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Introduction and overview

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Abstract

This introductory paper gives the motivation for the EMF 19 study on technology and climate change policy, an overview of the design of the study, some aggregate model comparison results, and a brief introduction to the rest of this volume. The description of the study design includes the models, regions, and scenarios included in the study. The model comparison results focus on aggregate projections of economic growth, energy use, carbon emissions, fuel choice, and carbon taxes required to control carbon emissions.

This Special Issue of the Energy Journal is the first comprehensive report on a comparative set of analyses of the technologies and technology change specifications incorporated in climate change policy analyses. Organized by the Stanford Energy Modeling Forum (EMF), the objectives of this study were the same as for previous EMF studies: (1) identifying policy-relevant insights and analyses that are robust across wide ranges of models, (2) providing explanations for differences in results from different models, and (3) identifying high priority areas for future research. This study has produced a particularly rich set of results in all three areas, which is a tribute to the active participation of the modeling teams and the care each team took in preparing a paper for this volume.

The volume consists of a paper prepared by each modeling team on what it did and what it concluded from the model runs that were undertaken, preceded by this introduction and summary paper. This summary focuses on the motivation for the study, the design of the study scenarios, and the interpretation of results for the core scenarios, which all the teams ran. Each succeeding chapter contains ideas and insights drawn by the modeling teams from applying their models to issues they were able to address selected from a small set of important areas on which the group had mutually agreed to focus.

The reader is cautioned not to view the wide range of model results presented here as an expression of hopeless ignorance on the part of the analysts, but as a manifestation of the

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uncertainties inherent in projecting how the future will unfold with and without climate change policies. The uncertainties highlighted here are endemic in the operation of our world or the result of limitations in our understanding of it. The models do not produce these uncertainties. They make them more transparent and help assess their magnitudes. This is important in the analyses of climate policies because of the complexities and interdependencies involved.

The climate change debate is often posed as an all or nothing choice about whether or not we are serious about a problem that could have disastrous consequences. However, we know that the problem may turn out to be more or less serious than currently envisioned and that we can change our course of action in subsequent years as more is learned about the nature of the problem and its potential solutions. It is also often asserted that the models do not provide useful information because they sometimes produce different results. Nothing could be further from the truth; by comparing results from alternative modeling systems we gain additional information about the relationships between assumptions and outputs that are not available when results from a single model or a single expert are considered.

This introduction starts with a brief discussion of the UN Framework Convention on Climate Change (UNFCCC), and the Conference of Parties process set out in the UNFCCC. Next the scenarios designed by the group to examine the implications of different carbon emission reduction pathways are described. A summary of key common results and interpretations of model differences that were developed from a review of results for the core scenarios follows. This sets the stage for the papers prepared by the modeling teams which follow.

1. A brief history of the FCCC

The United Nations Framework Convention on Climate Change was adopted on May 9, 1992, and was opened for signature at the UN Conference on Environment and Development in June 1992. The Convention entered into force on March 21, 1994, 90 days after receipt of the 50th ratification. 188 countries currently have ratified it. One of the key elements of the UNFCCC was a set of voluntary commitments to stabilize carbon emissions at 1990 levels by 2000 by the developed countries listed in Annex I of the Convention document (dominantly the OECD countries, the countries in Eastern Europe and the states of the former Soviet Union—e.g., the Russian Federation, the Ukraine, Belarus, etc.,—which, thus, became known as the "Annex I" countries). Most countries have still not achieved this objective.

The first meeting of the Conference of the Parties to the FCCC (COP-1) took place in Berlin from March 28–April 7, 1995. In addition to addressing a number of important issues related to the future of the Convention, delegates reached agreement on what many believed to be the central issue before COP-1-adequacy of commitments, the "Berlin Mandate" to establish binding emission limitations for Annex I countries beyond the year 2000. At that point, an open-ended Ad Hoc Group on the Berlin Mandate (AGBM) was established to begin a process toward appropriate action for the period beyond 2000, including the strengthening of the commitments of Annex I Parties through the adoption of a protocol or some type of legal instrument. COP-1 also requested the Secretariat to make arrangements for sessions of a Subsidiary Body on Science and Technological Advice (SBSTA) and a

Subsidiary Body on Implementation (SBI). SBSTA would serve as the link between scientific, technical and technological assessments, the information provided by competent international bodies, and the policy-oriented needs of the COP. During the AGBM process, SBSTA addressed several issues, including the treatment of the Intergovernmental Panel on Climate Change's (IPCC's) Second Assessment Report (SAR). SBI was created to develop recommendations to assist the COP in the review and assessment of the implementation of the Convention and in the preparation and implementation of its decisions.

The AGBM met eight times between August 1995 and December 1997. During the first three sessions delegates focused on analyzing and assessing possible policies and measures to strengthen the commitments of Annex I Parties, on how Annex I countries might distribute or share new commitments and on whether commitments should take the form of an amendment or Protocol. AGBM-4, which coincided with COP-2 in Geneva in July 1996, completed an in-depth analysis of the likely elements of a Protocol and the participating States appeared ready to prepare a negotiating text. At AGBM-5, which met in December 1996, delegates recognized the need to decide whether or not to allow mechanisms that would provide Annex I Parties with flexibility in meeting quantified emission limitation and reduction objectives (QELROs).

As a protocol on climate change was drafted during the sixth and seventh sessions of the AGBM, in March and August of 1997, respectively, delegates created a negotiating text by merging or eliminating some overlapping provisions within the myriad of proposals. Much of the discussion centered on a proposal from the European Union (EU) for a 15% cut in a "basket" of three greenhouse gases by the year 2010 relative to 1990 levels. In October 1997, as AGBM-8 began, US President Bill Clinton made a call for "meaningful participation" by developing countries in the negotiating position he announced in Washington. This statement rekindled some of the major debates that had preceded the tentative agreement reached in 1995; G-77/China[1] involvement was once again linked to the level of commitment acceptable to the US. In response, the G-77/China distanced itself from anything that could be interpreted as new commitments.

The Third Conference of the Parties (COP-3) to the FCCC was held from December 1–11, 1997 in Kyoto, Japan. Over 10,000 participants, including representatives from governments, intergovernmental organizations, Non-Government Organizations (NGOs) and the press, attended the Conference, which included a high-level segment featuring statements from over 125 ministers. Following a week and a half of intense formal and informal negotiations, Parties to the FCCC adopted the Kyoto Protocol on December 11, 1997; it was opened for signature on March 16, 1998 at United Nations Headquarters, New York. Subsequent COPs in Buenos Aries in 1998 (COP-4), Bonn in 1999 (COP-5), the Hague in 2000 (COP-6), Marrakech in 2001 (COP-7), New Dehli in 2002 (COP-8), and Milan in 2003 (COP-9) largely focused on discussion and debate regarding the possible implementation of the Kyoto Protocol.

The Protocol is subject to ratification, acceptance, approval or accession by Parties to the Convention. It enters into force on the 90th day after the date on which not less than 55 Parties to the Convention, incorporating Annex I Parties which accounted in total for at least

[1] The G-77 was originally a group of 77 developing countries, but now refers to a coalition of virtually all non-Annex I countries except China which joins it in supporting positions on many matters.

55% of the total carbon dioxide emissions for 1990 from that group, have deposited their instruments of ratification, acceptance, approval or accession. As of March 15, 2004, 120 countries had signed the Kyoto Protocol, but those countries represent only 44.2% of global carbon emissions in 1990.

2. The EMF 19 process

Whether one questions the ultimate implementability of the Kyoto Protocol, or simply recognizes the need to go beyond it in the longer term, attention has shifted back to longer-run policies that might stabilize the concentration of greenhouse gases in the atmosphere by mid- to late in the new century. One high leverage way to achieve this objective is the development and dissemination of new greenhouse gas emission reduction technologies. These would range from improved efficiency fossil fuel technologies, to renewable energy technologies, to improved energy efficiency technologies to carbon capture and sequestration technologies.

The EMF 19 study was entitled, "Technology and Global Climate Change Policies." The primary focus of this effort was understanding how models being used for global climate change policy analyses represent current and potential future energy technologies, and technological change. The working group for this study included key government and industry technology evaluators, developers and keepers of relevant technology databases, economists interested in technology, technological change and technology policy, and global climate policy modelers. This study includes models developed from around the world (e.g., Australia, Germany, Netherlands, Japan and the U.S.).

Estimates of the costs of alternative global climate change policies depend strongly on assumptions about the cost and performance of current and future technologies. The technology assumptions that have been made in constructing many widely cited baseline scenarios and policy excursions made from them are not well understood. This situation leads to confusion about what technologies and technology strategies are already included in the available projections.

This effort involved global models developed around the world (e.g., Australia, Germany, Netherlands, Japan and the United States) will also allow us to develop the appropriate international research support for adopting a more global perspective. An organizational meeting for this study was held in Snowmass, CO in August of 1999 Presentations were made by representatives of each of the groups mentioned above and it was decided to ask the modeling teams to provide information on: (1) the technologies included in the model's typical baseline scenario, (2) what technologies would be employed if no new technologies were introduced after 2000, and (3) the technologies included in the model's projection of a 550 ppm carbon dioxide in the atmosphere scenario. It was also decided to look at a very broad range of technology options. The following categories of technologies were included: (1) energy supply technologies, including solar, wind, advanced nuclear, hydrogen, biomass, etc., (2) energy demand technologies, (3) carbon sequestration technologies, and (4) biological sequestration.

A second meeting was held in March 2000 in Washington, DC. The March meeting focused on the available estimates of the costs and performances of carbon-sequestration technologies, the costs of abating other, non-carbon greenhouse gases, and the various approaches for representing technological change in the available global models. The modelers will simulate several scenarios that will help to identify the major technology options that are important in both the baseline and the constrained greenhouse-gas cases. This work will be combined with technical assessments of the costs and performances of promising technologies, based upon available databases.

The group reviewed initial results from technology scenarios at its third meeting in Snowmass, CO, in early August of 2000. Where appropriate, participants updated these technology scenarios. A fourth meeting took place at Stanford University in February 2001. At that meeting, sensitivities on GDP growth and sequestration costs were examined and new scenarios considering alternative rates of increase in a global carbon tax and alternative baseline assumptions were proposed. The results for these scenarios were reviewed at a modelers meeting at the International Institute for Applied Systems Analysis (IIASA) in Vienna in June of 2001. A large workshop on modeling technological change took place in Washington, DC on June 5–7, 2001, and a modelers meeting in conjunction with the 20th annual meeting of the International Energy Workshop (IEW) at the International Institute for Applied Systems Analysis (IIASA) on June 19–21, 2001. A fifth meeting of the Working Group took place in February of 2002. In mid-2002 it was decided to put together a book length report on the study focusing on how the models currently represent technology and technological change and the implications of those specifications/assumptions on model results for a number of simple baselines and intervention scenarios. Subsequently, it was decided to publish the report in the form of a special issue of this journal and papers were prepared, reviewed, and revised over the ensuing year.

3. EMF 19 scenarios

The modeling teams were asked to run three types of scenarios with respect to restrictions on carbon emissions: (1) reference scenarios, assuming no new climate policies, (2) stabilization scenarios where the concentration of CO_2 in the atmosphere is assumed to be limited to 550 parts per million, and (3) scenarios where a tax (or its equivalent) of US$100 per ton is assumed to be phased in at various rates over the century.

Two Reference scenarios were included—a Modeler's Reference Scenario and a Standardized Reference Scenario based on the IPCC Special Report on Emissions Scenarios (SRES) B1 Scenario. Three carbon tax trajectories were included with the rate of the increase in the tax range from US$10 per ton per decade, to US$25 per ton per decade to the whole US$100 in one decade. Finally, Sensitivity analyses on sequestration costs for the stabilization and US$10 per ton per decade scenarios. The 10 study scenarios are shown in Table 1.

Due to space limitations here and the fact that all the teams ran the Modelers Reference and 550 PPM Stabilization Scenarios, results from those two scenarios are emphasized in this overview. In addition, the focus here is predominantly on global totals, although most of the modeling teams produced detailed regional projections. Table 2 shows the regional reporting scheme adopted for the study. For additional model comparisons for other

Table 1
Scenarios considered

Scenario	Description
(1) Modeler's Reference	Each team uses the "no new climate policy" assumptions it feels most comfortable with.
(2) Standardized Reference	Each team uses standardized population and GDP assumptions from the IPCC's Special Report on Emissions Scenarios B1 scenario.
(3) 550 PPM wrt Modelers Reference	The concentration of CO_2 in the atmosphere is limited to 550 ppmv run relative to the Modeler's Reference case.
(4) 550 PPM/High Sequestration Costs	A 550 ppmv case (scenario 3) with a 50% increase in sequestration cost assumptions
(5) 550 PPM/Low Sequestration Costs	A 550 ppmv case (scenario 3) with a 50% decrease in sequestration cost assumptions
(6) +US$10/ton per Decade Carbon Tax	A carbon tax increase case which starts with a US$10/metric ton carbon tax in 2010 and increases by US$10 per decade from then on.
(7) +US$10/ton per Decade Carbon Tax/High Seq. Costs	A +US$10/ton per decade case (scenario 6) with a 50% increase in sequestration cost assumptions.
(8) +US$10/ton per Decade Carbon Tax/Low Seq. Costs	+US$10/ton per decade case (scenario 6) with a 50% decrease in sequestration cost assumptions.
(9) +US$25/ton per Decade Carbon Tax	A US$25/metric ton carbon tax in 2010, increasing by US$25/metric ton per decade until 2040, and then held at the US$100/metric ton level through the end of the century.
(10) A +100/metric ton carbon tax	A US$100 per ton carbon tax imposed in 2010 and held at that level through the end on the century.

regions and scenarios, see the EMF Web site at: http://www.stanford.edu/group/EMF/home/index.htm.

4. The models

The models that participated in the study so far are shown in Table 3. All of the modeling teams listed have expressed an interest in continuing to participate in the work of the technology study group.

Table 2
EMF 19 regional reporting scheme

Annex I	Non-Annex I
US	China
OECD-Europe	India
Japan	Mexico and OPEC
CANZ (Canada/Australia/New Zealand)	ROW (Rest of World)
OECD Total	Non-Annex I Total
EEFSU (East Europe and Former Soviet Union)	Non-OECD Total
Non-OECD Annex I	(=Non-Annex I+non-OECD Annex I)
Annex I Total	
Global Total	

Table 3
Models participating in EMF 19 study

ABARE-GTEM (Global Trade and Environment Model)	Brian Fisher/Vivek Tulpule/Darren Kennedy/Steve Brown (ABARE)
AIM (Asia Integrated Model)	T. Morita, M.Kainuma (NIES, Japan) Yuzuri Matsuoka (Kyoto University)
AMIGA (All Modular Industry Growth Assessment)	Don Hanson (Argonne National Laboratory)
(DNE21) (Dynamic New Earth 21)	Kenji Yamaji/Yasumasa Fujii (University of Tokyo) Keigo Akimoto (RITE)
FUND (Climate Framework for Uncertainty, Negotiation, and Distribution)	Richard Tol (Vrije Universiteit Amsterdam)
TIMER (TARGETS-IMAGE Energy Regional model)	Detlev Van Vuuren, Tom Kramm, Bert DeVries
GRAPE (Global Relationship Assessment to Protect the Environment)	Atsushi Kurosawa (Institute for Applied Energy, Japan)
Maria-8 (Multiregional Approach for Resource and Industry Allocation)	Shunsuke Mori (Science University of Tokyo)
MARKAL-Europe (MARKet Allocation Model)	Kloen Smekens (ECN, Netherlands)
MERGE 4.2 (Model for Evaluating Regional and Global Effects of GHG Reductions Policies)	Alan Manne (Stanford University) Richard Richels (EPRI)
MESSAGE (Model for Energy Supply Strategy Alternatives and Their General Environmental Impact)	Leo Schrattenholzer (IIASA) Keywan Riahi (IIASA) Shilpa Rao (IIASA)
MiniCAM (Mini-Climate Assessment Model)	Jae Edmonds (Pacific Northwest National Lab) Sonny Kim (Pacific Northwest National Lab) Hugh Pitcher (Pacific Northwest National Lab) Ron Sands (Pacific Northwest National Lab)
MIT-EPPA (Emissions Projection and Policy Analysis Model)	Henry Jacoby/John Reilly (MIT) Mustafa Babiker/Ian Sue Wing (MIT)
SGM (Second Generation Model)	Jae Edmonds (Pacific Northwest National Lab) Hugh Pitcher (Pacific Northwest National Lab) Ron Sands (Pacific Northwest National Lab)

In many models, technologies are represented with "production functions" that specify what combinations of inputs are needed to produce particular outputs. The production function specifies the rates at which inputs can be substituted for one another in response to shifts in input prices. As new capital investment occurs and older capital is retired, the technology mix within the model will change.

Two basic types of production functions may be specified. Some models (e.g., ABARE-GTEM, SGM, and EPPA—see box for information on models cited in the text) use smooth and continuous aggregate production functions that allow incremental input substitutions as prices change, even if the resulting input configuration does not correspond to a known technology. These models do not represent individual technologies. Such models often assume 'nested' production functions: For example, at one level, substitutions are possible between energy, capital, and labor in producing final commodities; at a second level, substitutions are possible between electricity and fuel oil in producing energy; and, at a third level, substitutions are possible between coal and natural gas in producing electricity.

In contrast, other models (e.g., Markal-Europe) draw from a 'menu' of discrete technologies, each requiring fixed input combinations—i.e., each technology is essentially represented with its own production function. This approach is often referred to as "process analysis." These combinations correspond to those employed in actual, or anticipated, technologies that the modeler specifies. The technology-rich Markal-Europe model specifies over 200 separate technologies. For discrete technology models, different technologies become cost effective as input prices change. Modelers then assume that these technologies are selected and used to produce outputs. A number of models use a process analysis approach within the energy sector and an aggregate production approach for the remainder of the economy (e.g., MERGE, DNE21, GRAPE). When using either approach, it is important to be able to distinguish between the causes of changes in the selections the models make among the existing technologies. Sometimes the technology choice changes because of changing prices, and sometimes it changes because of new technologies becoming available.

Some models represent both individual energy supply technologies and individual energy consumption technologies, and do not represent the remainder of the economy explicitly. With these models, however, the analyst must either: (1) assume that "end-use" energy demands (such as the demand for home heating and automotive transport) do not respond to changes in the prices of those services, or (2) employ a complex statistical estimation technique (that requires some historical data on the cost of end-use energy equipment) to estimate the price responsiveness.

Thirteen modeling teams participated in this exercise, with half of them based in the US and half outside of it. Each team made a special effort to run the five scenarios discussed here, and selected additional scenarios to run in accordance with their interests and model capabilities. The models are identified in Table 3. For a list of principal model architects, see the individual papers in the balance of this volume.

Given space limitations, it is not possible to give a complete report on what was learned from the model comparisons, but we can give the reader a good feel for the kinds of insights that were developed by focusing on one issue (international emissions trading), and a small number of economic and environment variables (carbon emissions, GDP, total primary energy and carbon taxes/incremental value of carbon emissions). With this background we can also describe what happens when one looks beyond these scenarios/measures in more detail.

