO_2, CH_4, N_2O, HFCs, CF_4, and SF_6. In contrast to the traditional model integration through 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, ensuring 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 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 (Gross Domestic Product) as well as regional population trajectories. Through a combination of decomposition and optimization methods world regional scenario results are then first disaggregated to the level of countries. In a subsequent second step, national results are further disaggregated to the grid-cell level, providing spatially explicit patterns of population and economic activities (see Gruebler et al., forthcoming). The latter indicators are particularly important for the spatially explicit modeling of land-cover changes in the forest and agricultural sector as they provide the basis for the estimation of consistent, internationally comparable indicators (such as relative land prices) defining the relative comparative advantage of agricultural and forestry based GHG mitigation options.

The regional, national, and spatially explicit demographic and economic projections serve as exogenous inputs to the three principal models of the IA-framework (Figure 10): DIMA (Rokityanskiy et al., fothcoming), AEZ/BLS (Fischer et al., forthcoming), and MESSAGE-MACRO (cf. Nakicenovic et al., 2000, and Rao and Riahi, 2006):

The DIMA model is used for the estimation of 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 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 (see Rokityanskiy et al., forthcoming).

The AEZ/BLS modeling framework provides a detailed account of the evolution of the agricultural sector. AEZ (agro-ecological zones) uses agronomic-based knowledge to simulate land resources 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 gridded intervals over the entire globe (e.g., Fischer et al., 2002a). In addition to land resource assessment and computation of potentially-attainable yield, this analysis included an agro-economic model for estimation of 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 (see, e.g., Fischer et al., 2002b). The BLS model consists of 34 national and regional geographical components covering the globe. In this study the AEZ/BLS framework was used for 1) the estimation of agricultural impacts of climate change and adaptation needs in terms of water supply, 2) the assessment of potential conflict of bioenergy and forest activities with food security, and 3) the estimation of changes in agricultural demand and commodities, the principal drivers of non-CO_2 greenhouse gases.

The MESSAGE-MACRO modeling framework comprises the systems engineering optimization model MESSAGE (Messner and Strubegger, 1995) and the top-down macroeconomic equilibrium model MACRO (Manne and Richels, 1992). MESSAGE and MACRO are linked iteratively, permitting 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 on 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 agricultural and forest 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 full integrated assessment framework. Its principal results comprise the estimation of technology specific multi-sector response strategies for a range of alternative climate stabilization targets.

A set of linkages between the models guarantee scenario consistency for a number of physical and financial scenario indicators. In particular, competition for land between food security, bioenergy, and afforestation/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 as well as primary agricultural drivers of non-CO_2 emissions.

A typical scenario development cycle comprises four main steps, 1) the development of spatially explicit economic and demographic projections, 2) the 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 MESSAGE-MACRO model at the level of 11 world-regions, and 4) the 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. emission reduction measures are assumed to occur when and where they are cheapest to implement. For the intertemporal optimization, we use a discount rate of 5 percent throughout all of the calculations reported here.