5. Baseline emission, energy, and technology projections

One of the major determinants of the cost of satisfying the constraint in each region is the level of emissions projected to occur in that region in the absence of the constraint during the budget period. Other things being equal, the higher the projected baseline emissions, the higher the cost of satisfying the constraint. In the EMF 19 study we asked each modeling team to prepare its own reference case (or baseline) projection of carbon emissions in each world region.

Modelers' Reference case global carbon emission projections for Annex I countries are shown here in Fig. 1. A wide range of projected carbon emissions reveals itself by the

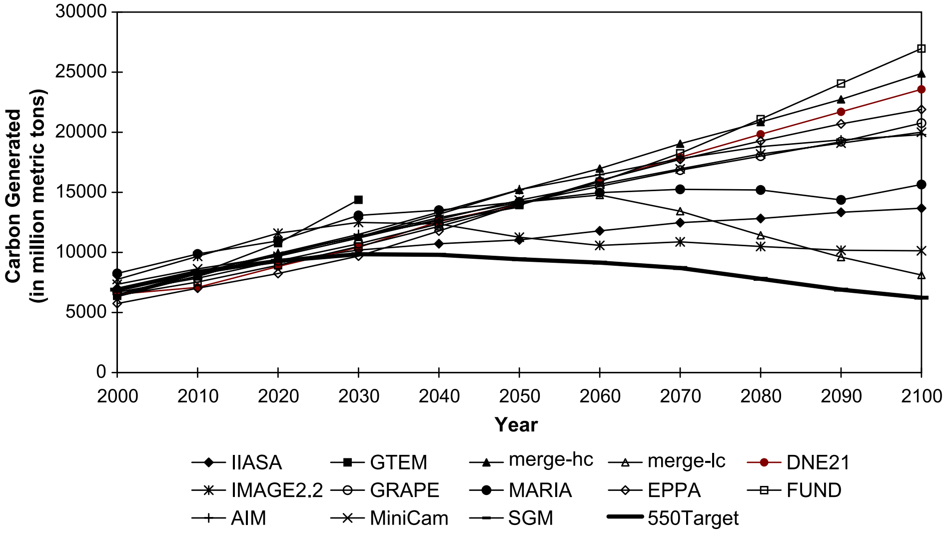

Fig. 1. Range of world carbon emission projections from models and WRE 550 ppmv CO_2 concentration target emissions limits.

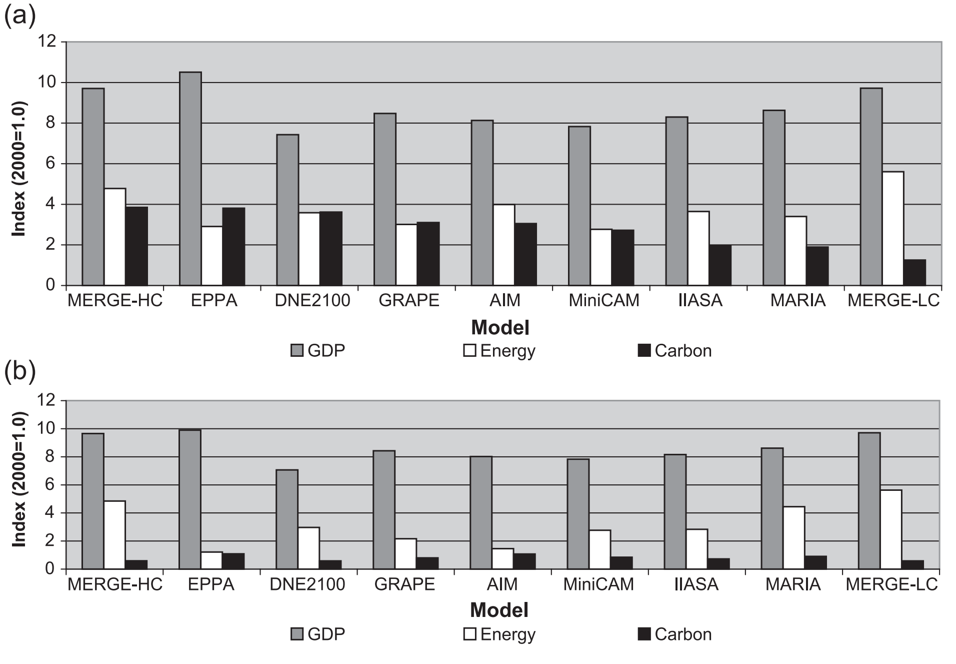

Fig. 2. (a) World carbon emissions drivers for the reference scenario between 2000 and 2100. (b) World carbon emissions drivers for the 550 ppmv scenario between 2000 and 2100.

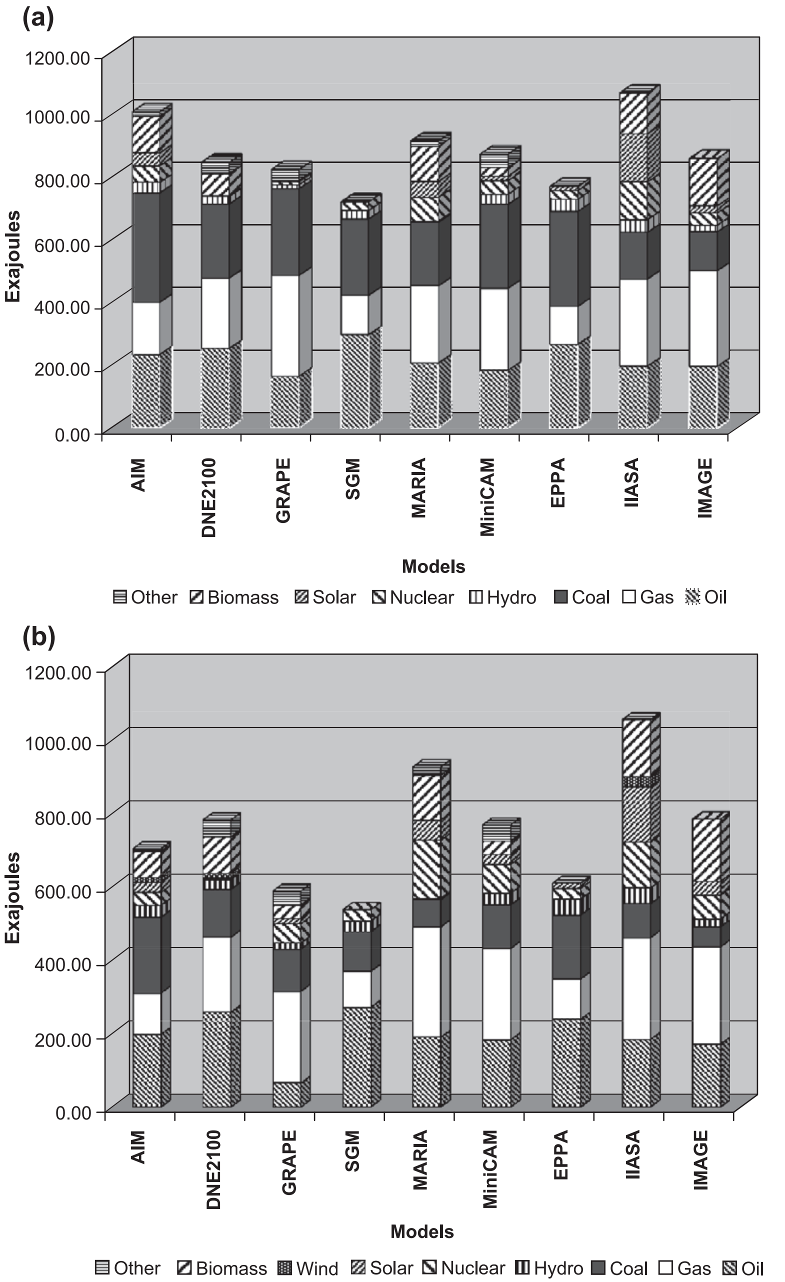

Fig. 3. (a) Reference scenario world primary energy—2050. (b) World primary energy in the 550 PPM scenario in 2050.

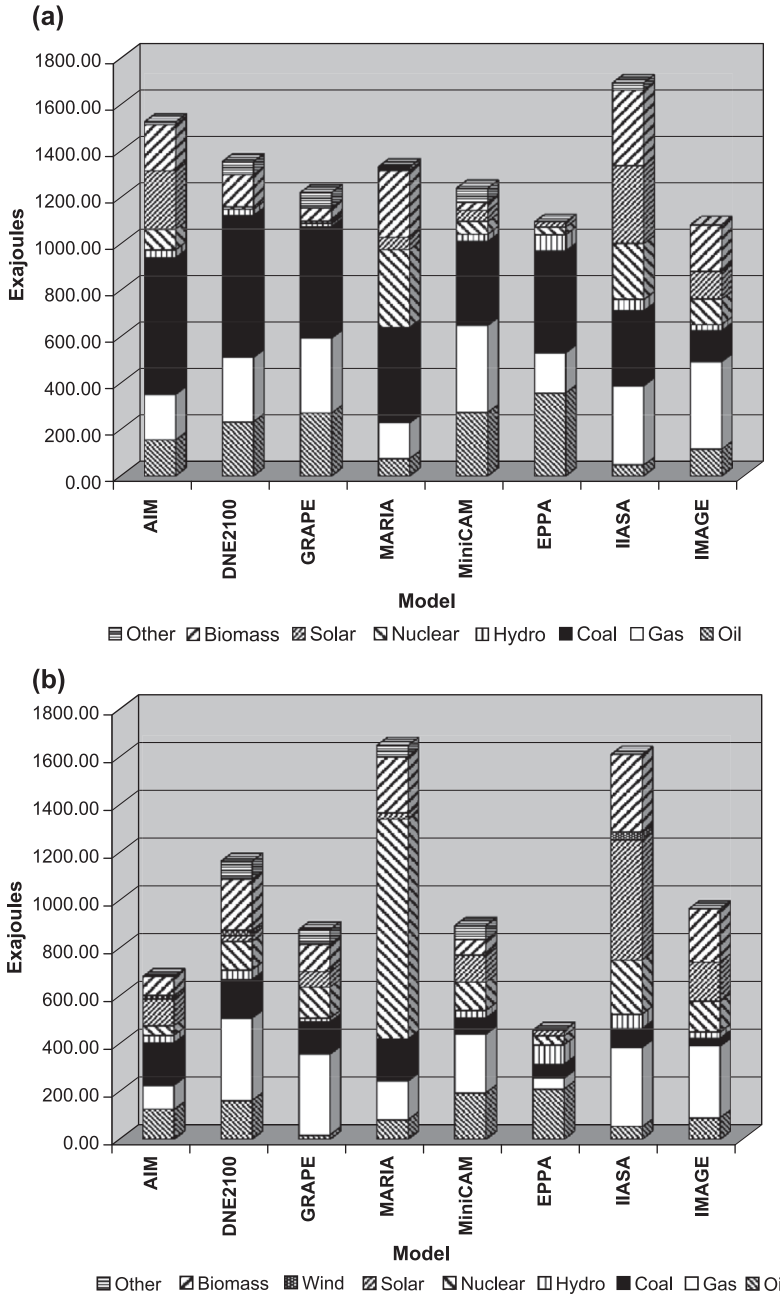

Fig. 4. (a) Reference scenario world primary energy in 2100. (b) World primary energy in the 550 PPM scenario in 2100.

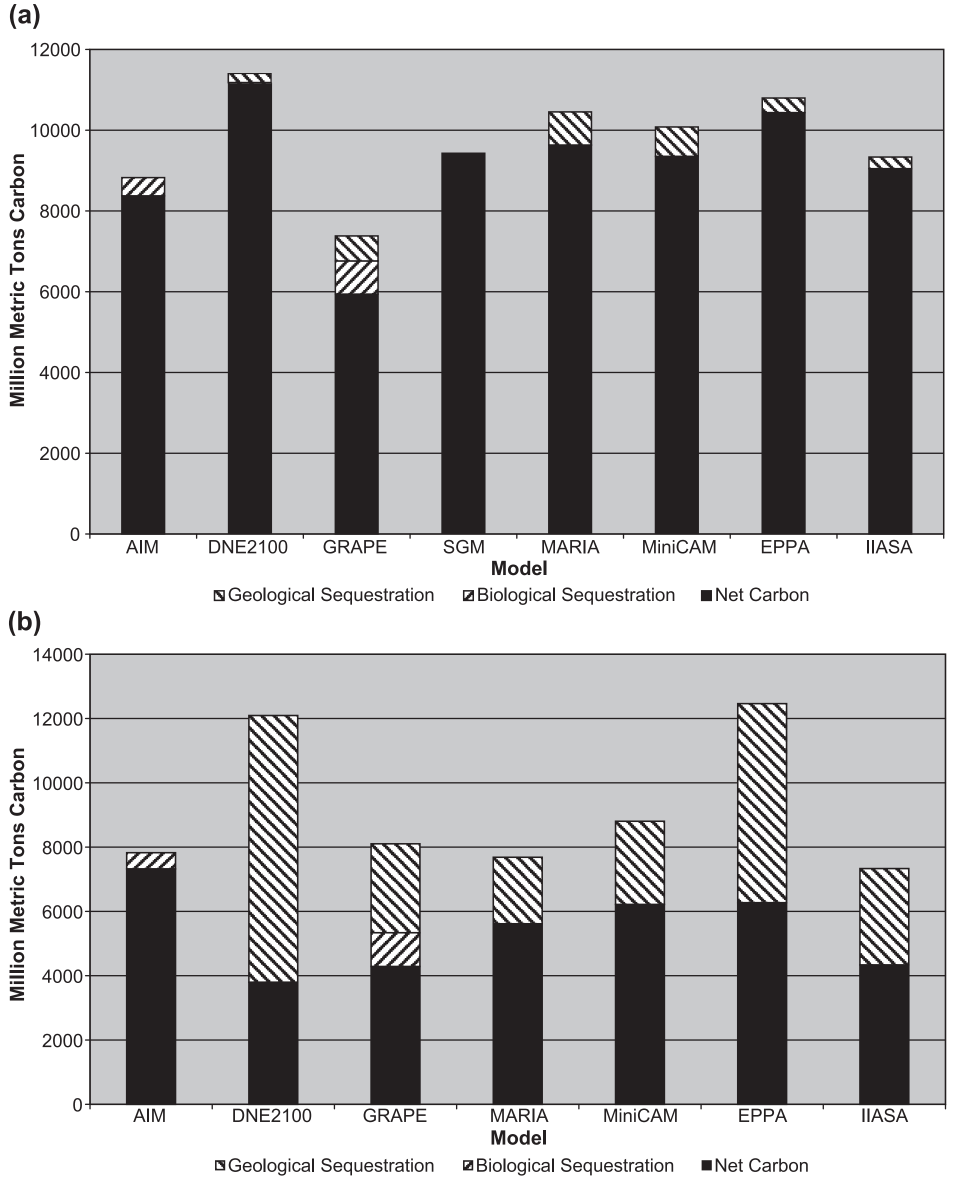

Fig. 5. (a) World carbon sequestration and emissions in the 550 ppmv scenario in 2050. (b) World carbon sequestration and emissions in the 550 ppmv scenario in 2100.

latter part of the next century, but even by 2020 significant differences are observed. Also shown in Fig. 1 is one path of carbon emissions leading to a atmospheric concentration of carbon dioxide in the atmosphere of 550 parts per million by volume. Obviously some models require much greater emissions reductions than others to reach the target levels.

These differences are the result of different assumptions about economic growth, fuel costs, capital stock turn over, etc. Fig. 2(a) shows how reference case GDP, Total Primary Energy, and carbon emissions are projected to change between 2000 and 2100 in each model. For example,

The differences in the carbon emissions relative to primary energy consumption projections from each of the models depend in large part on the projected mix of primary energy sources. Figs. 3(a) and 4(a) show the mix of primary energy sources projections from each of the models in 2050 and 2100 in Fig. 3(a) and (b), respectively.

6. Comparisons of results for the stabilization scenario

Figs. 2(b) contrasts the Projected changes in carbon emissions, GDP, and energy consumption for the 550 PPM Stabilization Scenario with those for the reference case shown in Fig. 2(a). Figs. 3(b) and 4(b) contrasts the projected mixes of primary energy sources from the models for the 550 ppm stabilization case with those shown for the Reference Scenario for 2050 and 2100, respectively.

Figs. 3(b) and 4(b) show substantial differences in fossil fuel use between the models in 2050 and 2100 for the 550 PPM Stabilization Scenario. This is partially explained by differences in the carbon emissions trajectories leading to atmospheric stabilization of carbon dioxide, partly to changes in the mix of fossil fuels projected to be used, but mostly to differences in projections of geological and biological sequestration projected by the models. Geological sequestration results fossil fuels are burned, but the carbon produced is stored underground in depleted oil and gas wells, coal beds, deep level aquifers or deep in the ocean. Biological sequestration involves the growing of new trees and plants that take up carbon which helps off set the carbon being emitted. Fig. 5(a) and (b) show the amount of geological and biological sequestration assumed in 2050 and 2100 for the 550 PPM Stabilization Scenario. The choice of technologies and the use of sequestration and other new technologies depends on how large the carbon tax needs to be to restrict carbon emissions which depends in turn on the reference level of carbon emissions and the resource, technology and demand responsiveness assumptions embedded in the model. One indication of how difficult it is to achieve stabilization of the CO_2 concentration in the atmosphere is the carbon tax required to reduce net carbon emissions enough to achieve the stabilization. These projections are shown in Fig. 6.

Another interesting difference in model results is the degree to which electricity generation is projected to increase in the reference scenario and the response of electricity generation to the imposition of carbon constraints. As shown in Fig. 7, some models project an increase in electricity generation in the 550 PPM scenario, while others project a decrease.

7. Overview of special issue

Since each modeling team ran and reported results for the Modelers Reference and 550 PPM Stabilization Scenarios, each of the 12 papers that follow contains some discussion of the comparison of the different simple trading options in more depth, but basically

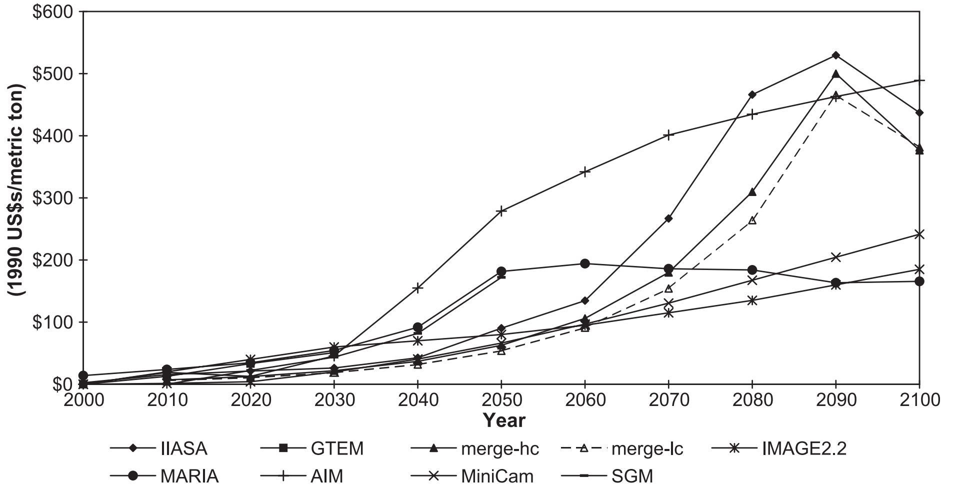

Fig. 6. Carbon tax projections for the 550 PPM stabilization scenario.

reaches the same bottom line as that reported here. In addition to that comparison, each modeling team focused on sensitivities, additional results, and sets of scenarios (many drawn from Table 3) that seemed particularly interesting to them and that the structures of their models allowed them to address. Other groups focused their analysis on key sensitivities that could potentially affect results for both the core and other types of scenarios.

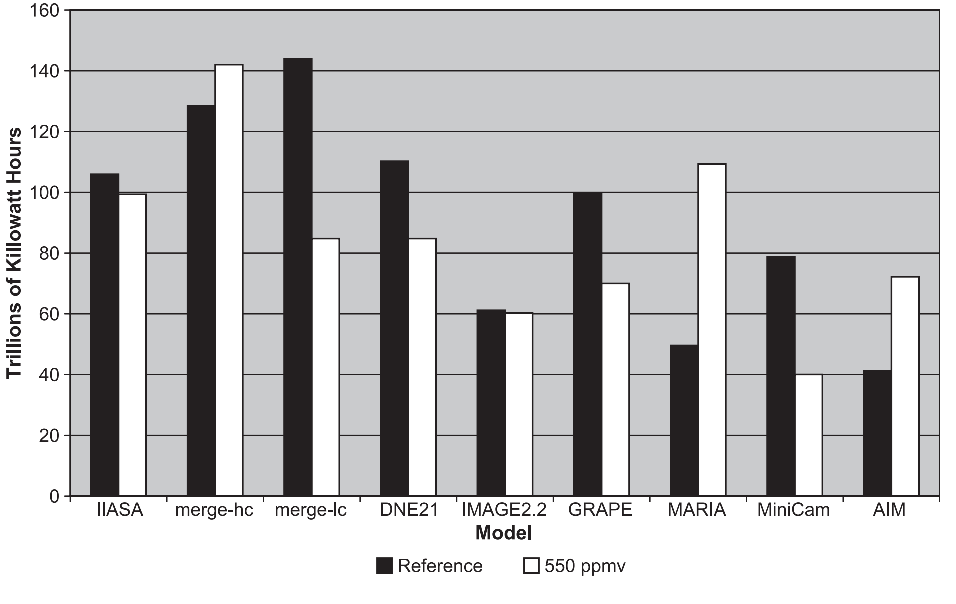

Fig. 7. Projected world electricity production in 2100.

Despite these considerable uncertainties, a number of common results and insights emerge from the set of model results considered here. First, stabilizing the atmospheric concentration of carbon dioxide will require significant development and implementation of new energy technologies—large scale changes in how people produce, transform, and use energy and dispose of undesirable by-products. Second, the transitions required will be take time (many decades) and be costly to implement. Finally, the costs can be moderated significantly if many options are pursued in parallel, if there is time for the new technologies to be phased in gradually, and if policies designed to facilitate the introduction of the new technologies starts sooner rather than later.

With this introduction, the stage has been set for the set of papers that follows. We hope you find them as interesting and insightful as we did. That the study has produced such a rich a set of results owes everything to the active participation of the modeling teams and the care each team took in preparing a paper for this volume.

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Stabilization of CO_2 in a B2 world: insights on the roles of carbon capture and disposal, hydrogen, and transportation technologies

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Abstract

We examine the potential role of several energy technologies, including carbon capture and dispose (CC and D), hydrogen and advanced transportation systems, on the cost of stabilizing CO_2 concentrations. While not currently deployed at scale, CC and D, hydrogen energy systems, and biotechnology have the potential to be major components of the global energy system by the middle of the 21st century. Other technologies, such as renewables, nuclear power and energy efficiency also play critical roles in addressing climate change. The development of advanced technologies in the absence of limitations on the concentration of carbon dioxide need not lead to CO_2 stabilization.

JEL classification: Q25; Q40

Keywords: Greenhouse; Climate Change; Energy; Integrated assessment; Technology

1. Introduction

Technology is one of the most important determinants of the cost of stabilizing the concentration of greenhouse gases in the atmosphere. The character of its role is both complex and evolving. The purpose of this paper is to examine the potential role of a

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suite of technologies that could have a profound impact on the cost of stabilizing the greenhouse gas concentrations. These technologies include those which capture and dispose[1] of carbon in reservoirs permanently isolated from the atmosphere (CC and D), technologies that make and use hydrogen (H_2), and advanced transportation technologies. While this paper will focus on the impact of this group of technologies, other energy technologies, not examined in detail in this paper, such as biotechnology, renewables, nuclear power and energy efficiency also hold substantial potential for addressing climate change.

Several results emerge from this analysis. The first clear implication of the exercise is that technology plays a major role in shaping the structure of the global energy system and exerts a powerful influence on the cost of responding to climate change.

It is worth noting however that the development of advanced technologies in the absence of limitations on the concentration of carbon dioxide need not lead to reductions in emissions, depending on the nature of the technological advances.

Several technologies, which are not currently deployed at scale, have the potential to be major components of the global energy system by the middle of the 21st century. These include carbon capture and disposal (CC and D), hydrogen (H_2) energy systems, and modern commercial biomass. Furthermore, technologies interact in important ways. In some instances, they compete for the same market, e.g. conservation and renewable energy, and in other instances technologies complement each other, e.g. carbon capture and disposal can complement fossil fuel use.

In order to examine the role of the technologies described above, the MiniCAM version 2001.02 was employed. Several modifications were incorporated in this version that distinguishes it from earlier versions of the model. These changes will be discussed as well as the implications of potential technology developments in the areas of CC and D, H_2, and transportation technologies.

2. Overview of the MiniCAM

MiniCAM is a long-term, global, market equilibrium model of energy, agriculture, land-use, and economy interactions. While much of the paper focuses on the global implications of technology, MiniCAM is a geographically disaggregated model with 14 regions: (1) The United States, (2) Canada, (3) Western Europe, (4) Australia and New Zealand, (5) Japan, (6) Eastern Europe, (7) The Russian Federation and other countries of the former Soviet Union, (8) China, (9) the Mid-East, (10) Africa, (11) Latin America, (12) Korea, (13) Southeast Asia, and (14) India.[2] The model is calibrated to 1990 and contains 15-year time steps to the year 2095. It takes inputs such as labor productivity growth, population, fossil and non-fossil fuel resources, energy technologies[3] and productivity

[1] The term disposal is used here rather than the more conventional term "sequestration" to distinguish between storage of carbon in the terrestrial biosphere, e.g. soils and trees, from the permanent geologic storage of carbon.

[2] Three other regions are being disaggregated: Mexico, Argentina, and Brazil.

[3] There are 69 energy technology options explicitly considered in MiniCAM version 2001.02.

growth rates and generates outputs of energy supplies and demands by fuel (nine primary, five final) greenhouse gas emissions (CO_2, CH_4, N_2O, SO_2), and economic activity. The model has its roots in Edmonds and Reilly (1985), and has been continuously up graded and updated. Changes to the energy–economy–greenhouse–emissions model are documented in Edmonds et al. (1986) and Edmonds et al. (1996a,b). MiniCAM also incorporates a model of carbon cycle, atmospheric processes and climate change, see Hulme and Raper (1993), Wigley (1994a,b), Wigley and Raper (1987, 1992, 1993, 2001).

One interesting feature of MiniCAM is the integrated nature of energy and land-use markets. Land-use considerations are important in two determinants of greenhouse gas emissions: land-use change emissions and the production of biomass for energy use. Both are treated explicitly in the agriculture-land-use module of MiniCAM. MiniCAM handles two types of biomass: traditional and modern. For the purposes of this analysis it is assumed that per capita use of the former declines with increasing incomes, while the latter competes with other modern fuels on the basis of cost. In MiniCAM commercial biomass must be grown as a crop, harvested, and refined before proceeding to end-use applications. To be planted in the first place it must compete for market share with other crops, livestock, forest products, and urban uses. As profitable opportunities increase, pressure to expand land applications to increasingly less attractive land categories grows, as does pressure to deforest unmanaged ecosystems. Changes in stocks of terrestrial carbon determine land-use change emissions. The agriculture-land-use module is discussed in greater detail in Edmonds et al. (1986).

Several new elements have been added to the MiniCAM recently. These include a variety of new technologies—wind power, gas-to-liquids transformation, hydrogen production and consumption—and a new transportation sector.

3. Wind power

Wind power is treated similarly to solar-electric power generation technologies. That is, it is a technology choice available at a marginal cost that varies over the course of the century. Because wind is not continuously available, there are two different types of wind power, simple wind power and wind power with backup storage. The latter is more expensive, but is unnecessary at smaller market shares. However, as wind power becomes an increasingly larger share of total power generation backup storage becomes necessary to insure power system reliability.

4. Gas to liquids technology

The MiniCAM has introduced an option to create liquids from natural gas. This transformation technology is handled similarly to any other refining process. That is, the technology is described by two parameters, the energy efficiency of transformation from gas to liquids, and the non-energy cost of refinement plus infrastructure.

5. Hydrogen production

Hydrogen is a fuel that is currently produced and consumed in relatively small quantities today. When combusted its byproduct emission is water vapor. Water vapor is not a conventional air pollutant. While it is a greenhouse gas, emissions in the quantities that could be expected to be emitted in a global energy system are insufficient to perturb the biogeochemical balance of water vapor in the atmosphere. Hydrogen is therefore of interest as a potential energy carrier both in a regime that controls local air pollutants and one in which greenhouse gas emissions are limited, though it should be noted that the technology is not without issues. Storage and transport of H_2 will doubtless entail losses and the effect of H_2 on local and global air chemistry remain to be examined.

The production of hydrogen can be accomplished using either inputs of hydrocarbons-liquids, gas, coal or biomass, or electricity. The future cost of producing hydrogen is treated as a stochastic variable whose probability density function is prescribed by a Weibull function. The mean cost of producing hydrogen using feedstock j in region L is given by,

$$P_{\text{hydrogen},j,L} = g_{\text{hydrogen},j,L} P_{j,L} + h_{\text{hydrogen},j,L}, \tag{1}$$

where $P_{j,L}$ is the cost of feedstock j in region L, $g_{\text{hydrogen},j,L}$ is the energy efficiency of transformation of feedstock j into hydrogen delivered to the final consumer in region L, and $h_{\text{hydrogen},j,L}$, is the levelized non-energy operation and maintenance cost to produce and transport the fuel.[4]

The share of total hydrogen production provided by the jth feedstock is $S_{\text{hydrogen},j,L}$ and is estimated to be a logistic function of the median cost,

$$S_{\text{hydrogen},j,L} = P_{\text{hydrogen},j,L}{}^{r_{\text{hydrogen},L}} \Big/ \sum_{l} P_{\text{hydrogen},i,L}{}^{r_{\text{hydrogen},L}}, \tag{2}$$

where $r_{\text{hydrogen},L}$ is the Weibull distribution's shape factor, which measures the variance of regional energy costs.

The average cost of hydrogen production is given by the Clarke and Edmonds (1993) equation,

$$P_{\text{hydrogen}L} = \left[\sum_{l} P_{\text{hydrogen},i,L}{}^{r_{\text{hydrogen},L}} \right]^{(1/r_{\text{hydrogen},L})}. \tag{3}$$

The quantity of hydrogen produced using feedstock j in region L is given by,

$$F_{\text{hydrogen},j,L} = S_{\text{hydrogen},j,L} F_{\text{hydrogen},L}, \tag{4}$$

where $F_{\text{hydrogen},L}$ is the market clearing quantity of hydrogen purchased at an average cost of $P_{\text{hydrogen},L}$.

[4] Thus, it includes both the capital cost of plant and equipment to produce the hydrogen and the transportation and storage facilities needed to deliver the fuel to the final consumer.

6. The transportation sector

The MiniCAM's transportation sector is being replaced. The old sector used a simple formulation in which a general transport service was demanded in each economy, and four generic modes of providing that service (with liquids, gas, coal, biomass, or electricity) were available. Using this approach the MiniCAM could be calibrated to represent the present day transportation sector behavior, but it could not represent transportation technology in any detail.

In MiniCAM version 2001.02 the transportation sector is disaggregated into two components, freight and passenger. Passenger transport demand is divided into two parts, demands by those who are drive and those who do not. We take a driver's license as the indicator for inclusion in the former group. The aggregate demand for passenger transport, $E_{\text{passenger},L}$, depends on the price of passenger transportation services in region L, $P_{\text{passenger},L}$, the price elasticity of demand for passenger transportation services in region L, $r_{p,\text{passenger},L}$, percapita income in the region, the income elasticity of demand for passenger transportation services in region L, $r_{y,\text{passenger},L}$, and the total regional population, POP_L via,

$$E_{\text{passenger},L} = a_{\text{passenger},L} P_{\text{passenger},L^{r_{p,\text{passenger},L}}} X_{L^{r_{y,\text{passenger},L}}} POP_L, \tag{5}$$

and a constant, $a_{\text{passenger},L}$. Note that the aggregate price of passenger transport for drivers and non-drivers will be different.

There are six modes of passenger transport in the model: automobile, motor cycle, rail, bus, ship and air. Each of these modes of transportation can be provided by any number of alternative technologies using any of the end-use fuels. At present technology options are limited. For automobiles for example the options are liquids (gasoline/diesel), natural gas, hydrogen, and electricity. The cost of providing a vehicle-km of service using mode m and fuel input j depends on the efficiency of fuel transformation using fuel input j, $g_{\text{passenger},j,L}$, the non-energy costs of transport $h_{\text{passenger},j,L}$, and the value of time in transit, where $W_{\text{passenger},m,j,L}$ is the wage rate and $T_{\text{passenger},m,j,L}$ is the time in transit.

$$P_{\text{passenger},m,j,L} = (g_{\text{passenger},m,j,L} P_{j,L} + h_{\text{passenger},m,j,L})^* \text{loadfactor}^{-1} + W_{\text{passenger},m,j,L} T_{\text{passenger},m,j,L}. \tag{6}$$

The final term is included to explain a shift toward more convenient modes of transport with increasing income. This helps explain the increasing market share for automobiles and air travel with income increases. This is not the only factor explaining modal shifts. Even though motor cycles are in general faster than other modes of ground transport, their use does not grow to dominate the market as incomes increase.

The market share of modal technology m using fuel j in region L is given as in Eq. (2),

$$S_{\text{passenger},\,m,j,L} = P_{\text{passenger},\,m,j,L^{r_{\text{passenger},L}}} \Big/ \sum_{l} P_{\text{passenger},i,L^{r_{\text{passenger},L}}}, \tag{7}$$

where, $r_{\text{passenger},L}$ is the distribution parameter.

The demand for freight transport is handled similarly to the treatment of passenger transport. Demand for ton-kilometers is assumed proportional to the gross domestic product, Y_L.

$$E_{\mathrm{freight},k,L} = c_0 P_{\mathrm{freight},L}{}^{rp_{\mathrm{freight},L}} Y_L \tag{8}$$

where $rp_{\mathrm{freight,L}}$ is the price elasticity of demand for freight services and $ry_{\mathrm{freight},L}$ is the income elasticity of demand for freight services.

7. The reference case

For the conduct of this analysis we used the MiniCAM B-2 SRES. The B-2 scenario is described in Nakicenovic et al. (2000) as follows:

> The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2[5], intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1T[6] storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels. (Nakicenovic et al., 2000, Summary for Policy Makers, p. 5).

While each of the modeling groups participating in the SRES process agreed to create a B2 scenario that was consistent with the storyline and with certain prescribed external parameters, every modeling team's B2 scenario differed in detail. For the purposes of presentation, one modeling team's efforts were reported as the "marker" scenario. Outputs from the MESSAGE model developed and employed at the International Institute for Applied Systems Analysis (IIASA) were used for the B2 marker scenario. The MiniCAM B2 scenario differs in several regards from the MESSAGE B2 scenario. For example, in the MiniCAM B2 scenario technological improvement in the reference case is not as dramatic as in the SRES marker scenario developed by the MESSAGE model.

In the MiniCAM B2 scenario the global population grows to 9.4 billion people in the year 2100 with a steadily declining rate of growth over the entire period. Incomes per capita disparities shrink between regions, but do not close. The average GDP/capita growth rate is 1.85%/year. Gross World Product increases by an order of magnitude from

[5] In the A2 scenario "Fertility patterns across regions converge very slowly, which results in continuously increasing global population" (Nakicenovic et al., 2000, Summary for policy makers, p. 5).

[6] "The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B)." (Nakicenovic et al., 2000. Summary for Policy Makers, p. 4). "Balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies." (Nakicenovic et al., 2000, Summary for Policy Makers, fn 3, p. 4).

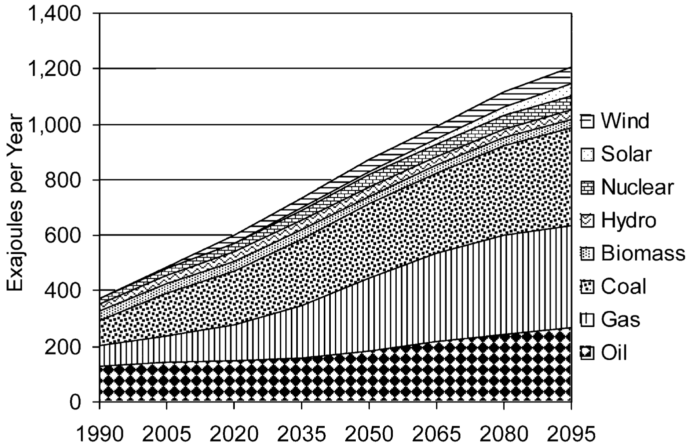

Fig. 1. MiniCAM B2 global primary energy by source.

$23 trillion/year to $200 trillion/year. Energy technologies improve dramatically. As with all B2 representations, the share of the global energy and economic systems associated with developing nations increases over the course of the 21st century.

The global energy systems grow steadily throughout the 21st century but at a declining rate (Fig. 1). Fossil fuels remain the principal source of global primary energy supplying about 80% of global energy needs—and the production of all fossil fuels rise. Between the fossil fuels the share of natural gas and coal rise relative to oil. Renewable and nuclear energy continue to supply about one fifth of the world's energy supplies. However, within this group many changes occur. The share of energy supplied by traditional biomass—dung, straw and wood—declines steadily, as does the relative reliance on hydro-electric power, due primarily to resource limitations. These energy forms are eclipsed by production from solar and wind power. Nuclear power continues to grow, but does not keep pace with the rate of expansion in the rest of the global energy system because, in the face of dedicated opposition, little additional nuclear technology development is assumed in these scenarios. It is important to note that there is considerable development potential in nuclear energy technology, which if realized, would result in a considerably larger contribution to future energy supply, with or without carbon constraints.