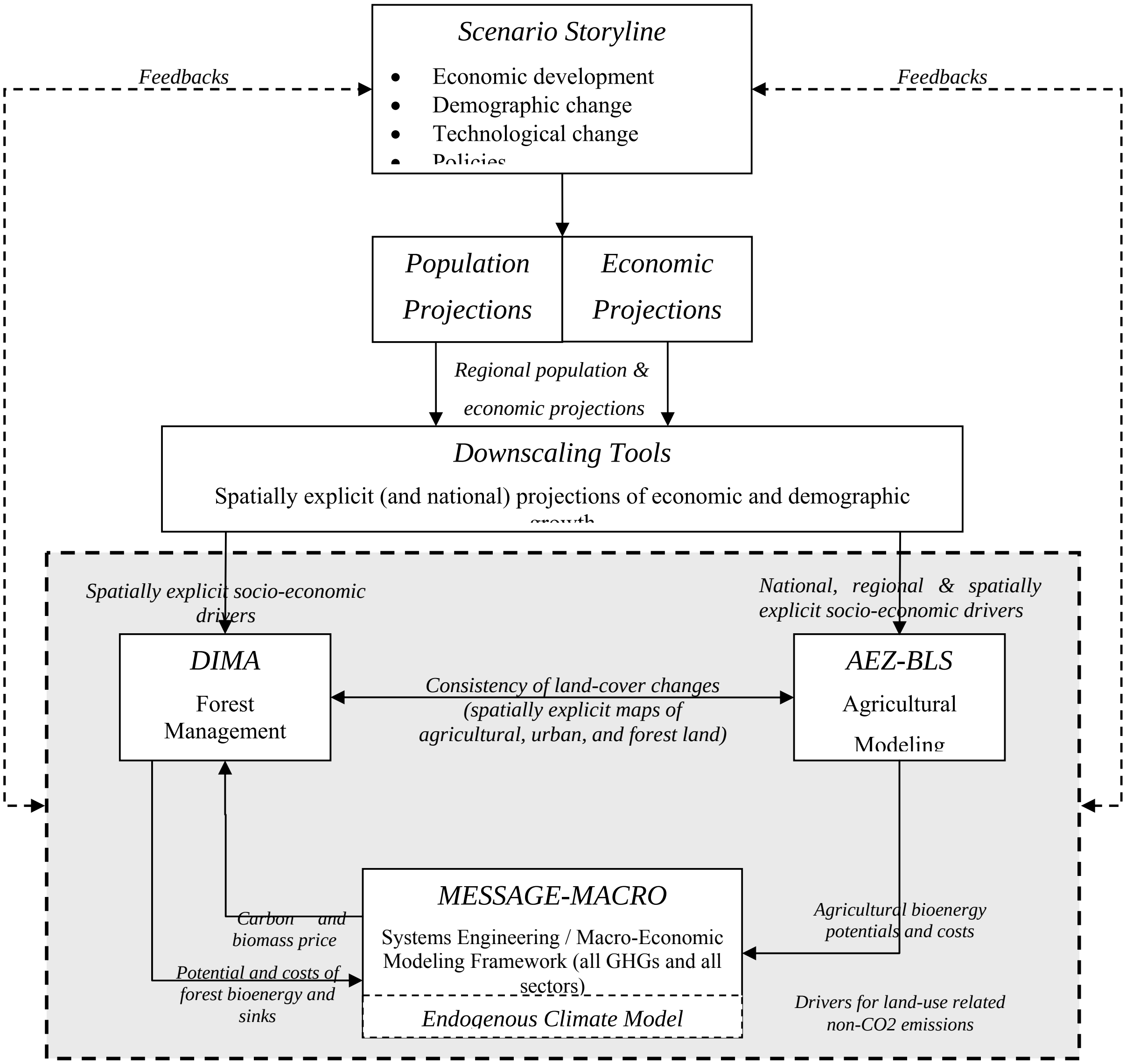

Figure 10: IIASA Integrated Assessment Modeling Framework

4 Summary of Scenario Results

This section summarizes main scenario results with respect to the portfolio of mitigation measures and the contribution of individual options for achieving various levels of stabilization of atmospheric GHG concentrations. Our scenario set considers two principal dimensions of uncertainty – the uncertainty with respect to the development path (baseline uncertainty), and the uncertainty 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 at the identification of measures that appear as robust choices given these uncertainties. For this purpose, we first explore the implications of 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 agricultural sectors as response to mitigation. Finally, we will look more deeply into the technological options within individual sectors, their potential, and deployment over time. By doing so we address the following main questions: Which economic sectors are central in 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 options that show significant contribution at modest carbon prices? What are the potential implication of stabilization for the forestry and agricultural sectors? And 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.

GHG mitigation options:

The abatement of GHG emissions can be achieved through a wide portfolio of measures in the energy, industry, agricultural and forest sectors, the principal sources of emissions and thus global warming. Measures for reducing 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 towards energy conservation and efficiency improvements. In addition, the capturing of carbon during energy conversion processes with subsequent storage in geological formations or the ocean (CCS) provide an “add-on” “end of pipe” approach for the decarbonization of fossil fuels allowing their continued use with low CO_2 emissions to the atmosphere (Riahi et al., 2004). 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 (Obersteiner et al., 2001): the carbon removed by plant growth from the atmosphere is captured and permanently stored (e.g. in geological formations) resulting 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 (for a discussion see Rokityanskiy et al., forthcoming).

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 percent of global warming since pre-industrial times (IPCC, 2001). Sources of CH_4 emissions include both, energy related ones like the extraction and transport of coal, natural gas, and oil, as well as 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 are agricultural soils. To a smaller extent N_2O emissions stem also 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. For more details on mitigation technologies and the methodology used to derive cost estimates see Rao and Riahi, 2006.

Baseline implications:

Assumptions concerning the future development path in absence of climate policies, such as socio-economic, demographic, and technological developments have important implications on emissions. The resulting wide range in baseline emissions reflect these baseline uncertainties, ranging from high emissions in A2r to more intermediate levels B2, and relatively low levels of emissions 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 have also major implications for feasibility and costs of mitigation options for any given stabilization level.

The three panels of Figure 11 illustrate the contribution of main mitigation measures in the three different baseline scenarios for achieving stabilization of GHG concentrations at an illustrative level of 670 ppmv CO_2-equivalent. The figure clearly shows the difference in the required mitigation efforts across the baseline scenarios that 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 Figure 16), 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.[11] In that sense, in a B1 world the stabilization at the 670 ppmv target is achieved primarily by adding “a bit more of the same” technologies as already included in the baseline. The main reason for this characteristic of the B1 stabilization scenario are the favorable technology

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[11] For details on the possible deployment of hydrogen technologies based on B1 see Baretto et al., 2003.