The continued expansion of fossil fuel use, and in particular the use of natural gas and oil, are somewhat at odds with conventional wisdom (Nakicenovic et al., 2000), which holds that the limited nature of *conventional* oil and gas resources limit their contribution to providing energy services in the 21st century. In the MiniCAM B2 scenario it is assumed that conventional oil and gas resources are systematically supplemented by increases in occurrences from abundant *unconventional* oil and gas resources throughout the century.[7]

[7] For example, tar sands and tight gas become increasingly accessible over time with the advent of improved acquisition technologies. Eventually gas hydrates are assumed to become economically recoverable in this reference case.

As discussed in the following section, energy technologies, with some notable exception such as nuclear power and hydrogen production, continue to improve throughout the 21st century. These improvements, especially those associated with fossil fuel production and use, lead to a general decline in the energy to gross world product ratio, energy intensity. The average annual rate of decline of energy intensity during the 21st century is 0.9% per year.

Several trends are relatively well pronounced in the composition of the global energy system (Fig. 2). First, the world becomes increasingly electrified, and electricity comes increasingly from non-carbon emitting sources.

The transportation sector increases in scale by almost a factor of four and continues to be dominated by liquid fuels. In the residential buildings sector the use of traditional biomass fuels declines steadily as residential sector and commercial buildings continue to turn to modern commercial energy sources to provide energy services.

Fossil fuel carbon emissions from the MiniCAM B2 scenario are shown in Fig. 3 along with the six SRES marker scenarios and the IS92a emissions scenario developed by the IPCC and published in Leggett et al. (1992). Note that year 2000 IS92a emissions are substantially in excess of the SRES scenarios estimate for a variety of reasons such as the breakup of the former Soviet Union and associated dramatic drop in emissions. However, the MiniCAM B2 scenario's emissions grow to approximately 20 billion tons of carbon per year by the end of the 21st century is similar in scale to that of IS92a. The assumed abundance of fossil fuels results in a MiniCAM B2 scenario with significantly higher emissions than the SRES B2 marker scenario. Because of that fuel abundance and the associated lower cost of fossil energy,

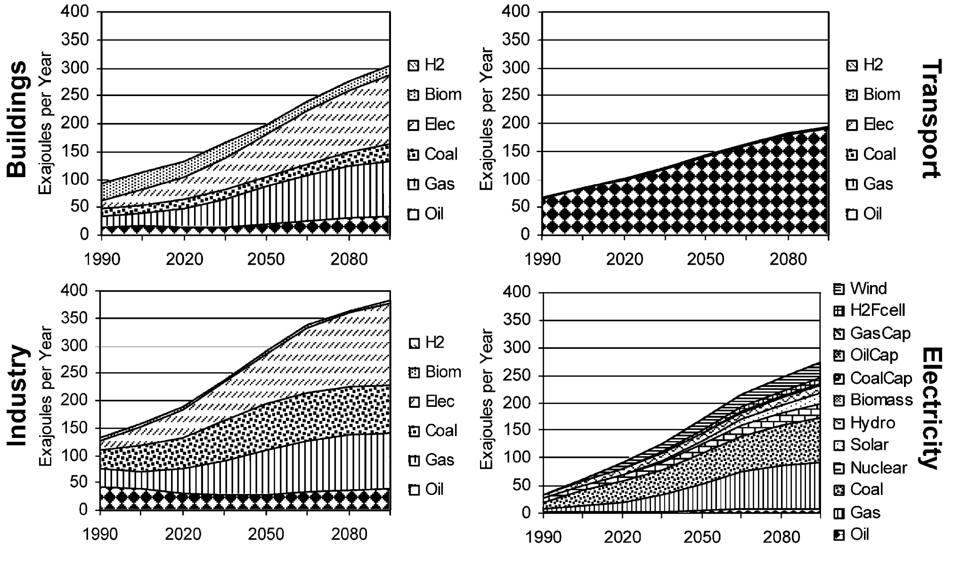

Fig. 2. MiniCAM B2 energy use by sector (EJ/year).

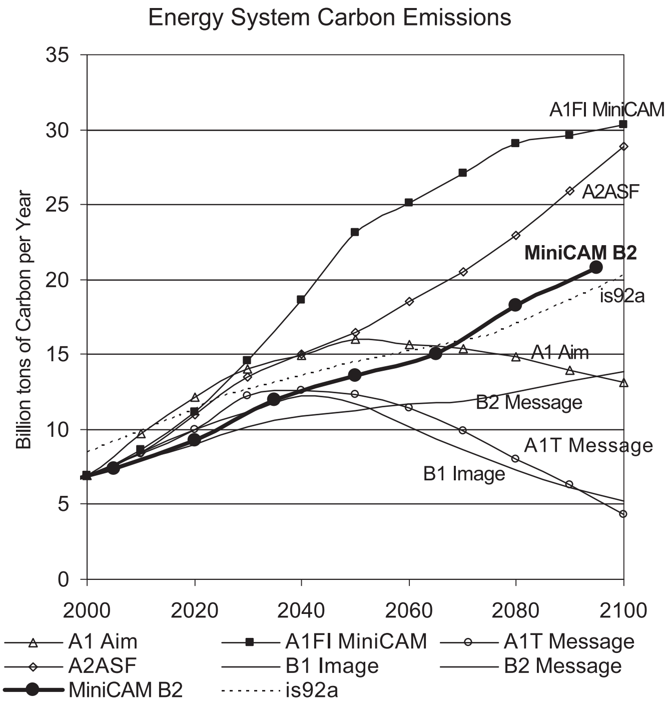

Fig. 3. Fossil fuel emissions, MiniCAM B2 and SRES marker scenarios.

advanced technologies do not penetrate the market as readily as in the B2 marker scenario.

8. Technology performance

Four cases are examined as part of the EMF-19 study architecture, a reference case in which no greenhouse gas emissions mitigation policy is introduced, and an advanced technology case in which no greenhouse gas emissions mitigation policy is introduced, and two cases with the same technology availability, but in which the concentration of CO_2 was limited to 550 parts per million volume (ppmv). The examination of a case in which concentration of CO_2 is limited so as to remain at or below 550 ppmv should not be taken to signify that this concentration has some special claim as a goal. At present, there is no scientific consensus as to a concentration that would avoid "dangerous anthropogenic interference with the climate system."[8] In the remainder of this paper, results from the application of the MiniCAM

[8] United Nations (1992, article 2) studies often examine a range of concentrations. The IPCC (2001) considers concentrations ranging from 350 to 1000 ppmv.

to this reference case are considered. The following designations will be used to distinguish the four cases considered:

- MiniCAM B2: the reference case, without emissions mitigation policies.
- MiniCAM B2 550: the reference case with long-term CO_2 concentration of 550 ppmv.
- MiniCAM B2 AT: the reference case with advanced technology, but without emissions mitigation policies.
- MiniCAM B2 AT 550: the MiniCAM B2 AT and long-term CO_2 concentration of 550 ppmv.

The purpose of this exercise is to examine the role that technology could play in energy futures with and without limitations on greenhouse gases. Table 1 displays key technology assumptions used in the examination of these four cases.

Several technology options are available that do not play a significant role in the MiniCAM B2 scenario (i.e. the reference scenario), but which are very important in the other three cases. These include hydrogen production, H_2 fuel cells, and CC and D technologies. While technically available, their costs and performance leave them unable to compete successfully for market share against other technology options.

The two cases in which CO_2 concentrations were constrained not to exceed 550 ppmv (MiniCAM B2 550 and MiniCAM B2 AT 550) were derived by limiting global emissions to the trajectory defined in Wigley et al. (1996). Emissions were limited by levying a

Table 1
Technology assumptions

Technology	Units	1990 Base	Year 2100	
			Mini-CAM B2	Mini-CAM B2 AT
US automobiles	mpg	18	60	100
Land-based solar electricity	1990 c/kW h	61	5.0	5.0
Nuclear power	1990 c/kW h	5.8	5.7	5.7
Biomass energy	1990$/gJ	$7.70	$6.30	$4.00
Hydrogen production (CH_4 feedstock)	1990$/gJ	$6.00	$6.00	$4.00
Fuel cell	mpg (equiv)	43	60	98
Fossil fuel power plant efficiency (coal/gas)	%	33	42/52	60/70
Capture efficiency	%	90	90	90
Carbon capture power penalty (coal)[a]	%	25	15	5
Carbon capture power penalty (gas)[b]	%	13	10	3
Carbon capture, incremental capital cost (coal)[c]	%	88	63	5
Carbon capture, incremental capital cost (gas)[d]	%	89	72	3
Geologic disposal (CO_2)	$/tC	37.0	37.0	23.0

[a] Expressed as a percentage reduction in net power production.

[b] Expressed as a percentage reduction in net power production.

[c] Expressed as the percentage increase in reference technology capital costs required to add carbon capture capability to the plant.

[d] Expressed as the percentage increase in reference technology capital costs required to add carbon capture capability to the plant.

common carbon fee on all emissions everywhere in the world. This approach is admittedly unrealistic. The prospect for a uniform value of carbon efficiently allocated to all emissions sources over all time and space is vanishing small. The purpose of this is purely to understand the role of technology under well-defined circumstances and to define the minimum cost at which the CO_2 concentration could be constrained to 550 ppmv or below.

One important observation is that fossil fuel carbon emissions in the MiniCAM B2 and MiniCAM B2 AT cases are very similar. The existence of advanced technologies, including high efficiency vehicles, does not significantly lower emissions in the absence of policies that limit CO_2 emissions (Fig. 4). The reasons are relatively simple. First, CC and D technologies are always dominated by non-CC and D options. CC and D adds to the cost of power generation and fuel refining. Without a constraint on carbon emissions they are never a cost-effective option. Similarly, the deployment of hydrogen in stationary and mobile applications does not reduce emissions. This is despite the fact that H_2 has no carbon emissions associated with its use. The problem lies in the association of carbon emissions with the production of H_2. As hydrocarbons are the most attractive sources of H_2, the lack of a constraint on CO_2 emissions leads to the venting of carbon in the H_2 production process.

While there is no difference between the emissions trajectories between the MiniCAM B2 550 and MiniCAM B2 AT 550 cases there is a significant difference between the value of a ton of carbon in each case (Table 2). The presence of advanced technologies lowers the marginal cost of meeting the CO_2 concentration constraint. By the end of the century the value of a ton of carbon is more than two-and-a-half times higher without advanced technologies than with them. Because it takes time for advanced technologies to penetrate the market, the reduction in marginal cost, both absolutely and relatively, is greater in later years than in earlier years.

In addition, there are major differences between the technology deployments in MiniCAM B2 and MiniCAM B2 AT scenarios with and without emissions limitations. The AT cases have a sufficiently different technology cost structure that the global energy

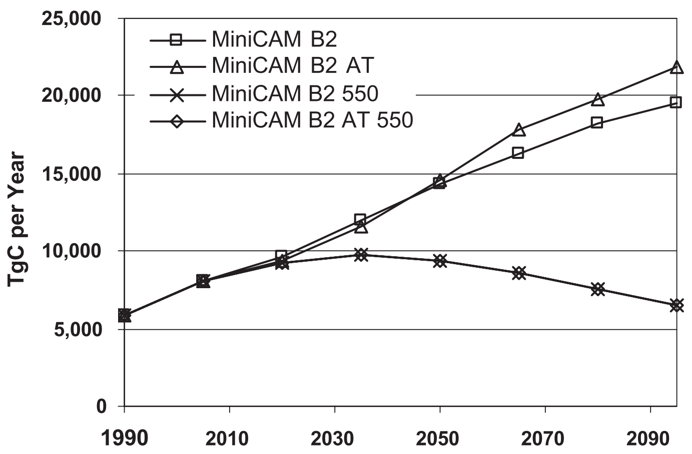

Fig. 4. MiniCAM B2 and MiniCAM B2 AT emissions.

Table 2
Carbon values limiting CO_2 concentrations not to exceed 550 ppmv

Year	Carbon Tax (90$/tC)	
	MiniCAM B2 AT 550	MiniCAM B2 550
2005	$0.00	$0.00
2020	$0.69	$4.11
2035	$18.97	$27.58
2050	$34.49	$66.31
2065	$46.18	$112.14
2080	$65.04	$167.43
2095	$85.60	$223.01

system evolves differently in the MiniCAM B2 AT cases than in the MiniCAM B2 reference cases. Advanced technology improvements in fossil fuel technologies not only reduce the amount of primary energy necessary to perform a specific service, but also make energy services cheaper and thereby increase final energy use. Final energy is higher in the MiniCAM B2 AT scenarios than in the MiniCAM B2 scenario. In the MiniCAM B2 AT cases, the cost of a suite of technologies is sufficiently low, relative to their alternatives that a hydrogen market materializes. In the AT scenarios the composition of final energy use is dramatically altered. The majority of final energy is provided by electricity and hydrogen. This increase in the use of these two energy carriers is accomplished at the expense of the direct use of energy in final applications. Even in the transportation sector, hydrogen in conjunction with fuel cells competes directly with liquids as a final energy carrier.

In the emissions control cases important differences are observed between the MiniCAM B2 and MiniCAM B2 AT cases. In power generation solar and nuclear expand their

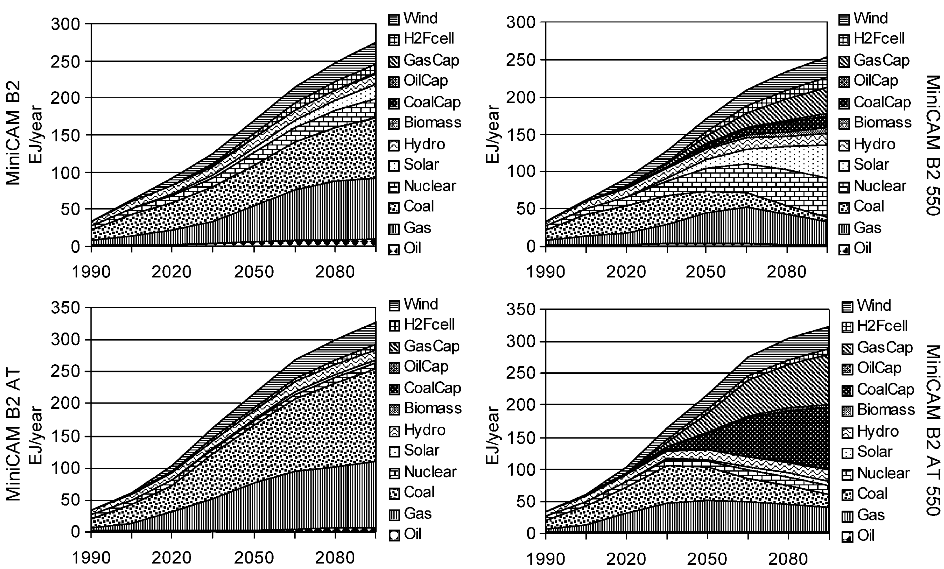

Fig. 5. Electric power generation by mode (EJ/year).

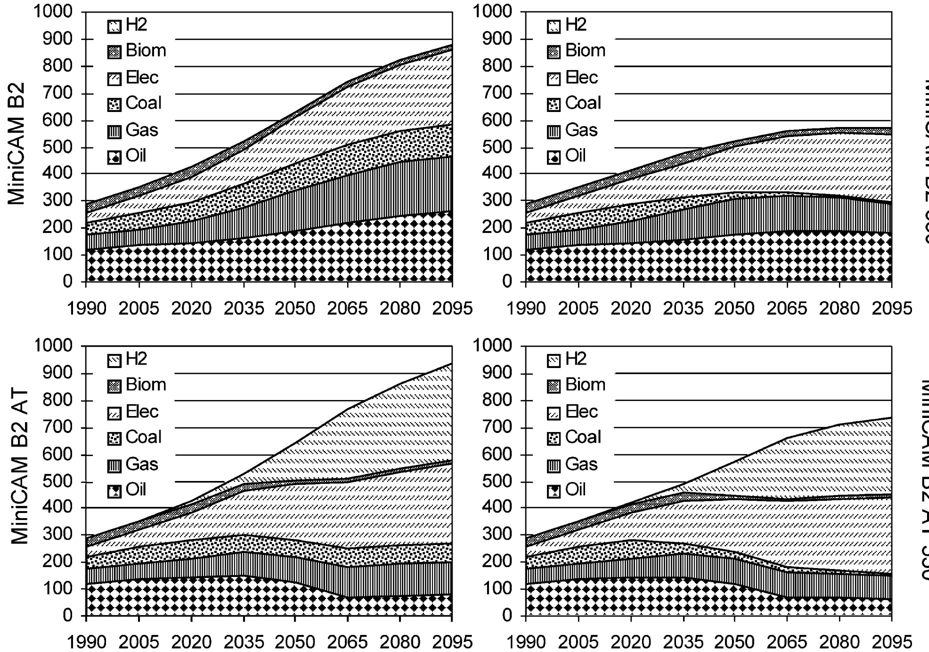

Fig. 6. Final energy use by energy carrier (EJ/year).

deployments dramatically in response to limitations on carbon emissions with MiniCAM B2 reference case technologies (Fig. 5). The expanded deployment of wind, solar and nuclear energy are the direct result of the application of the carbon constrain in the MiniCAM B2 550 case which changes relative costs among power generation technologies. In the MiniCAM B2 AT scenario the application of a CO_2 concentration constraint leaves the use of fossil fuels is almost unchanged in power generation, though after 2035 almost all new fossil fuel power generation facilities have the capacity to capture and dispose of carbon. Similarly the cost differential between fossil fuel power generation technologies and non-fossil fuel technologies is relatively small, as compared to the MiniCAM B2 550 case, and therefore the expansion of solar, nuclear and wind deployment between the MiniCAM B2 AT and MiniCAM B2 AT 550 cases is relatively modest.

Final energy demand changes are more pronounced in the MiniCAM B2 technology case, where energy conservation is a major response to emissions limitations. Final energy demands decline by more than one third with MiniCAM B2 technologies, while the decline is only about half as great in the MiniCAM B2 AT scenario (Fig. 6).

9. Carbon capture and disposal

It is not surprising that carbon capture and disposal technologies are not deployed in the MiniCAM B2 reference case. These technologies impose additional costs on those who employ them and are therefore only deployed as a response to emissions constraints. The discussion that follows is limited in that it only considers large-scale capture of carbon dioxide and its disposal in sites that permanently isolate carbon from the atmosphere. We therefore leave to others the consideration of terrestrial and soil sequestration technology and attendant technical and institutional issues, though these technologies have potentially important roles to play in a long-term strategy to address climate change. Beyond that, this paper does not consider technologies that might be configured to remove carbon directly from the atmosphere and transform it to mineralized carbon (Butt et al., 1998; Goff and Lackner, 1998; Lackner et al., 1999). Nor, will it address issues associated with large-scale storage of carbon in oceans, though this option is being seriously studied in the United States, Europe, and Japan. Important issues remain to be illuminated in both cases.