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 (incl. CCS), and methane emissions reductions. High growth of population and thus increasing demand for agricultural products together with heavy reliance on coal explains the high emissions in the A2r scenario baseline and the corresponding vast CO_2 and CH_4 emission reductions in a A2r world. In addition, biomass and nuclear are seen as main complementary technological building blocks of a future, which predominantly relies on conventional technologies and the classical steam cycle. Demand-side measures play also a particular important role, since the increase of energy prices due to the stabilization constraint is most pronounced in A2r (see also 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 are the mitigation of N_2O and F-gases, which show comparatively small potentials for abatement across all three scenarios examined.

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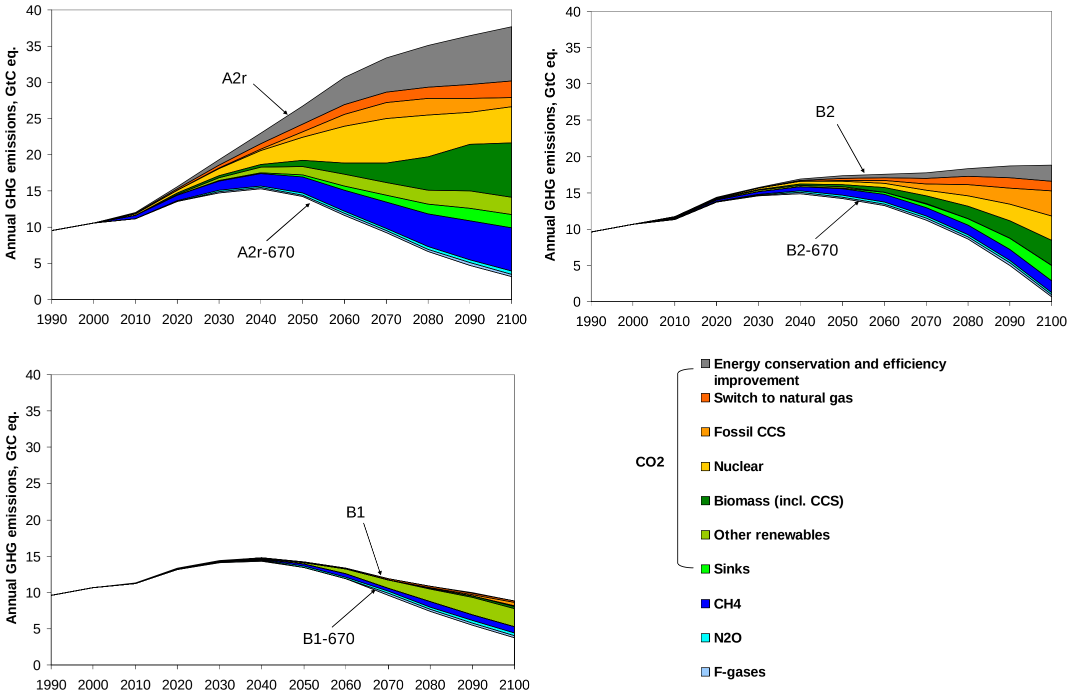

Figure 11: Contribution of main mitigation measures for the stabilization of CO_2-equivalent concentrations at 670 ppmv. The different panels show the portfolio of reduction measures deployed in the A2r, B2, and B1 scenario respectively.

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.

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 European Union-- have thus far been little analyzed in the literature (notable exceptions are Azar et al., 2006; Van Vuuren et al., forthcoming; and Rao and Riahi, 2006).

It is important to note that not all of the stabilization levels are attainable for each baseline scenario. While the B1 and B2 scenarios can each 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, 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 limiting 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, emphasizing again the importance of baseline scenario uncertainty or 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, for exploring 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 is covering the upper part of the range from 1400-670 ppmv CO_2-equivalent, B1 explores the lower range of stabilization levels (670-480 ppmv CO_2-equivalent).

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

- First, the figure illustrates the dominant role of CO_2 as the major source of GHG emissions and as target for emissions reductions across all baseline scenarios and stabilization targets. In both the A2r and B1 stabilization scenarios, the portfolio of measures for reducing CO_2 emissions account for between 55 to more than 80 percent of the total GHG emissions abatement. While the relative importance of CO_2 reductions for a specific stabilization level (see e.g., the overlapping 670 ppmv CO_2-equivalent stabilization scenarios in Figure 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 by Hyman et al., 2002 (that analyzed only a single baseline scenario, and put into questions claims (e.g. Hansen et al., 2000) that non-CO_2 gases could solve the climate stabilization problem “without sweat”.

- Second, our scenario results suggest that methane is the by far the most important non-CO_2 gas. Across all stabilization scenarios methane management contributes at least as much to total emissions reductions as all other remaining non-CO_2 gases combined. Like 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 & industry sectors. All stabilization scenarios concur that (independent of the baseline uncertainty) more than 80 percent of total emissions reduction would 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 agricultural and forest sectors are seen to contribute together between 10 to 17 percent of total emissions reductions. The relative contribution of these sectors is strongly dependent on the scenario baseline. Due to a number of cheap mitigation options (e.g., methane reduction from rice cultivation and life-stock; De Angelo et al., 2006), emission reductions in the agricultural sector are important contributors in scenarios of relatively modest stabilization targets. In contrast, the forest sector gains in relative importance at more stringent stabilization levels and thus higher marginal prices of carbon.

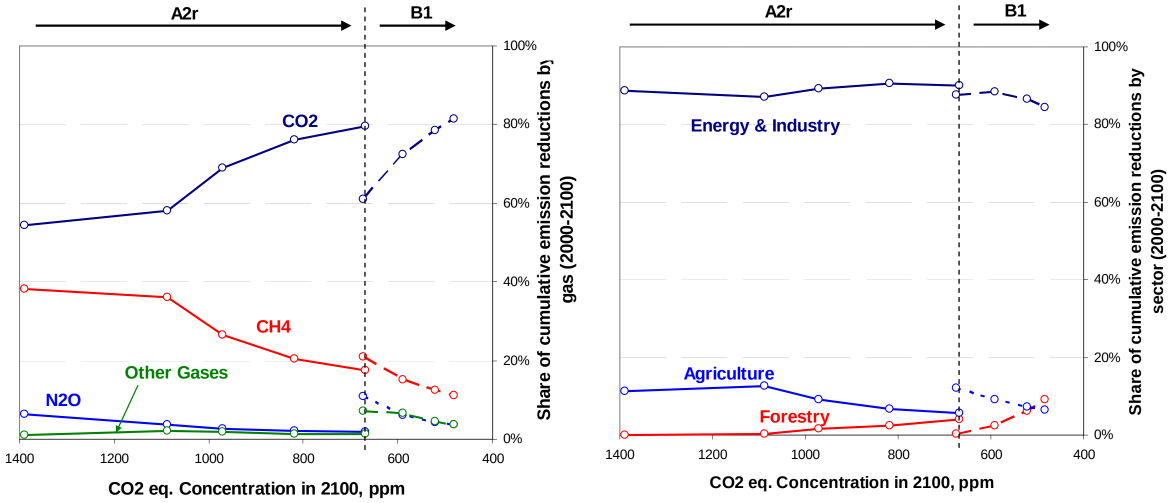

Figure 12: Contribution of principal sectors and GHGs as a function of the stabilization target (A2r scenarios from 1400 to 670 ppmv CO_2-equivalent, and B1 scenarios from 670 to 480 ppmv CO_2-equivalent.).

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 for meeting the respective stabilization target cost-effectively. Recent analysis using the MESSAGE-MACRO model (Rao and Riahi, 2006) indicate potential cost savings from the inclusion of non-CO_2 gases and forest sinks in the order of 50 percent. Similarly, an international modeling comparison exercise (Energy Modeling Forum 22; Van Vuuren et al., 2006) estimate ranges of cost savings of such a “multi-gas” stabilization strategy across different models of between 25 to 70 percent when considering the marginal price of carbon and of between 40 to 70 percent for the macroeconomic costs (GDP losses) of climate stabilization.[12]

Results from our analysis indicate also that the implementation of climate policies may lead to fundamental changes in the economics of the agricultural and the forest sector. This concerns in particular 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 would yield additional bioenergy expenditures of up to 450 billion US$ and 260 billion for sink enhancement activities (by 2100). This corresponds on aggregate to monetary flows into these sectors bigger than the present value of the global timber market or more than 50 percent 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 agricultural sector (see Table 5, and for a discussion Fischer et al., forthcoming).

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

(billion 1990US$)	2000	2020	2050	2100
Bioenergy expenditures*				
A2r	48	78	140	294
A2r-stab.	48	78 - 87	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.**	200	337	743	1537
Agricultural GHG mitigation costs				
A2r	0	0	0	0
A2r-stab.	0	0 - 3	0 - 11	4 - 13
Agricultural GDP***				
A2r	1273	1684	2384	3217
A2r-stab.**	1273	1684 - 1684	2384 - 2386	3242 - 3254

* Including non-commercial energy accounted at 1$/EJ

**Values refer to an intermediate target of 670 ppmv Co2-eq.

***Exclusive bioenergy. Data for 2100 are based on extrapolations from Fischer et al. (this Special Issue). Ranges for different climate scenarios from alternative GCMs (500-550 ppmv CO2 or approximately 670 ppmv CO2-eq.)

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[12] 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.

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 for reducing 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 Figure 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 don't. For example, while the contribution of nuclear is vast in the most stringent A2r stabilization scenario (equivalent to a reduction in cumulative carbon emissions of some 300 GtC), 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 for assessing the robustness of a particular 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 Figure 13). The combination of the two indicators, the average contribution across all scenarios and the robustness factor (RF), is used for estimating the importance of any individual measure/technology within the overall mitigation portfolio. Nuclear for example combines a high ranking with respect to average contribution with a very low robustness factor (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 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 robustness factor of 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 "robustness factor".[13] Biomass, in contrast, combines both a top ranking as well as a high calculated robustness factor (0.7), indicating its importance as part of the mitigation portfolio in the majority of the stabilization scenarios (irrespective of the baseline development path as well as the target uncertainty).