Carbon capture and disposal technologies are assumed to impose incremental costs equivalent to approximately \$300 per ton of carbon in carbon taxes. Those costs are assumed to fall to about \$190 per ton of carbon in the MiniCAM B2 cases and to approximately \$60 per ton of carbon in the MiniCAM B2 AT cases. Cost estimates for the MiniCAM B2 cases are based on Herzog et al. (1997), and are consistent with Audus (2001) and Freund and Ormerod (1997). Cost estimates for the MiniCAM B2 AT cases are based on U.S. Department of Energy (2000), *Vision 21* programmatic goals. Because the private sector has experience with all of the components of the carbon capture and disposal system, there is a sense that the technologies are technically feasible. Yet important questions remain before they enter into general use.

At present CO_2 capture is practical only at large facilities. Power plants and large industrial facilities are potentially attractive candidates for capturing carbon either through flue gas separation or through retrieval from a gasification process such as from an integrated gasification combined cycle facility. In addition, carbon could also be captured during the transformation of hydrocarbons into hydrogen and various other industrial practices that produce relatively concentrated CO_2 streams.

Numerous potential geologic disposal sites have been considered including depleted oil and gas wells, deep saline reservoirs, unminable coal seams, and basalt formations. Estimated reservoir capacities are highly varied (Table 3).

Each of the reservoirs has its relative attractions and challenges. CO_2 could be used to recover additional occurrences of oil in existing wells, and therefore could command a

Table 3
Estimates of global capacity of storage reservoirs

Carbon storage reservoir	Range (PgC)
Basalt formations[a]	>100
Deep saline reservoirs	87–2727
Depleted gas reservoirs	136–300
Depleted oil reservoirs	41–191
Unminable coal seams	>20

Sources: Herzog et al. (1997), Freund and Ormerod (1997), McGrail et al. (2002).

[a] Estimate for the Columbia River Basalt only.

Table 4
Cumulative carbon capture by year and case (PgC)

Year	MiniCAM B2 550	MiniCAM B2 AT 550
2005	0	0
2020	1	0
2035	4	5
2050	12	29
2065	27	89
2080	52	182
2095	84	302

positive economic value, but permanence of storage is an issue. Basalt formations are not everywhere, and the experimentation necessary to determine the mineralization rate has not been undertaken.[9]

Cumulative emissions of carbon are large in both the MiniCAM B2 550 and B2 AT 550 cases (Table 4). Carbon is captured primarily from electric power generation, but also from the production of hydrogen in the B2 AT 550 case. While these emissions are within the range of geologic storage reservoir capacities cited in Table 3, little work has been done to consider the geographic proximity of potential sources of carbon and geologic sink reservoirs. One exception to this is Dahowski et al. (2001). Dahowski et al. have developed a geographic information system tool to facilitate the analysis of sources and geologic reservoirs for the long-term storage of CO_2 in the United States. Work is proceeding at the IEA Greenhouse R&D Programme to develop a similar tool for Europe (Van Bergen et al., 2002; Keppel et al., 2002).

Another major issue facing the large-scale deployment of carbon capture and disposal technologies is the issue of permanence. It takes very little sophistication to realize that even an apparently small average rate of release over all CO_2 reservoirs, such as 1% per year, could imply substantial and growing emissions by the end of the century. There is no reason to believe that loss rates would be as high as 1% per year, but the science necessary to establish retention rates for specific systems and reservoirs has yet to be undertaken. Insuring that loss rates are low could have important implications for emissions along a path that did not wish to exceed a specific limit. In the year 2100 fugitive emissions from reservoirs with a 1% per year loss rate would be 0.7 and 2.6 PgC/year for the MiniCAM B2 550 and MiniCAM B2 AT 550 cases, respectively. Year 2100 emissions along the WRE trajectory are 6.8 PgC/year. Emissions from reservoirs are growing and emissions along the WRE 550 trajectory are falling.

It is also worth noting that even small leaks can have significant repercussions if they are highly concentrated in either a populated area or an area in which protected species reside.

The availability and cost of a large-scale carbon capture and disposal option has a significant impact on the minimum cost of stabilizing the concentration of CO_2. Similarly the cost of stabilizing the concentration of CO_2 will affect the relative desirability of

[9] Mineralization at too rapid a rate could clog injection, while mineralization at too slow a rate could give rise to potential for escape to the atmosphere. See McGrail et al. (2002).

alternative concentrations. Consequently, developing a rigorous understanding of the permanence of reservoirs and the scientific ability to monitor the integrity of reservoirs would seem to be a potentially high-value priority.

10. Transportation and the hydrogen economy

Hydrogen is an energy carrier. It can be derived from hydrocarbons such as fossil fuels or biomass, or from electrolysis. It has the desirable property that its application to the production of energy services emits no conventional pollutants nor does it affect the atmospheric concentration of greenhouse gases. It is currently used in industrial applications, but its cost is significantly greater than that of fossil fuels from which it is produced. Thus, while there is reason to expect that a hydrogen system could be developed, it is not as clear that such a system could be developed as a competitive alternative to the present, fossil–fuel-based alternative.

The hydrogen system has numerous components including production, carbon capture and disposal, transport and storage, and use. Some of the characteristics of this system are identified in Table 5.

In the MiniCAM analysis, the energy-economy system always has the option to produce hydrogen and employ it as an energy carrier. However, against a background of the MiniCAM B2 scenario hydrogen never becomes a significant component of the global energy system—its cost remains a barrier to entry. Importantly the presence of an emissions constraint in the MiniCAM B2 550 case does not provide sufficient leverage to make hydrogen systems competitive.

It is only with the significant improvements in technology hypothesized to be available in the MiniCAM B2 AT and MiniCAM B2 AT 550 cases that the hydrogen option is exercised. Here the cost of a suite of technologies declines to the point where hydrogen can be produced, transported, stored, and used in a manner that allows competition with traditional fossil fuel services (Fig. 6). By the end of the century more than one third of final energy services are provided by hydrogen in both the MiniCAM B2 AT and MiniCAM B2 AT 550 cases. However, the system does not deploy in any significant way until after the year 2020 and it does not begin to measurably penetrate the

Table 5
Components of a H_2 system

H_2 Source	Production location	Carbon capture and disposal	Transport and storage	Applications
oil gas coal	Near users?	Required for fossil fuels to limit net emissions; CO_2 pipeline to disposal sites	For production near the users, short pipelines or truck routes; For production near feedstocks, trunk lines to distribution points; Local storage; health and safety; H_2 losses	Stationary or mobile; fuel cells or direct combustion; health and safety; ancillary consequences of H_2 loss, local and global air consequences, exotic materials
biomass	Near feedstock?	Creates a negative emissions option, CO_2 pipeline to disposal sites		
electrolysis	Near users; Co-production with electricity	If electricity source uses hydrocarbon fuels, CC and D with electricity production		

transportation market until after 2035. It is a major contributor to the system by 2050 and its presence expands throughout the second half of the 21st century.

While H_2 systems are generally associated with a regime that constrains greenhouse gas emissions it is interesting to note that not only does an emissions constraint not necessarily bring H_2 into large-scale use, but a constraint on greenhouse gas emissions can actually reduce H_2 deployment. This is the case comparing MiniCAM B2 AT and MiniCAM B2 AT 550. This result follows from the fact that hydrocarbons are the principal feedstock for H_2 production. The presence of a value for carbon increases the cost of H_2 production up to the point where CC and D technologies provide the ability to continue to use fossil fuels without releasing carbon to the atmosphere. This increased cost of H_2 in the MiniCAM B2 AT 550 case relative to the MiniCAM B2 AT case leads to reduced end use demands for H_2 in the MiniCAM B2 AT 550 case relative to the MiniCAM B2 AT case.

The most cost effective sources for H_2 in the MiniCAM B2 AT cases are hydrocarbons, particularly gas and coal but also biomass (Fig. 7). The importance of gas and coal relative to biomass changes in a carbon constrained world, presumably because the ability to capture the carbon in the hydrogen production phase allows biomass to produce a net negative emission. Electrolysis plays only a minor role in determining H_2 production due to cost. However, neither the evolution of a hydrogen transport, storage and distribution system relative to distributed production from electrolysis nor the joint production of H_2 and electricity were considered, and both could be important. Adding the capability to consider those features is another prime area for model development.

In the modeling that has been done here, hydrogen is used in conjunction with fuel cells. The successful development of fuel cells is therefore a necessary, though not sufficient, condition for the large-scale development of a hydrogen economy. The path by which hydrogen enters the economy in the MiniCAM B2 AT scenarios is interesting, though it is only one of a variety of possibilities. In the MiniCAM B2 AT cases fuel cells are initially deployed in stationary applications. The model does not provide an explicit description of the dynamics of the evolution of the global energy system. One way that this chain of events could transpire is if the fuel cells are initially competitive in stationary applications, allowing relatively short, fixed fuel lines to be extended from refineries to commercial and industrial users. The economic incentives to deploy in the buildings and industrial sectors would be even more pronounced if the model were to include combined

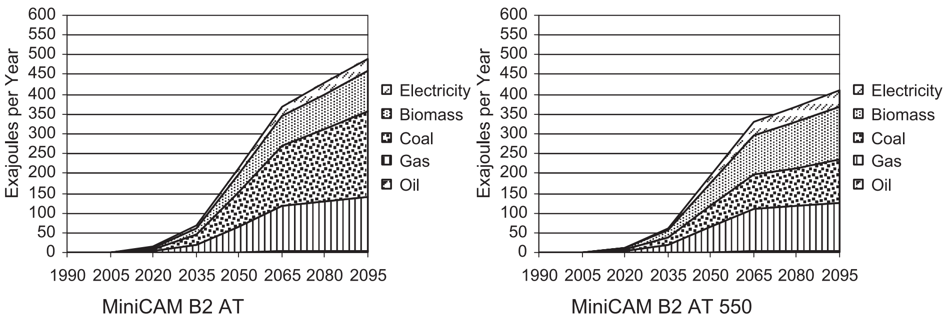

Fig. 7. Sources of H_2 production (EJ/year).

heat and power options, a direction for future model development. In such a scenario, the fixed users provide the motivation to build the backbone of the distribution system, which is followed by the application of fuel cells to transportation. By the middle of the century transport has become the largest H_2 consuming sector in both the MiniCAM B2 AT cases.

Technology development plays a particularly important role in shaping emissions from the transportation sector. Carbon taxes of the magnitude shown in Table 2 have almost no impact on behavior. Technology has a significant impact on emissions. Fig. 8 shows fuel use in the US against the background of the four MiniCAM B2 cases. Liquids remain the dominant source of motive power in all cases. However oil consumption is significantly reduced in the advanced technology cases until the end of the 21st century for two reasons. In the MiniCAM B2 AT case conventional fuel efficiency is higher than in the MiniCAM B2 case. While the higher efficiency lowers the cost of moving people and things per kilometer, and thus increases the demand for transportation services, the increase in services is not as large as the improved fuel efficiency. Second, hydrogen becomes a viable competitor and begins to take market share (Fig. 8).

The reason carbon taxes have so little effect on emissions is that the cost of fuels is such a small fraction of overall cost. For the United States the cost of providing a passenger kilometer of transport service is less than ten percent of the total cost in 1990. In the MiniCAM B2 cases that cost declines to less than 3% by the end of the century. Because

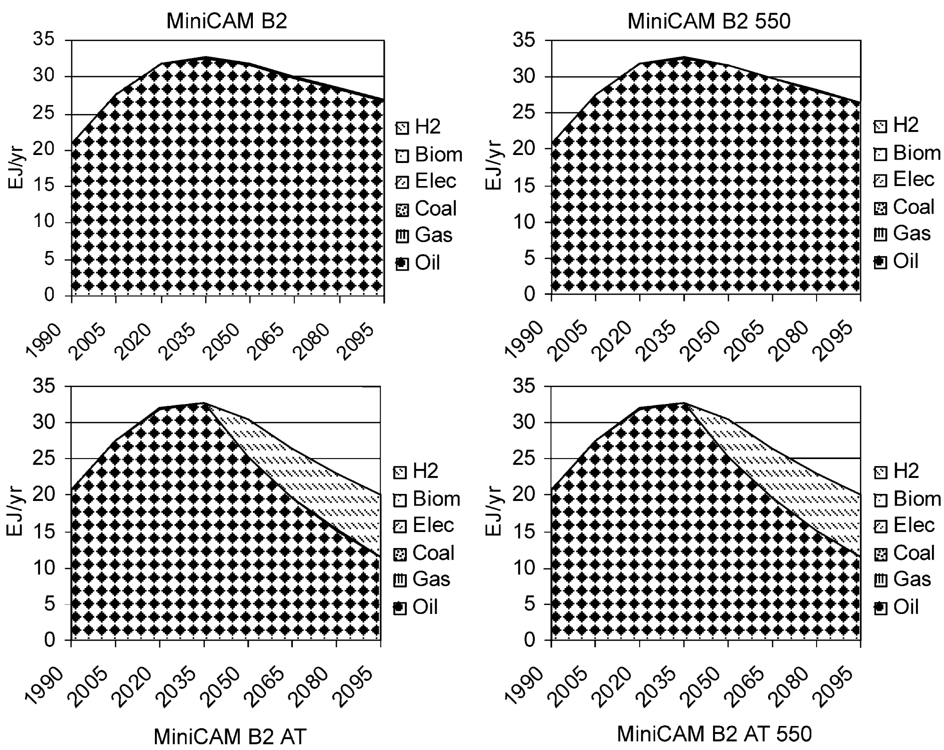

Fig. 8. USA transportation energy use (EJ/year).

each $100 per ton of carbon translates into approximately $0.25 per gallon of gasoline, the ability of carbon taxes to induce responses is small. The advanced technologies described in the MiniCAM B2 AT case on the other hand reduced emissions by more than half by the end of the century.

11. Some final thoughts

A primary purpose of modeling is to facilitate the development of insights on a critical issue. The following insights from the exercise of the MiniCAM model within the EMF-19 protocol particularly recommend themselves for consideration.

The first clear implication of the exercise is that technology plays a major role in shaping the structure of the global energy system in all cases. In addition, technology performance has a powerful influence on the cost of responding to climate change. The cost of meeting the 550 ppmv constraint was cut by more than half by the introduction of the advanced technologies of the MiniCAM B2 AT case.

Yet technology advances alone did not significantly change net carbon emissions. Advanced technologies in the absence of limitations on the concentration of carbon dioxide may not lead to reductions in emissions, depending on the nature of the technological advances.

A second observation to be drawn from the exercise is that the the global energy system could be dramatically different by the middle of the 21st century than it was at the beginning, if advanced technologies are developed and deployed. Of significant interest are the following:

1. carbon capture and disposal,
2. hydrogen energy systems,
3. transportation technologies, and
4. modern commercial biomass.

The transportation sector is of particular interest from the perspective of long-term technology development, as the cost of providing transportation services is predominantly non-energy related, yet the sector is an important source of carbon emissions. For the transportation sector, addressing the climate issue is all about technology.

A third observation is that technologies interact in important ways. In some instances, technologies compete for the same market. Conservation competes with renewables. Nuclear power competes with fossil fuels. But, in other instances technologies complement each other, each enhancing the cost-effectiveness of the overall energy system and thereby the market shares of all components. The hydrogen energy system has at least three major component technologies: (1) hydrogen production, transport, storage and distribution technologies, (2) carbon capture and disposal technologies, and (3) hydrogen use technologies. A failure in any of the three components has implications for the market performance of the suite.

Finally, technologies and policies interact in sometimes unexpected ways. We observe that the presence of an emissions constraint did not necessarily lead to wide-spread deployment of H_2 systems. In fact, when H_2 system technologies were cost-effective, their deployment could actually be retarded by the presence of a value for carbon.

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Technological learning for carbon capture and sequestration technologies

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Abstract

This paper analyzes potentials of carbon capture and sequestration technologies (CCT) in a set of long-term energy-economic-environmental scenarios based on alternative assumptions for technological progress of CCT. In order to get a reasonable guide to future technological progress in managing CO_2 emissions, we review past experience in controlling sulfur dioxide (SO_2) emissions from power plants. By doing so, we quantify a "learning curve" for CCT, which describes the relationship between the improvement of costs due to accumulation of experience in CCT construction. We incorporate the learning curve into the energy-modeling framework MESSAGE-MACRO and develop greenhouse gas emissions scenarios of economic, demographic, and energy demand development, where alternative policy cases lead to the stabilization of atmospheric CO_2 concentrations at 550 parts per million by volume (ppmv) by the end of the 21st century. We quantify three types of contributors to the carbon emissions mitigation: (1) demand reductions due to the increased price of energy, (2) fuel switching primarily away from coal, and (3) carbon capture and sequestration from fossil fuels. Due to the assumed technological learning, costs of the emissions reduction for CCT drop rapidly and in parallel with the massive introduction of CCT on the global scale. Compared to scenarios based on static cost assumptions for CCT, the contribution of carbon sequestration is about 50% higher in the case of learning, resulting in cumulative sequestration of CO_2 ranging from 150 to 250 billion (10^9) tons with carbon during the 21st century. Also, carbon values (tax) across scenarios (to meet the 550 ppmv carbon concentration constraint) are between 2% and 10% lower in the case of learning for CCT by 2100. The results illustrate that assumptions on

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technological change are a critical determinant of future characteristics of the energy system, indicating the importance of long-term technology policies in mitigation of adverse environmental impacts due to climate change.

Keywords: Carbon capture and sequestration; Technological learning; Climate change

1. Introduction

The mitigation of adverse environmental impacts due to climate change requires the reduction of carbon dioxide emissions from the energy sector, the dominant source of global greenhouse gas emissions. There are a variety of possibilities to reduce carbon emissions, ranging from the enhancement of energy efficiency to the replacement of fossil-based energy production by zero-carbon technologies. Most of the currently viable mitigation technologies, however, are more costly and inferior in some ways compared to the older and more "mature" fossil alternatives. Thus, there is an increasing interest among experts and policy makers in "add-on" environmental strategies to combine state-of-the-art fossil technologies with advanced technologies that capture carbon for subsequent sequestration. Such strategies, if successfully implemented, could enable the continuous use of fossil energy carriers at low (or almost zero) emissions.

Carbon capture and sequestration is not a completely new technology, e.g., the United States alone is sequestering about 8.5 million tons of carbon for enhanced oil recovery each year. Nevertheless, present costs for carbon capture technologies (CCT) to reduce emissions are between US$35/t C and US$264/t C (DOE, 1999), corresponding to a prohibitive cost increase for electricity of at least US$25/MW h. Given the current costs, it is unlikely that CCT can successfully enter the energy market, even if international agreements and efficient institutions for CO_2 abatement would exist. Their pervasive diffusion will require substantial efforts to induce "technological learning", which could accomplish considerable cost reductions in the long run.

With this perspective, this paper examines future market perspectives of carbon capture and sequestration by analyzing the dynamics, pace, and future potential for technological learning of CCT. Generally, costs—and other indicators of technology performance—improve as experience is gained by producers (learning-by-doing) and consumers (learning-by-using). In order to get a reasonable guide to future technological progress of carbon capture technologies, we review past experience in controlling sulfur dioxide (SO_2) emissions from power plants. By doing so, we quantify a "learning curve" that we apply to CCT to describe the relationship between the improvement of costs due to accumulation of experience in CCT construction.