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[13] 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, making this option seemingly less "robust". An important area of future research will be to improve upon the definition of robustness factors in scenario analysis, including also deployment rates in baseline scenarios (e.g. by benchmarking all scenarios to a hypothetical static, calculatory baseline).

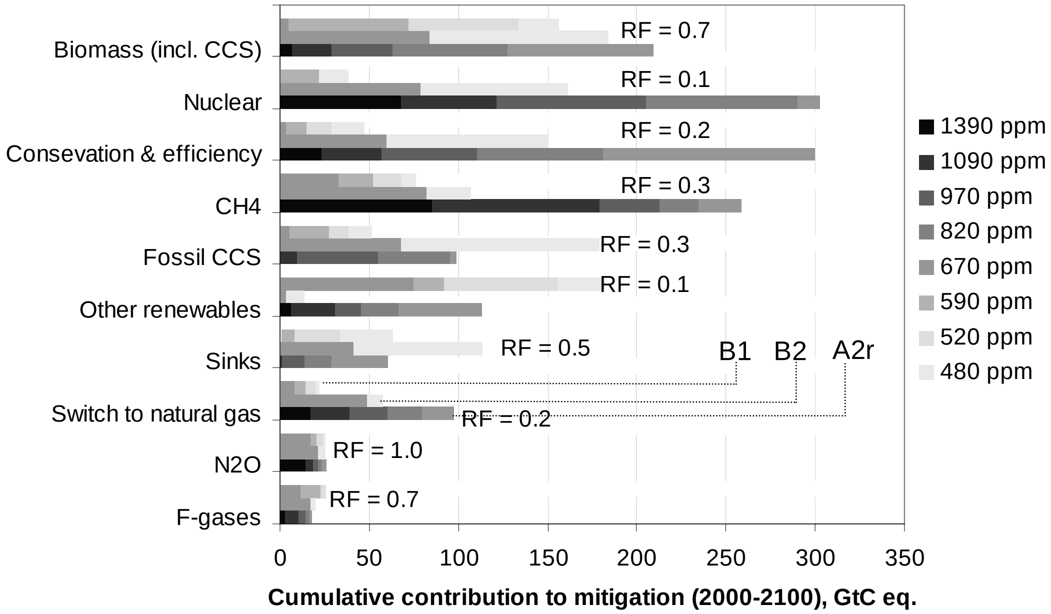

Figure 13: Cumulative contribution to emission reductions over the time horizon 2000-2100 by main mitigation measures (all stabilization levels and baseline scenarios) ranked according to their average contributions across all scenarios. RF denotes the robustness factor for individual measures.

The importance of biomass in the mitigation portfolio across different scenarios is primarily due to its flexibility as a fuel. It can be used in combination with fossil fuels (co-firing with coal; Robinson et al., 2003) e.g. in the A2r scenario, as well as stand-alone to produce electricity, hydrogen (Makihira et al. 2003) 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 (carbon capture and sequestration; Obersteiner et al., 2001). In the latter case the use of biomass would lead to net removal of CO_2 from the atmosphere, or negative emissions. Thus, biomass combined with CSS plays the part of a classical "backstop" technology in our scenarios explaining its comparatively robust deployment across all stringent mitigation scenarios. Its robustness in the mitigation portfolio is therefore also a function of the (non-)availability of alternative "backstops" portraying similar features, but which were however not examined in the present study.

Figure 14 shows the contribution of the three top-ranked mitigation measures as a function of the stabilization level in the A2r and B1 scenarios respectively. 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 1GtC per year over the course of the century). Also apparent from the figure is the more limited role of the two other top-ranked measures (nuclear and demand-side management) in the B1 scenario. To a large extent this conclusion results from our scenario design. The B1 baseline incorporates assumptions of rapid energy intensity and efficiency improvements. From the perspective of our mitigation modeling framework this is an “autonomous” process. The potential for additional mitigation induced by climate policy is limited as most of the efficiency and conservation potentials are already exhausted in the B1 scenario baseline. Similarly, the relatively low contribution of nuclear is due to the technology cost assumptions in B1, which tend to favor renewable alternatives.[14]

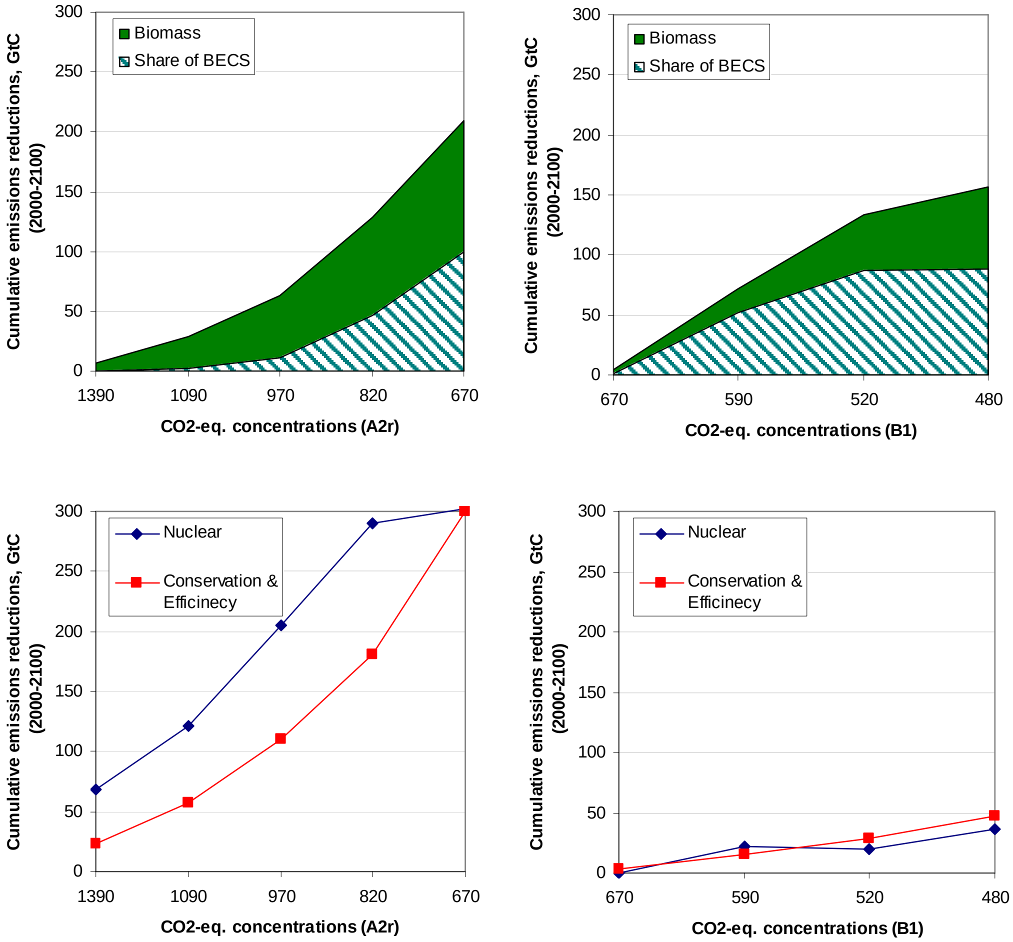

Figure 14: Cumulative contribution of top-ranked mitigation options (2000-2100) as a function of the stabilization target. Upper panels show biomass-related mitigation measures including the share of biomass-based carbon capture and storage (BECS). Lower panels give the contribution of nuclear and demand-side measures. A2r scenarios (left-hand panels) and B1 scenarios (right-hand panels). Note that the low contribution of nuclear and conservation and efficiency measures in the B1 stabilization scenarios are to a large degree dependent on assumptions that

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[14] A fuller scenario analysis on the respective uncertainty of the contribution of nuclear energy in a low demand, “high efficiency” scenario is provided in Nakicenovic et al., 1998. (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 in the Nakicenovic et al., 1998 study.)

define the B1 scenario baseline and that limit the potential contribution of these options in the stabilization scenario variants of the B1 baseline.

A number of mitigation measures cluster in the mid-ranks of Figure 13 above, depicting average cumulative contributions well above 50 GtC over the course of the 21st century. These are in particular CH_4 emisisons reductions, fossil CCS, non-biomass renewables (predominantly wind, solar and hydro), and forest sink enhancement. Most of these options (with exception of non-biomass renewables, which play a relatively minor role in the technologically cautious B2 scenario) generally share also a relatively high calculated robustness factors of 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 addressing N_2O, F-gases and the substitution among fossil fuels (in particular the shift towards 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 climate change constrained world. It is obvious from our analysis though that the prime target of mitigation measures are the energy and industry sectors. There is, however, less agreement as to which technologies will be the biggest contributors to future mitigation efforts.

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 changes 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 in order to meet the respective stabilization target. Reasons for this inertia are manifold. First, is the long-lived infrastructure of the energy system, with life-times in the order of 30 to 50 years, which makes replacement of the existing capital stock a lengthy process as accelerated rates of change would require a (costly) pre-mature retiring of capital stock. Secondly, the diffusion process of new and advanced technologies itself, from early stages of innovation to niche market applications, and large-scale commercial use, requires 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 e.g. illustrated by the example of nuclear, which was heavily supported by government subsidies from its early onset. It 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 (Grubler, et al., 1999).

Thus, many of today's most advanced technological options, such as e.g., the production of hydrogen through solar (or nuclear) processes or the combination of biomass with carbon capture and storage (BECS) are seen 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 methane with subsequent use for energy purposes.