The long-term nature of climate change and its inherent uncertainties call for robust strategies taking into account a number of possible alternative futures. Hence, we incorporate the learning curve into the energy modeling framework MESSAGE-MACRO and develop a set of global greenhouse gas emissions scenarios of economic, demographic, and energy demand development, where alternative policy cases lead to the stabilization of atmospheric CO_2 concentrations at 550 parts per million by volume (ppmv). Within this frame, we analyze the potential of CCTs in the context of other main mitigation options, such as fuel switching and enhanced energy conservation. As we shall show in this paper, under the assumption that learning in the application of CCT technologies occurs at a pace that is similar to that experienced for SO_2 abatement technologies in the past, the long-term reduction potential for CCT is vast. Even though their widespread deployment requires decades to come, at the end of the 21st century, almost all fossil power plants in the scenarios are equipped with CCT.

This paper is structured as follows: Section 2 describes how the learning curve for carbon capture and sequestration technologies was developed. A brief introduction into how technological learning is implemented into the MESSAGE-MACRO is given in Section 3. Section 4 presents our scenario analysis, including estimates of future potentials of carbon capture technologies. Section 4.1 summarizes the main characteristics of the baseline and mitigation scenarios. The main mitigation measures to decarbonize the future energy system are analyzed in Section 4.2, with Section 4.3 focusing mainly on the role of carbon scrubbing and sequestration. Finally, Section 5 concludes.

2. Estimation of learning curves for carbon capture and sequestration technologies

In 1936, a seminal paper by Wright (1936) introduced a quantitative model of ‘‘learning by doing’’ to describe the time savings (and associated cost reductions) achieved in manufacturing aircraft. Wright found that the time required to assemble an aircraft decreased with increasing production levels. The relationship was well-predicted by an equation of the form

$$y = ax^{-b} \tag{1}$$

where a equals the costs (hours) to manufacture the first unit, x depicts the cumulative number of units produced, y is the costs (hours) required to produce unit number x, and $-b$ gives the slope for the improvement in costs (hours) in producing the units.

On a log–log scale, this equation plots as a straight line with slope $-b$. Wright coined the term ‘‘progress ratio’’ to describe the ratio of current cost to initial cost after a doubling of production. Thus, a progress ratio of 0.80 meant that costs decreased by 20% for each doubling of cumulative production. Some authors therefore prefer the term ‘‘learning rate’’ for the latter quantity.

Wright’s ‘‘learning curve’’ equation was subsequently found to describe the decline in production costs for a wide range of manufacturing activities remarkably well (e.g., Dutton and Thomas, 1984). The concept of learning-by-doing was further extended to model the anticipated capital cost reductions in new generations of a technology, including a variety of advanced energy technologies (Nakicenovic et al., 1998; McDonald and Schrattenholzer, 2001). In this paper, we measure the overall rate of progress or learning from its two principal components: new and improved generations of the technology and learning how to operate existing equipment more efficiently. These two components contribute to what is often referred to as ‘‘experience curves’’ that represent the change in technology cost as a function of its cumulative installed capacity (IEA, 2000).

We have estimated learning rates of capital and operating cost reduction for the most common flue gas desulfurization (FGD) technology used at coal-fired power plants for SO_2 capture. This FGD system employs a slurry of lime or limestone as the chemical reagent to absorb SO_2 from flue gases. Fig. 1 shows the historical growth in installed capacity of these systems since they were first introduced in Japan in the late 1960s. The largest market has been the United States, which adopted stringent standards for SO_2 control under the Clean Air Act Amendments of 1970 and 1977. A decade later, Germany adopted FGD systems as part of its acid rain control strategy. Subsequently, the technology was deployed more widely in Europe and elsewhere.

Both the capital and operating costs of FGD systems depend on a large number of plant-specific design and operating factors such as plant size, plant utilization, coal properties, emission reduction requirements, and other parameters (Rubin, 1983). To obtain a systematic measure of FGD cost reductions attributable solely to technology innovation, we used a set of engineering-economic analyses of new FGD systems applied to a fixed US plant design. These studies were performed primarily by two major utility–industry organizations (the Tennessee Valley Authority [TVA] and the Electric Power Research Institute [EPRI]) at different points in time, using consistent methodologies and assumptions (McGlamery et al., 1976, 1980; Keeth et al., 1986, 1990, 1991, 1995). Thus, differences in FGD cost over time (adjusted for inflation) reflected real improvements in the cost of FGD technology for the standard plant application (i.e., 90% SO_2 removal at a new 500-MW plant burning a bituminous coal with 3.5% sulfur and a plant capacity factor of 65%). In a few cases, a power plant cost model (Rubin et al., 1997) was used to adjust reported cost figures to a consistent design basis where power plant design premises differed slightly from earlier studies.

Fig. 2 shows the resulting decline in FGD capital cost as a function of total cumulative capacity installed in the US, Germany, and Japan over the past several

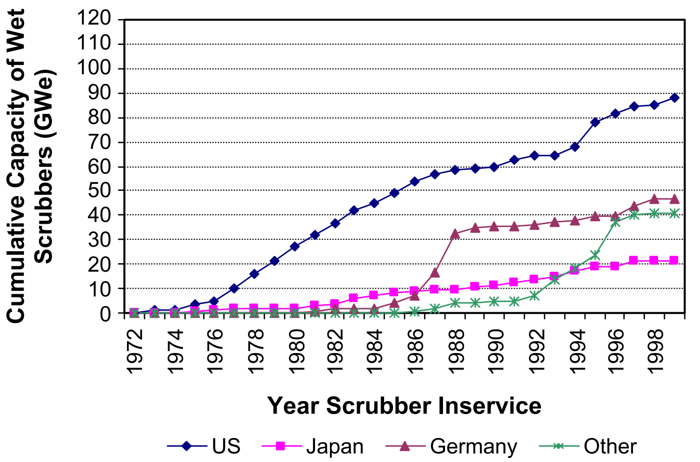

Fig. 1. Cumulative installed capacity of wet lime or limestone scrubbers in the US, Japan, Germany, and the rest of the world. Years after 1993 where under construction or firmly planned as of 1994 (source: Soud, 1994).

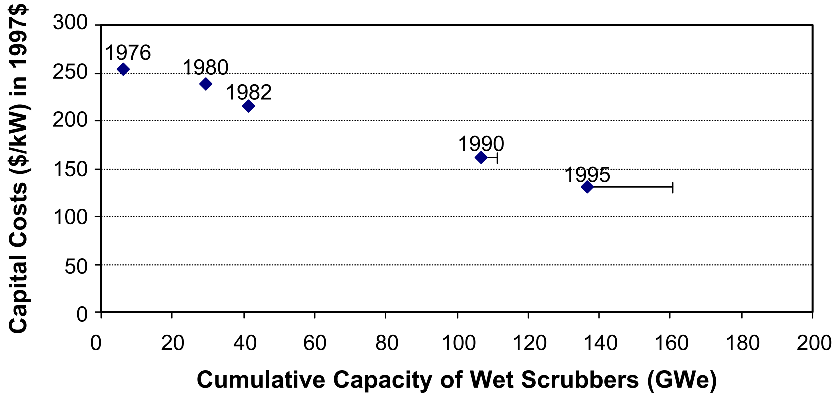

Fig. 2. Reductions in capital cost of a new wet limestone FGD system for a standardized coal-fired power plant (500 MWe, 3.5% sulfur coal, 90% SO_2 removal). Cumulative GWe capacity based on wet lime/limestone scrubbers in the US, Germany, and Japan, with the error bars including the rest of the world.

decades. This measure of cumulative capacity was used as the basis for the estimation of an experience curve because other research showed that these three countries dominated (and shared) inventive activities and innovations in this technology (Taylor, 2001).

For the purposes of this study, the data in Fig. 2 was normalized and fitted with an equation of the form of Eq. (1) to obtain an experience curve showing the rate of cost decline with increasing capacity. This function shows that as cumulative worldwide scrubbed capacity doubled, capital cost declined to about 87% of its original value. This relationship (Fig. 3) is used in the MESSAGE-MACRO model to represent the expected cost decrease for CO_2 capture systems in coal- and natural-gas-based power plants.

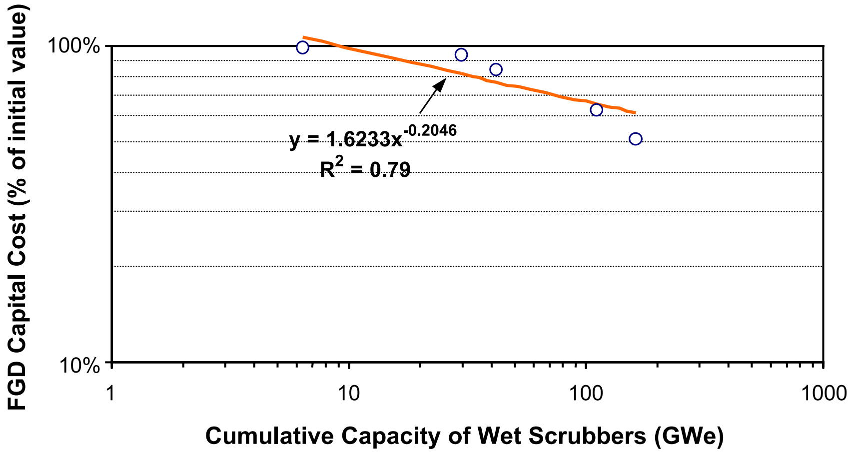

Fig. 3. Normalized experience curve for FGD capital cost.

3. Representation of technological change in MESSAGE-MACRO

This section briefly summarizes the main features of the modeling framework MESSAGE-MACRO (Messner and Schrattenholzer, 2000), which was used for the development of the scenarios analyzed in this paper. In particular, we describe how the concept of technological learning is introduced into the models and give a brief description of the reference energy system with focus on the representation of carbon capture technologies.

The Systems Engineering Model *MESSAGE* (version IV) is a linear programming (LP) systems engineering optimization model, used for medium- to long-term energy system planning and policy analysis. The model minimizes total discounted energy system costs and provides information on the utilization of domestic resources, energy imports and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions, and interfuel substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy.

MACRO is a top–down macroeconomic model. In the form it is as it is used here, it has its roots in a long series of models by Manne et al. The latest model in this series is MERGE 4.5 (Manne and Richels, http://www.stanford.edu/group/MERGE/). Its objective function is the total discounted utility of a single representative producer–consumer. The maximization of this utility function determines a sequence of optimal savings, investment, and consumption decisions. In turn, savings and investment determine the capital stock. The capital stock, available labor, and energy inputs determine the total output of an economy according to a nested constant elasticity of substitution (CES) production function. Energy demand in two categories (electricity and nonelectric energy) is determined within the model, consistent with the development of energy prices and the energy intensity of GDP. When MACRO is linked to MESSAGE, internally consistent projections of realized GDP and energy demand are calculated in an iterative fashion that takes price-induced changes of demand and GDP into account.

A typical model application is constructed by specifying performance characteristics of a set of technologies and defining a reference energy system (RES) that includes all the possible energy chains that MESSAGE can make use of. In the course of a model run MESSAGE will then determine how much of the available technologies and resources are actually used to satisfy a particular end-use demand, subject to various constraints, while minimizing total discounted energy system costs. A simplified illustration of the MESSAGE reference energy system is shown in Fig. 4. The gray box (Fig. 4) shows where the carbon capture technologies (CCT) are linked into the reference energy system. In sum, MESSAGE distinguishes between three types of CCTs:

(1) carbon capture from conventional coal- and natural-gas-based power plants (flue gas decarbonization)
(2) carbon capture from coal-based integrated gasification combined cycles (IGCC)
(3) carbon capture during the production of synthetic gaseous and liquid fuels (predominantly hydrogen and methanol)

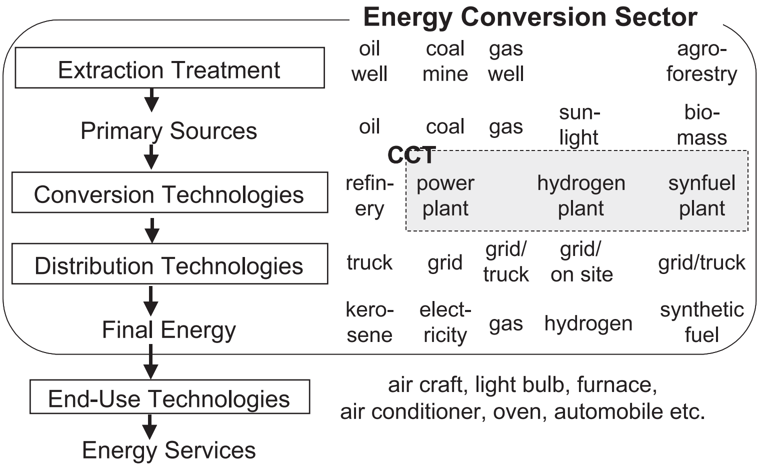

Fig. 4. Schematic illustration of the Reference Energy System (RES) in MESSAGE.

Important inputs for MESSAGE are technology costs and other technology parameters, which are taken from the energy technology database CO2DB[1] (Strubegger et al., 1999). For the scenarios included in this paper, technical, economic, and environmental parameters for over 400 energy technologies are specified explicitly in the model. Costs of technologies are assumed to decrease over time as experience (measured as a function of cumulative output) is gained.[2] As described earlier (Section 2), the relationship between costs and cumulative deployment of individual technologies is described by learning curves, characterized by a single learning rate and initial unit cost. However, assuming fixed learning rates ex ante is not possible within an LP formulation, because of the nonlinearity of the relationship and the resulting nonconvexity of the optimization problem, which would have to be tackled for example with Mixed Integer Programming (MIP). Illustrative MIP versions of MESSAGE to endogenize technological change through uncertain returns from learning have been developed (Messner, 1997) but are computationally infeasible for the detailed scenarios described in this study (which include over 400 energy technologies and operate on 11 world regions).

Thus, an iterative, ‘‘ex post’’ approach was used to obtain scenario results with the full-scale MESSAGE model, where technological improvements follow patterns consistent with those of learning curves. For this purpose, we assume that specific costs of technologies decrease at predefined rates over time. Such a time profile of costs will at first not necessarily mimic the behavior as postulated by learning curves. Hence, we increase the consistency of MESSAGE results with the learning-curve concept by

[1] CO2DB currently includes more than 1600 technologies and associated information on their recent, current, and projected costs, efficiencies, and environmental characteristics.

[2] Note that cost improvements for specific technologies differ from scenario to scenario, representing alternative pathways for technological change consistent with the respective scenario storyline (narrative). Hence, we do not assume cost improvements for the whole set of 400 technologies in each scenario. In some cases, costs are assumed to stay constant, in particular for mature technologies, which are phased out early in time.

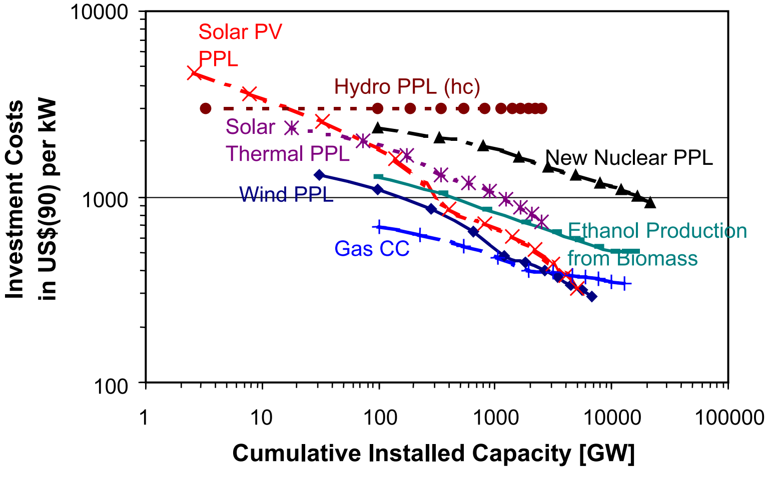

Fig. 5. Examples of investment cost (1990–2100) as implemented in MESSAGE. Literal learning curve would appear as straight lines on this double-log scale. Abbreviations: PV: photovoltaic, PPL: power plant, Gas CC: gas combined cycle power plant, New Nuclear PPL: future design of a new nuclear reactor.

iteratively adjusting technology costs and cumulative installed capacities. This approach is made possible with additional dynamic market penetration constraints in order to avoid "flip-flop" behavior for the most important technologies and to emulate the initial slow growth in niche markets of newly introduced technologies due to upfront investments. Fig. 5 shows examples of resulting cost decrease curves vs. cumulative installed capacities in a typical baseline scenario. Since investment costs are a power function of cumulative installed capacities, they appear as straight lines when plotted with double-logarithmic axis. All in all, the results in Fig. 5 show that the unit costs for the main technologies follow roughly a dynamics consistent with learning curves.[3]

4. Long-term perspectives for carbon capture and sequestration technologies

In order to estimate future potentials of CCT technologies, a set of global greenhouse gas emissions scenarios of economic, demographic, and energy demand development are analyzed. Frequently, scenario analyses are based on a static view of CCT technologies, where technology costs and performance are assumed to stay constant over time. Hence, important feedbacks on technology characteristics of, e.g., gaining experience in CCT construction and accumulated knowledge due to targeted R&D efforts, are often not taken into account. We will analyze the future prospects of CCT technologies using a more dynamic representation of technology, where costs improve as a function of cumulative experience (i.e., CCT deployment).

[3] Although the applied methodology permits the emulation of the learning process, in some cases, the resulting learning curves deviate slightly from the classical straight line in a double-log scale (see, e.g., wind, nuclear, and solar PV in Fig. 5).

Our assumptions on the learning potential for CCT are guided by the past experience of sulfur abatement technologies (see Section 2). In particular, we compare scenario results including learning for CCT technologies with scenarios based on static cost assumptions, and study the market potentials, costs, and impacts of CCT as a long-term carbon abatement technology.

For this purpose, we selected two baseline scenarios of the IPCC Special Report of Emissions Scenarios (IPCC, 2000) as our reference scenarios. For each, we develop two carbon mitigation scenarios (one with and one without CCT learning) aiming at the stabilization of atmospheric carbon concentrations at about 550 ppmv. The sequel of this section first presents the main characteristics of the respective baseline and carbon mitigation scenarios, proceeding later to the implications for CCT.

4.1. Baseline reference scenarios

Baseline assumptions of technological and socioeconomical development are paramount drivers of future GHG emissions, strongly influencing the choice of emissions mitigation strategies. As shown by the recent set of IPCC baseline scenarios (IPCC, 2000), the uncertainty associated with the drivers as well as the future GHG emissions is vast. In order to obtain a plausible range of estimates for the deployment of CCT, we analyze two alternative baseline scenarios, depicting future worlds of increasing carbon emissions with presumably high impacts due to climate change.