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

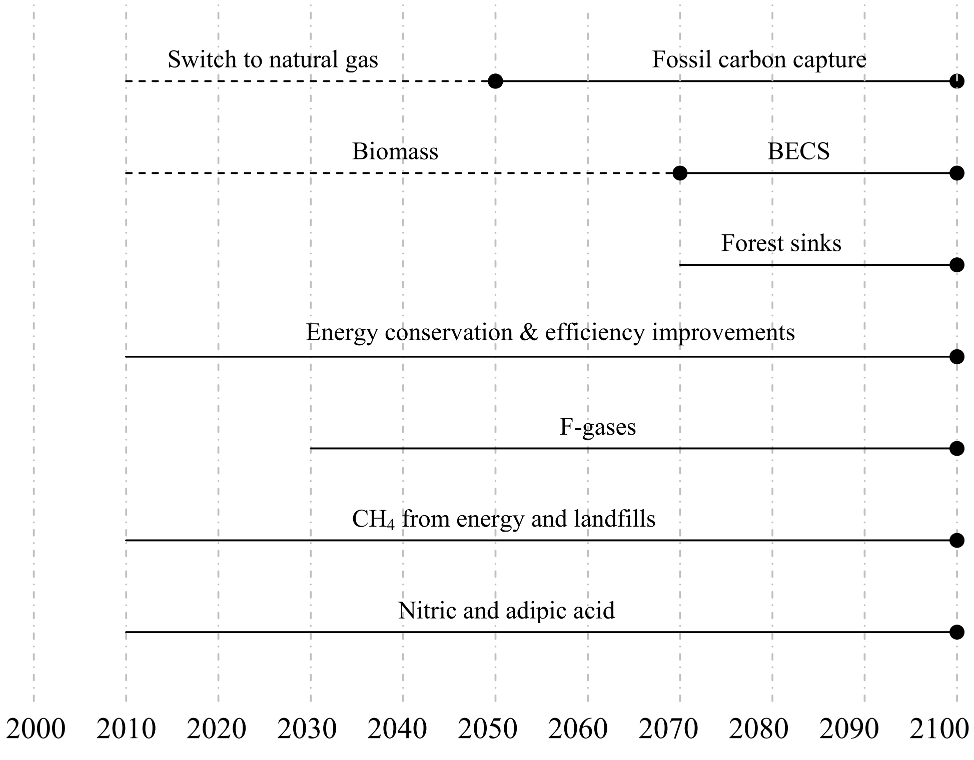

Figure 15: Timing of selected mitigation technology clusters in the scenarios.

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[15] For identifying whether a technology is contributing at a specific point in time, we use a threshold of 5 % of 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.

A number of mitigation options play out as important elements of climate stabilization efforts throughout the entire century-long time scale of our scenarios. These are in particular the above mentioned demand-side measures and CH_4 reductions from energy and landfills. In addition, industrial sources with mitigation potentials with low marginal costs, such as high efficiency catalytic reduction technologies in nitric acid production, also contribute to mitigation throughout the entire 21st century.

Mitigation Costs:

Figure 16 presents the development of costs for meeting 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 energy system costs differences over the entire time period of our scenario simulations.[16] 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 sector of GHG emissions, while the loss in GDP accounts for corresponding impacts of mitigation costs on the whole economy.

Costs generally increase with the stringency of the concentration target. Cost generally increase only modestly for meeting 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 due to uncertainties with respect to the socio-economic, demographic and in particular technological change in absence of climate policies is about 40.6 trillion in the B1 scenario, compared to more than 44.6 trillion in the most “expensive” A2r baseline scenario, i.e. some 4 trillion Dollars. The cost difference between the baseline scenarios is thus of similar magnitude as the cost impact of mitigation in order to attain the lowest possible stabilization level in the B1 scenario, where 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, also the cost for meeting a specific stabilization target is highly baseline dependent – for example, the system costs for a 670 ppmv target correspond to 40.8 trillion US$ in B1, 43.5 in Br, 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 percent (by 2100) in the case of 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 to 4.5 percent; Figure 16) would 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.

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

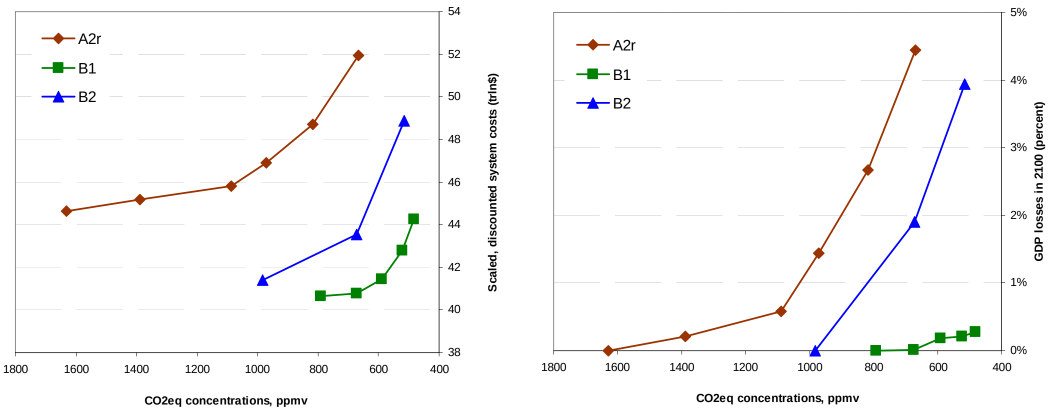

Figure 16: Net present value of energy system costs (2000-2100) and GDP losses (2100) for the three baseline scenarios and as a function of stabilization targets.