Both baseline scenarios are selected from the set of 40 IPCC-SRES reference scenarios. The B2-MESSAGE scenario (Riahi and Roehrl, 2000a) was selected because it is a kind of “middle-of-the-road” (dynamics-as-usual) scenario. In addition, we selected the A2-MESSAGE scenario (Riahi and Roehrl, 2000b), since A2 portrays a fossil-intensive future characterized by heavy reliance on coal-based energy production. A2 and B2 are based on different assumptions of socioeconomic development, technological progress, and political change. They result in widely differing world energy systems, which are cost-optimal strategies under the given assumptions, and lead to a wide range of emissions levels (Fig. 6). Assumptions for the main scenario drivers and results are presented in Table 1.

4.1.1. The A2 baseline scenario (narrative)

The A2 world represents a differentiated world, which “consolidates” into a series of economic regions. Economic growth is uneven across regions, and the income gap between poor and rich regions does not narrow as much as in the other SRES scenarios. Global average per capita income in A2 is low relative to B2, and global gross domestic product (GDP) reaches about US$243 trillion. International disparities in productivity, and hence income per capita, are largely maintained or increased in absolute terms.[4] Fertility rates decline relatively slowly, which leads to a steadily increasing world population reaching 15 billion by 2100.

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[4] When not mentioned explicitly otherwise, gross world product (GWP), gross domestic product (GDP), and related parameters are reported at market exchange rates, in 1990 US$.

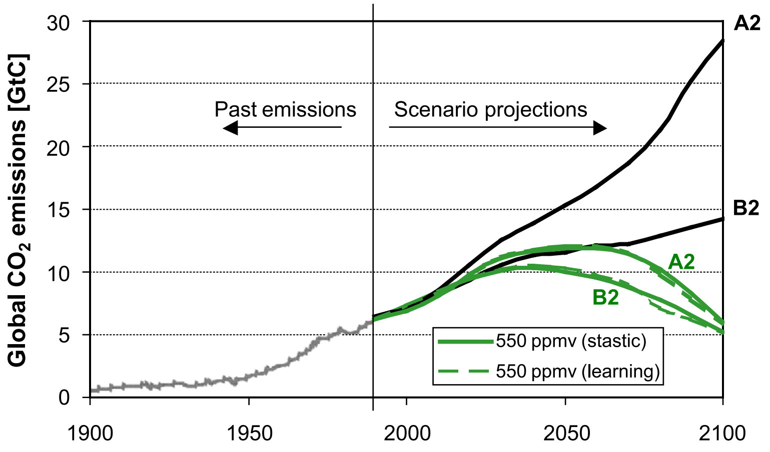

Fig. 6. Global carbon dioxide emissions in the A2 and B2 baseline scenarios and in the respective stabilization scenarios with and without learning for CCT.

A combination of slow technological progress, more limited environmental concerns, and low land availability because of high population growth means that the energy needs of the A2 world are satisfied primarily by fossil (mostly coal) and nuclear energy. However, in some cases, regional energy shortages force investments into renewable alternatives, such as solar and biomass. Regions with abundant energy and mineral resources evolve to more resource-intensive economies, while those poor in resources place a very high priority on minimizing import dependence through technological innovation to improve resource efficiency and make use of substitute inputs. The fuel mix in different regions is determined primarily by resource

Table 1
Overview of scenario drivers and results

Scenario	Year	Baseline scenarios		Stabilization scenarios			
				Static CCTs		Learning CCTs	
		A2	B2	A2-550s	B2-550s	A2-550t	B2-550t
Population (billion)	2050	11.3	9.4	11.3	9.4	11.3	9.4
	2100	15.1	10.4	15.1	10.4	15.1	10.4
Global gross domestic product (trillion 1990 US$)	2050	82	110	81	109	81	109
	2100	243	235	236	231	237	231
Primary energy (EJ)	2050	1014	869	959	881	960	883
	2100	1921	1357	1571	1227	1636	1257
Cumulative carbon emissions (Gt C)	1990–2100	1527	1212	992	948	990	950
Cumulative carbon sequestration (Gt C)	1990–2100	–	–	167	90	243	137
Carbon concentrations (ppmv)	2100	783	603	550	550	550	550

Compare with 1990 values for population (5.3 billion), GDP (US$20.9 trillion [1990]), primary energy (352 EJ), total CO_2 emissions (6.2 Gt C), CO_2 concentration (354 ppmv).

availability (limited to conventional reserves and resources). High-income but resource-poor regions shift toward advanced post-fossil technologies, while low-income resource-rich regions generally rely on traditional fossil technologies. The A2 world is characterized by relatively slow end-use and supply-side energy efficiency improvements and slow convergence between regions. All this leads to steadily increasing levels of GHG emissions (Fig. 6), with CO_2 emissions approaching 28 Gt C in 2100.

4.1.2. The B2 baseline scenario (narrative)[5]

In the B2 world, GDP grows from US$20 trillion in 1990 to US$235 trillion in 2100 (Table 1). This corresponds to a long-term average growth rate of 2.2% from 1990 to 2100. Most of this growth takes place in today's developing countries, but over the long term, economic growth rates in these regions also decline as labor productivity levels approach those of the leading countries. The B2 scenario uses the UN median 1998 population projection (UN, 1998), which describes a continuation of historical trends, including recent faster-than-expected fertility declines, toward a completion of the demographic transition within the next century. Global population increases to 10.4 billion by 2100.[6] Global primary-energy needs increase by almost a factor of 4 (in comparison to 1990) to 1360 EJ in 2100. Most of this increase takes place in today's developing regions. The aggregate global rate at which final-energy intensity declines is about 1% per year through 2100. Cost improvement rates for most technologies are moderate; however, they are largest for non-sulfur-emitting technologies due to local and regional pollution control. These include, in particular, wind and solar photovoltaics, but also gas combined-cycle, integrated gasification combined cycle (IGCC), solar thermal power plants, and advanced nuclear power plants.[7] Coal costs increase in regions with large shares of deep mined coal and high population densities, although coal costs are assumed to remain relatively low in regions with abundant surface coal reserves such as North America and Australia. Altogether, the B2 scenario exhibits linearly increasing global GHG emissions (Fig. 6), with CO_2 emissions reaching 14 Gt C by 2100.

4.2. Carbon mitigation scenarios

In order to study future potentials for CCT technologies, we developed carbon mitigation scenarios aiming at the stabilization of atmospheric CO_2 concentrations at about 550 ppmv. In sum, two stabilization scenarios for each baseline were developed—

[5] See Riahi and Roehrl (2000a) for more details.

[6] Although, in the long term, global fertility levels gradually approach replacement levels, the path and pace of fertility change vary greatly among the regions.

[7] Advanced nuclear power plants are defined as technologies that produce energy with higher efficiency and increased safety compared to today's nuclear standards. Their technological design is not prespecified in the model. Advanced nuclear technologies should be interpreted as a technology cluster (consisting of various different designs) rather than a single individual technology. The cluster might include, e.g., efficient high-temperature reactors (that produce hydrogen), new fast breeder reactors with modified designs, but also other imaginable options for nuclear fission.

one assuming constant costs for CCTs (A2-550s, B2-550s) and one including learning for CCTs (A2-550t, B2-550t).

All four stabilization scenarios are based on iterated runs of MESSAGE and MACRO. The macroeconomic model MACRO is important in this connection because the carbon constraint increases energy prices, which reduces energy demand and increases the demand for the other production factors (capital and labor), other things being equal. MACRO calculates this macroeconomic effect. Because both MESSAGE and MACRO are global optimization models, the model results are cost-optimal actions to meet the given carbon constraint. The results assume full spatial and temporal flexibility, including the free movement of investments. However, cost-optimal CO_2 emissions reduction possibilities do not necessarily occur in regions that give high priority to such reductions and that have the money to pay for them. Indeed, currently, the cheapest CO_2 reduction opportunities appear to be in developing countries, while it is the industrialized countries that currently appear most willing to pay for them. The stabilization scenarios can thus be seen as possible answers to the question: "Which are the best strategies to achieve stabilization if the world generally consistent with the (respective) baseline was able to successfully coordinate and cooperate on efforts to limit potential global warming?"

The resulting CO_2 emissions trajectories of the mitigation scenarios are shown in Fig. 6. They are characterized by a peak of about 9–12 Gt C around the middle of the 21st century. Subsequently, emissions decline to slightly less than the 1990 emissions level (6 Gt C) by 2100. These emissions profiles are similar to other emissions trajectories for 550 ppmv stabilization cases found in the literature (Wigley et al., 1996; Roehrl and Riahi, 2000). The similarity of the emissions pathways indicates limited flexibility of the timing and pace of emissions trajectories, to achieve CO_2 concentration stabilization at 550 ppmv with the least effort. Furthermore, the development of emissions is quite similar through 2020 in the stabilization runs and their baseline counterparts. Only after 2020 do emissions reductions become more pronounced. This is partly because power plants have lifetimes on the order of 30–40 years, which makes for slow turnover in the energy capital stock, and partly because of the temporal flexibility built into the concentration constraint. MESSAGE is free to choose when and where to reduce carbon emissions, and later reductions coinciding with turnover in capital plant are usually cheaper because of both technological progress and discounting.[8]

Although the resulting emissions trajectories of the four stabilization scenarios are similar, the contributions of individual mitigation measures to bring down emissions differ significantly. In particular, the choice of the mitigation strategy and the widespread deployment of specific mitigation options depend strongly on two factors:

(1) the socioeconomic and technological assumptions in the baseline scenarios and
(2) the assumptions with respect to technological learning for CCT technologies

We shall now discuss specific contributions of main mitigation options.

[8] For the scenarios presented in this paper, a discount rate of 5% was applied.

4.3. Three kinds of mitigation measures

In general, strategies to mitigate CO_2 emissions may be based on technological change, economic incentives, and institutional frameworks. They range from using the carbon sequestering potential of afforestation to demand-side- or supply-side-oriented measures in the energy sector, and even so-called geo- and cosmo-engineering schemes (Nakicenovic et al., 1993). Here, we confine our discussion to CO_2 abatement measures in the energy sector.

Applying the carbon concentration constraint to the baseline scenarios results in significant changes of energy demand and technology mix. Compared to the respective baseline scenarios, three principal contributors were identified by MESSAGE and MACRO as the most cost-effective route to meet the required stabilization target:

- fuel switching away from carbon-intensive fuels such as coal,
- scrubbing and removing CO_2 in power plants and during the production of synthetic fuels, mainly methanol and hydrogen, and
- lower energy demand (enhanced energy conservation) of the stabilization case compared to the baseline counterpart, due to higher energy costs in the stabilization cases compared to their baseline scenario counterparts.

The carbon reductions of specific mitigation measures in the stabilization scenarios are summarized in Table 2. In all stabilization scenarios, the comparatively largest contribution comes from structural changes in the energy system. Principally, this is a shift away from coal, which has the highest CO_2 emissions per unit of energy. To satisfy the carbon constraint, all mitigation scenarios make pronounced shifts to less carbon-intensive primary energy resources, and coal's share of primary energy decreases considerably.

The second most important contribution is due to carbon capture and sequestration, where the emission reductions are particularly high in the case of learning CCT technologies. Cost improvements in the case of technological learning for CCT result in additional markets for carbon capture and enable comparatively higher shares of fossil energy production, compared to the cases with static CCT costs. The contribution of main carbon capture technologies relative to other mitigation measures is shown in Fig. 7 for the A2-550t and in Fig. 8 for B2-550t, respectively.

Table 2
Emissions reductions (in Gt C) of the main mitigation measures in the stabilization scenarios for the years 2050 and 2100

	Demand reduction		Fuel switching		CO_2 capture and sequestration		Total	
	2050	2100	2050	2100	2050	2100	2050	2100
Static CCTs								
A2-550s	0.3	3.6	2.2	12.5	0.5	5.8	3.0	21.9
B2-550s	0.3	1.3	1.4	3.9	0.3	3.0	2.0	8.2
Learning CCTs								
A2-550t	0.3	3.7	2.1	9.5	0.4	8.9	2.9	22.0
B2-550t	0.3	1.5	1.1	4.0	0.3	4.0	1.7	9.5

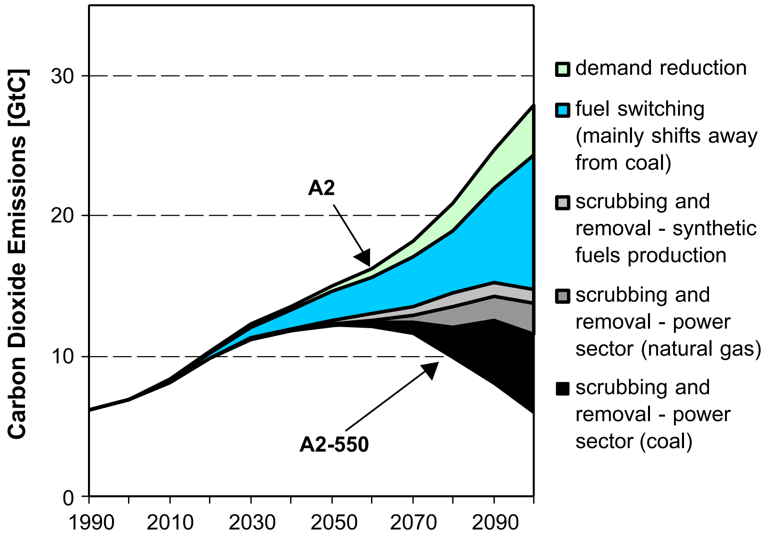

Fig. 7. CO_2 emissions in the A2 baseline scenario and in the CO_2 mitigation scenario in the case of learning CCTs (A2-550t). The shaded areas depict sources of CO_2 reductions in the global energy system of the mitigation scenario, compared to the baseline scenario.

As regards the timing of the mitigation measures, the first half of the century is dominated by structural shifts in the energy system, which is mainly due to the widespread diffusion of gas-combined-cycle (GCC) power plants at the expense of

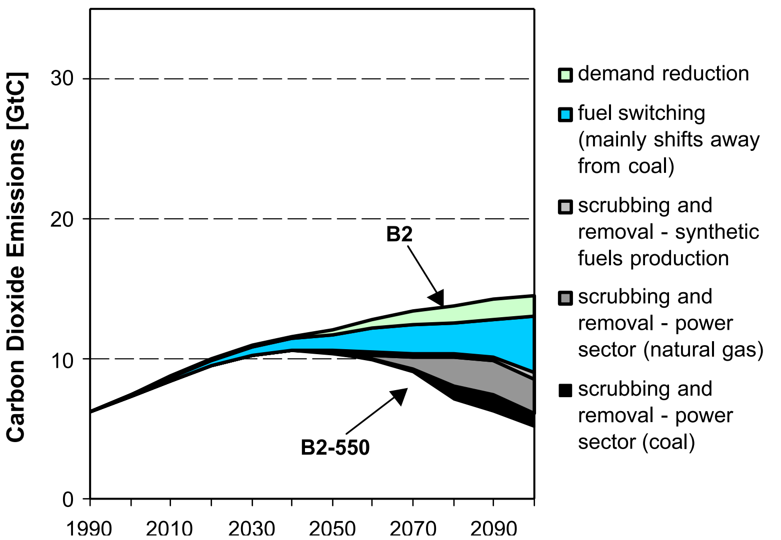

Fig. 8. CO_2 emissions in the B2 baseline scenario and in the CO_2 mitigation scenario in the case of learning CCTs (B2-550t). The shaded areas depict sources of CO_2 reductions in the global energy system of the mitigation scenario compared to the baseline scenario.

coal technologies. GCC's comparatively low carbon intensity and electricity generation costs makes GCC to a "transitional" technology, accomplishing a smooth and cost-effective transition to more pronounced changes in the energy structure in the latter half of the century. Generally, the pressure on the energy system to reduce emissions increases with time, since the reduction requirements in absolute quantities increases (Table 2). Eventually, this leads to the large-scale introduction of more costly abatement options, such as renewable energy and carbon capture from fossil fuels (Figs. 7 and 8).

As illustrated by the results, each of the three main mitigation measures is important, and none of the suggested mitigation options alone is sufficient to meet a 550-ppmv stabilization target. Hence, we conclude that effective mitigation strategies have to take into account the whole portfolio of technological possibilities, which includes also carbon capture with subsequent sequestration.

4.4. Potentials for carbon scrubbing and removal

The previous section analyzed the important role of carbon capture technologies as compared to other principal mitigation measures. In this section, we will focus on CCTs only. In particular, we will review estimates of global storage possibilities for the disposal of CO_2 and compare them with the carbon sequestration figures in the scenarios. In addition, we present the underlying assumptions for costs and performance of CCTs in the scenarios and analyze their dynamics of market penetration. Finally, we conclude on potentials and macroeconomic costs of carbon capture assuming technological learning for CCT vs. no learning (static costs).

4.4.1. Global carbon storage capacities

Generally, CO_2 removal by scrubbing and CO_2 recovery from flue gases is referred to as "add-on" environmental strategies. After its recovery from the energy system, CO_2 has to be disposed of, stored or otherwise used. One example of putting it to productive use is enhanced oil recovery, where CO_2 is injected in oil fields (originally to improve the oil recovery rate). CO_2 may also be stored in depleted natural gas and other underground reservoirs, eventually also in the deep ocean (Marchetti, 1989).

Original natural-gas production sites alone correspond to a potential storage capacity of about 150 Gt C. After the extraction of higher cost gas categories, this storage capacity may be larger than 250 Gt C. The Second Assessment Report of the IPCC estimated the potential storage capacity of depleted oil and gas fields alone to be as high as 500 Gt C (IPCC, 1996). If structural traps are needed for secure storage, deep subterranean sandstone aquifers have a long-term CO_2 storage capacity of at least 60 Gt C (Hendriks, 1994). Without structural traps, the estimated worldwide sequestering capacity of aquifers is about 15,000 Gt C. CO_2 is also stored in chemical feedstocks and basic materials, e.g., CO_2 is used in the synthesis of urea (>10 Mt C p.a.). By far, the largest reservoir for carbon disposal in the form of solid CO_2 ice is the deep ocean, which currently stores about 36,000 Gt C. Orders of magnitude estimates for the main global sequestration options are presented in Table 3. Various methods of storing carbon in solid form have also been proposed (e.g., Yamada et al., 1992; Steinberg,

Table 3
Global carbon sequestration capacities (Gt C)

Storage option	Capacity (Gt C)
Depleted oil and gas reservoirs	hundreds
Deep saline quifiers	hundreds to thousands
Coal seams	tens to hundreds
Ocean	thousands

Source: Herzog (2001).

1996).[9] Ongoing research and development is analyzing the technical and economic feasibility of these and other novel concepts for carbon capture and sequestration.

In none of the stabilization scenarios does the cumulative carbon sequestration from 1990 to 2100 exceed 300 Gt C (see Table 1). This means that the amount of carbon emissions that has been captured in the scenarios is well below the maximum potential of storage capacity of depleted oil and gas fields alone. Even though it seems that global storage possibilities are abundant compared to the sequestration requirements of the scenarios, it still has to be proved that the reservoirs proposed for carbon sequestration are effective, safe, and environmentally sound. Given the widespread deployment of CCT technologies in the scenarios, a better scientific understanding of the long-term fate of CO_2 in storage reservoirs appears to be called for.