5 Summary and Conclusions:

Through our scenario analysis we have illustrated the importance of considering the two most fundamental uncertainties surrounding future efforts to mitigate against climate change: uncertainty of magnitude of future emission levels as described by alternative scenario baselines, and the uncertainty surrounding the ultimate mitigation target, i.e., the stabilization levels. Feasibility and costs, as well as technological options needed for meeting alternative climate stabilization goals all depend critically on these two types of uncertainties. Policy advice, ignoring these fundamental and inherent uncertainties in the climate change debate is therefore not only ill-placed but could be straightforward misleading. Our calculations once more confirm the value of considering uncertainties through a multi-scenario approach that while time consuming is nonetheless and indispensable tool for climate policy analysis.

Consistent with the vast majority of the scenario literature, our analysis confirms that the costs for achieving climate stabilization increases with the stringency of the stabilization target. However, the costs of meeting a specific target are highly (baseline) scenario dependent. Long-term stabilization of GHG concentrations is order of magnitudes 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, which is characterized by rapid global technology diffusion and transfer, and where 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 670 CO_2-equivalent (500 ppmv “CO2 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 feasibility and costs of mitigation than the choice of the long-term target itself. This suggests that policies aiming to influence scenario baselines in direction of low-carbon futures are a sensible hedging strategy given continued uncertainty about the ultimate target of climate stabilization levels, i.e.

continued uncertainty what ultimately may constitute a “dangerous interference with the climate system” in the parlance of the UNFCC.

From all the variables involved in framing 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 as 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) not only could alleviate the problem “upfront” (through lower baseline emissions), but also widen 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 resulting changes in economic incentives than being inherent characteristics of potential mitigation technologies themselves. Such an “induced innovation” perspective (cf. the reviews contained in Clarke and Weyant, 2002, Grubler et al., 2002, or Löschel, 2002) suggests that long-term costs of meeting a wide range of climate stabilization targets are uncertain. However this uncertainty is rather technologically “constructed” than given *ex ante* (for an illustration see Gritsevskyi and Nakicenovic, 2000). (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, i.e. to explore possible linkages and responses between environmental policies and the technological change these may induce.

An important finding from our sectorial analysis is that the energy and industry sectors will play a central role for achieving 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 percent of total mitigation is to be achieved in this sector. These reductions are cost-effective independent from 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 emission 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 forest 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 emissions mitigation potentials over the course of the 21st century. The three top-ranked mitigation options comprise reductions through 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 as framing both scenario baselines as well as mitigation potentials. There are also important linkages between end-use efficiency improvements as for instance resulting from the deployment of advanced technologies such as fuel cells and corresponding structural changes in energy supply (e.g. hydrogen production from a variety of sources) that are accelerated in the mitigation scenarios. This suggests that a narrow focus on supply side mitigation options alone is likely to fall short to harness 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, electricity) generally emerge as the most robust technology options: natural gas in the short-term (if available) and biomass in the long-term (however produced outside the traditional energy sector, i.e. in agriculture and forestry). Other renewables (solar, wind, hydropower) and nuclear are important mitigation options, however 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/technologies such as conventional “electricity only” nuclear or hydropower).

Large scale carbon capture and sequestration (beyond forest sink enhancements) portray the classical 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 the deployment of individual technologies over time and identified measures that appear robust across a wide range of stabilization scenarios for both the short term as well as the long-term. The mitigation portfolios of our scenarios over the first 50 years are dominated by “conventional” technologies, which interact synergistically with 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 over the course of the 21st century carbon capture and sequestration (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 just in the latter half of the century the combination with CCS emerges as an active carbon management option. It is also important to note that fossil-based CCS is generally deployed earlier in time in our scenarios than biomass-based CCS applications. The deployment of CCS measures is primarily driven by the increasing price of GHG reduction over time and the need of 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 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 for achieving 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" for successfully solving 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 effects can be moderated by appropriate anticipatory technology development strategies (e.g. carbon capture and sequestration for coal). Climate policies may lead in particular to fundamental changes in the economics within the agricultural and the forest 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 as the present global timber market or 50 percent of today's agricultural GDP. Addressing climate change thus changes significantly both economic incentives as well as "the rules of the game" across all GHG intensive sectors of the economy, creating both opportunities as well as threats. This picture of potential loosers and winners from climate mitigation within and across sectors adds to the well-known picture of winners and loosers of climate change impacts across countries, sectors, and ecosystems. Reconciling these diverse perspectives and interests may ultimately be the greatest climate policy challenge.

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