4.4.2. Costs of carbon capture and sequestration

There are many viable and promising methods for CO_2 separation and capture from power plants. The most likely options currently identified are (U.S. DOE [Department of Energy], 1999)

- chemical and physical absorption,
- chemical and physical adsorption,
- low-temperature distillation,
- gas separation membranes, and
- minearalization and biomineralization

The capturing of CO_2 accounts for about three-fourths of the total cost of a carbon capture, storage, transport, and sequestration system. The cost assumptions in the scenarios are based upon estimates from several recent studies (Rubin et al., 2001; EPRI and USDOE, 2000; Simbeck, 1999; Herzog, 1999) assuming that CO_2 is captured from flue gases by currently available chemical absorption systems. For transportation and disposal, we assumed that captured CO_2 is transported in liquid state, through 250 km of pipeline and disposed of in geological formations. The cost for CO_2 transportation is based on estimates from the IEA (1999), assuming originally a distance of 500 km at US$45/t C. Here, half the distance and an economy of scale factor of 2/3, which results in US$28/t C

[9] Carnol System CO_2 Reduction: When methanol is used in automotive internal combustion engines, a CO_2 reduction by 56% compared to conventional system of coal plants and gasoline engines is achieved, and a CO_2 reduction by as much as 77% when methanol is used in fuel cells in automotive engines (Steinberg, 1996).

Table 4
Total carbon reduction costs, illustrated on the basis of two reference plants: (1) standard coal power plant, (2) natural gas combined cycle power plant

	Unit	Coal		Natural gas	
		Reference technology		Reference technology	
		Standard coal power plant	Incl. CCT	NGCC	Incl. CCT
Investment costs	$/kW	1000	1749	730	1089
Fixed O&M costs	$/kW	27	20.7	52	78.1
Variable O&M costs	$/kW year	n.a.	188.7	n.a.	n.a.
Efficiency	%	40	30.4	50	42.5
Plant life	years	30	30	30	30
Plant factor	%	65	65	65	65
Fuel cost	$/GJ	1.75	1.75	3.53	3.53
Levelized investment costs	mills/kW h	11.8	20.6	8.6	12.9
Levelized O&M costs	mills/kW h	4.8	30.4	9.2	13.8
Levelized fuel costs	mills/kW h	15.7	20.7	25.4	29.9
Electricity generation costs	mills/kW h	32.3	71.8	43.2	56.5
Carbon emissions	g C/kW h	232	30	110	13
Total carbon reduction costs	$/t C	–	196	–	137

of transport plus disposal cost is assumed. Technology costs and performance assumptions for coal- and natural-gas-based reference plants and the respective carbon capture plants are summarized in Table 4. Generally, the capturing of CO_2 is associated with efficiency losses of the power generation process and additional costs for the carbon capture facilities. As shown in Table 4, the carbon abatement costs for coal technologies resulting from our assumptions are US$196/t C, compared to US$137/t C for natural gas (both figures including transportation and disposal).[10]

In the stabilization scenarios with static costs (A2-550s, B2-550s), we assumed that the capital costs for CCTs remain constant over time, at the values shown in Table 4. In contrast, in the case of learning CCTs (A2-550t, B2-550t), we assumed that their costs decrease with accumulated experience in CCT construction. As described in Section 2, the investment cost declines by 13% for each doubling of CCT capacity. The development of carbon reduction costs as a function of cumulative installed CCT capacities in the scenarios is illustrated in Fig. 9.

Due to technological learning, CCT costs drop rapidly in the stabilization scenarios, leading to cost reductions by a factor of 4 by the end of the century. In line with the development of costs, CCT technologies diffuse pervasively into the energy markets, accomplishing the continuous use of fossil fuels at relatively modest costs and low carbon emissions. Total reduction costs for natural-gas technologies drop to US$34–38/t C, and those of coal technologies to US$41–61/t C (Fig. 9).[11]

[10] Costs of carbon removal in synthetic fuels production (and from IGCC) were assumed to be US$46/t C (inclusive transportation and disposal).

[11] As to initial carbon reduction costs for CCTs, both scenarios (A2 and B2) share the same assumptions for coal-based CCTs (US$196/t C) and natural gas-based CCTs (US$137/t C).

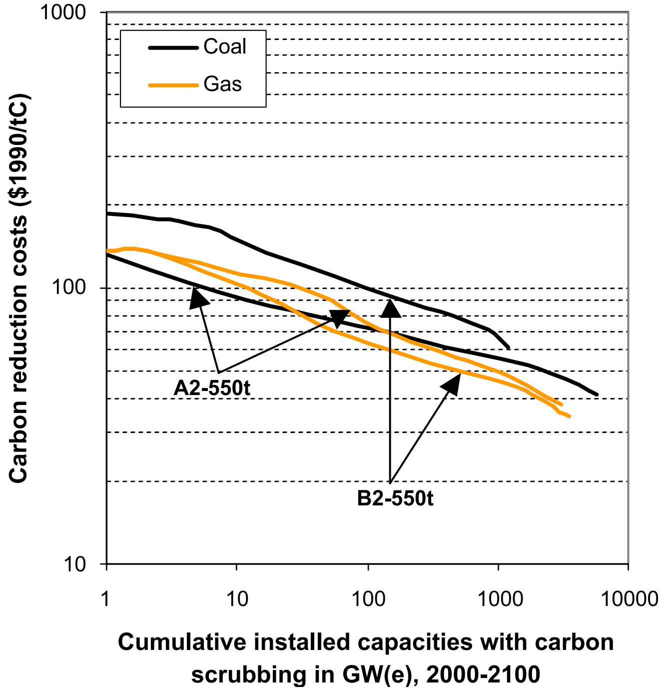

Fig. 9. Technological learning of carbon capture technologies in the A2-550t and B2-550t scenarios, illustrated as decreasing specific carbon reduction costs over accumulated experience (cumulative installed power generation capacities).

The development of the carbon reduction costs for CCTs depend also on regional resource availability and the development of fuel costs. In addition, assumptions on technological change for the power plants themselves influence the carbon reduction costs of CCTs. A sensitivity analysis using different initial costs for CCTs suggests that the learning rate might be the most decisive factor, not only for the costs, but also for the successful diffusion and dissemination of CCTs (given a specific carbon constraint).[12]

4.4.3. CCT market shares in the electricity sector

The scenario's market shares of CCT technologies are the result of complex interactions between demand-pull to supply-push activities. On the demand side, the carbon concentration limit enforces the introduction of new and advanced technologies with low carbon intensities. On the supply side, increasing returns from induced technological learning of

[12] Our iterative approach to approximating learning curves by time series is not perfect. This is why the two black curves for coal technology in Fig. 9 do not emanate from one and the same point (such as the two curves for gas). Forcing them to have the same initial costs (at one GW cumulative capacity) would have led to either inconsistent time profiles of cost developments or to cost lines that would not have resembled straight lines. We therefore opted for the approximation (and the error) shown in the figure.

CCTs pushes their market penetration from the supply side. Together, this results in very successful penetration of CCT technologies in the scenarios with technological learning, compared to scenarios with static cost assumptions.

Fig. 10 depicts the diffusion of carbon capture technologies (added to natural-gas and coal technologies) into the electricity generation market in the case of technological learning for CCTs. The graph shows the increasing shares of CO_2 capture plants, depicting examples of very successful market introduction. Initially, CCTs are expensive and limited in their application. They have to first prove themselves during the demonstration phase where performance rather than costs is the overriding criterion. Then subsequent improvements and cost reductions lead to wider application. Finally, growth rates slow down as markets become saturated. The diffusion of CCTs proceeds along a typical S-shaped pattern: slow at the beginning, followed by accelerating growth that ultimately slows down as markets become saturated. The literature on S-shaped diffusion is large, and there have been many studies, which have applied these curves to the spread of, e.g., transportation infrastructures and other types of technologies (Marchetti, 1983; Haegerstrand, 1967; Fisher and Pry, 1971; Nakicenovic, 1986; Grübler, 1998b).

Comparing the diffusion of CCTs in scenarios with learning (A2-550t, B2-550t) with those assuming constant costs of these technologies (A2-550s, B2-550s) shows that the market penetration of CCTs is accelerated due to technological learning. Particularly, the carbon capture from coal technologies benefits considerably from the learning effect, leading to global market shares of more than 90% in 2100 (compared to 60–70% in the

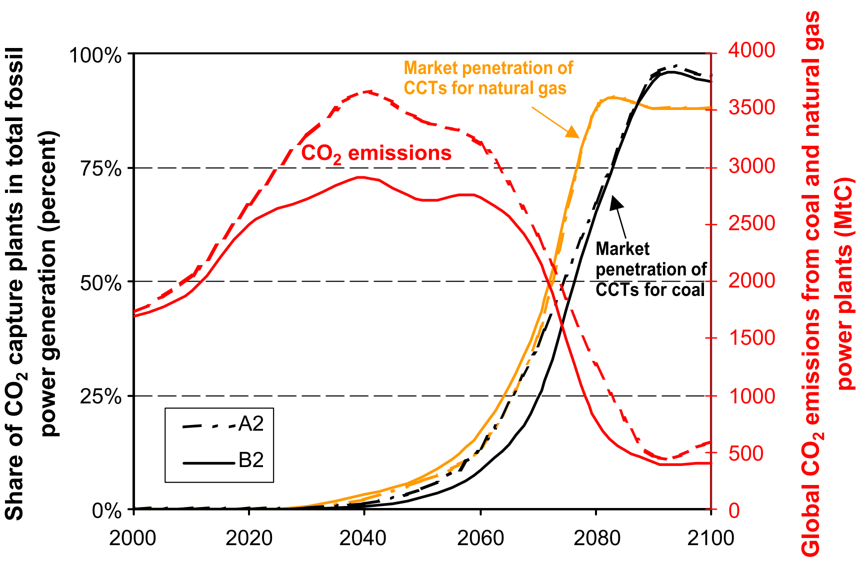

Fig. 10. Market penetration of "learning" CCT technologies for natural-gas and coal power plants in the A2-550t and B2-550t scenarios (left-hand axis). Dashed lines depict the development in the A2-550t scenario and uninterrupted lines in B2-550t. Also shown are the aggregated CO_2 emissions from coal and natural-gas power generation in the respective scenarios (right-hand axis).

case of static costs). At the end of the century, almost all fossil power plants are equipped with carbon capture technologies in the case of learning (Fig. 10).

The resulting CO_2 emissions from coal and natural-gas-based power generation are also shown in Fig. 10. The CO_2 emissions path in the scenarios follows an inverse U-shaped pattern similar to the environmental Kuznets curves observed for other pollutant emissions in the past, such as sulfur (Grübler, 1998a). After an initial growth phase, CO_2 emissions peak around the middle of the century and later decline, when the carbon capture and sequestration technologies gain considerable market share. Most notably, until the end of the century, global CO_2 emissions from coal and gas power generation decreases by more than a factor of 3, while power generation from these technologies grows to three to five times their present production (about 27 EJ).

Another characteristic of the scenarios is the comparatively late diffusion of CCTs. It requires decades for them to diffuse widely. In all four stabilization scenarios, large-scale applications first emerge as late as in the 2030s. However, once introduced, they continuously gain market shares. The entire diffusion of CCTs, from the initial introduction to saturation, spans, in all scenarios, about 50 years, which is similar to diffusion speeds of other types of technologies found in the literature (see, e.g., Grübler and Nakicenovic, 1991). Most importantly, our results should not be interpreted as a pretext to wait decades and then start the installation of CCTs. In fact, to realize the technology diffusion shown by the stabilization scenarios requires early action, including the creation of niche markets, the development of small-scale demonstration plants, and targeted R&D.

4.4.4. Cumulative carbon sequestration

The scenario's total cumulative carbon sequestration by time period—from 1990 to the years 2020, 2050, and 2100 respectively—are shown in Fig. 11. Generally, the amounts scrubbed depend strongly on (1) the socioeconomic and technological assumptions in the baseline scenarios and (2) the assumptions with respect to technological learning for CCT technologies. As illustrated in Fig. 11, cumulative carbon sequestration is higher in the

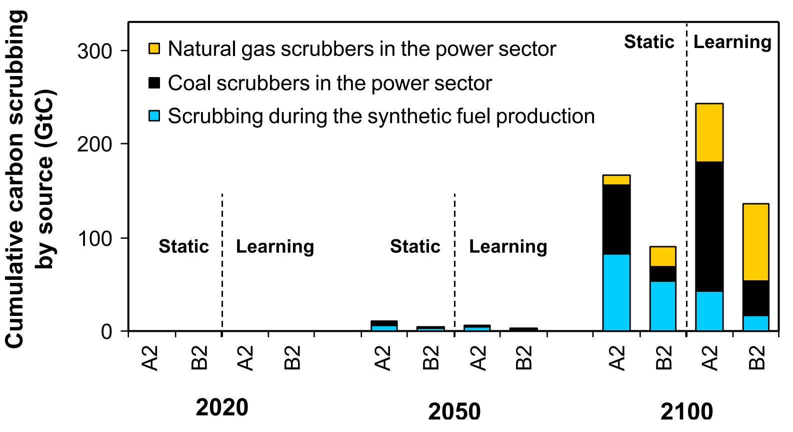

Fig. 11. Cumulative carbon capture and sequestration by source. Learning for CCT leads to comparatively high deployment of carbon capture technologies, in particular, in the electricity sector.

case of the A2 scenario compared to the B2 scenario and higher in scenarios with CCTs with learning than in those with static cost assumptions.

Since the A2 baseline depicts a future of heavy reliance on coal technologies, cumulative carbon sequestration is particularly high in A2, calling for environmentally compatible solutions that permit the continuous use of coal at low carbon emissions. In contrast, fossil-based power generation plays a less prominent role in the B2 baseline scenario and is mainly dominated by advanced natural-gas technologies, in particular gas-combined-cycle. Hence, in A2, coal scrubbers dominate, while in B2, natural-gas scrubbers account for the bulk of the emissions reductions (Fig. 11).

The relatively fast and more complete market diffusion of CCTs in the case of learning results also in considerably higher cumulative carbon sequestration (when compared to the scenarios with static CCT costs). In the case of learning, CCT's cumulative carbon emissions from 1990 to 2100 range between 137 and 243 Gt C. This corresponds to a 50% increase of sequestration due to learning effect for CCTs, compared to the scenarios with static CCT costs (90–167 Gt C).

4.4.5. Impact on the electricity price

The development of electricity prices in the baseline and the stabilization scenarios is shown in Fig. 12. As for total energy demand (see Section 4.2), electricity consumption is reduced in the stabilization cases compared to their respective baselines. This is due to the assumed price elasticity of electricity demand, which leads to demand reductions in response to higher prices in all mitigation cases, compared to the baseline scenarios. Due to the lower costs for CCT, the price increase is less pronounced in stabilization scenarios with learning CCTs than in the cases with static CCT costs.

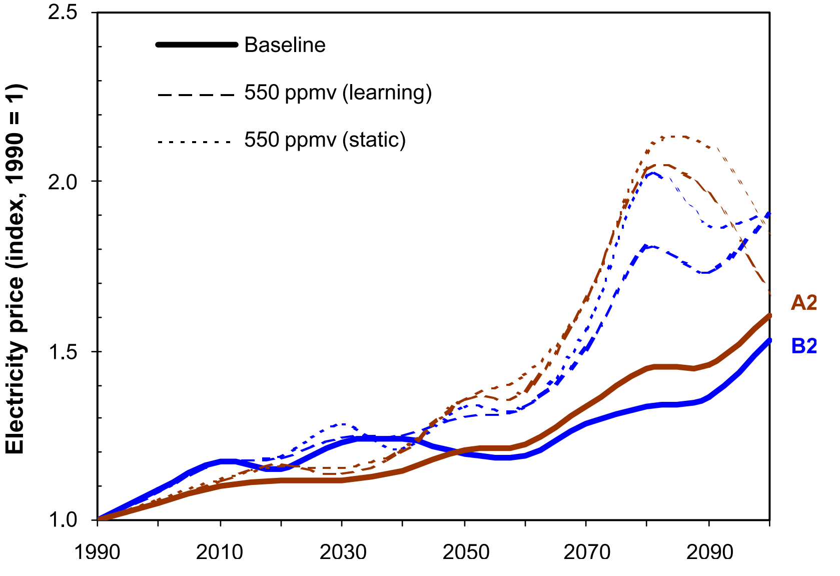

Fig. 12. Development of electricity prices in the scenarios.

Table 5
Carbon values in four stabilization scenarios

	Carbon tax (1990 US$/t C)		
	2020	2050	2100
Static CCT costs			
A2-550s	25	82	496
B2-550s	23	59	447
Learning CCTs			
A2-550t	19	27	490
B2-550t	18	64	406

The carbon values are an endogenous result of the model calculations and can be interpreted as the carbon tax that is required to meet the 550 ppmv stabilization target.

4.4.6. Carbon values and macroeconomic costs of the emissions reduction

Table 5 shows the resulting carbon values in the mitigation scenarios. The carbon value is an endogenous output calculated by the MESSAGE model. It can be interpreted as the average carbon tax that has to be introduced in a carbon-constrained world in order to meet the stabilization target. Due to steadily increasing emissions in the baselines, the pressure on the global energy system to reduce emissions increases over time, particularly in the latter half of the century. In the stabilization scenarios, carbon values grow steadily from about US$20/t C in 2020 to about US$400–500/t C in 2100. Due to the increasing cost effectiveness of CCTs in the case of learning, the required carbon value (tax) is lower in stabilization scenarios with dynamic CCT costs, compared to those based on static costs. This result illustrates that assumptions on technological change is one of the most decisive factors in determining the cost effectiveness of long-term carbon abatement policies (see also Roehrl and Riahi, 2000).

Table 6 summarizes the macroeconomic costs of the emissions reductions, measured as the loss of global gross domestic product (GDP) in the stabilization scenarios, compared to the respective baselines.

Table 6
Global gross domestic product (GDP) and GDP losses from the reference case to the stabilization scenarios for the year 2100

	GDP (trillion 1990US$)	GDP losses (percent of baseline)
Baseline scenarios		
A2	242.8	–
B2	234.9	–
Static CCT costs		
A2-550s	236.4	2.65
B2-550s	230.8	1.74
Learning CCTs		
A2-550t	236.6	2.55
B2-550t	230.9	1.72

GDP losses are generally higher in the A2 stabilization scenarios (2.6% in 2100) than in B2 (1.7% in 2100), once more illustrating the importance of the socioeconomic and technological assumptions in the baseline scenarios in determining the choice and costs of mitigation strategies.

One striking result of our analysis is that the GDP losses do not differ significantly in the case of learning CCTs, compared to scenarios with static CCT costs. There seems to be no direct relationship between total amounts of cumulative carbon sequestration and GDP losses, indicating that the macroeconomic stabilization cost is the result of a more complex price formation system, in which CCTs are just one influencing factor among many. CCT costs contribute to the progression of prices, but do not completely determine them.

The range of GDP losses given in Table 6 are comparable to results from similar studies. For example, Edmonds and Richels (1995) report losses of 0.5–1% for a 500-ppmv stabilization constraint. Results for a 550-ppmv stabilization case from the 14th Energy Modeling Forum Study for four different models (CSERGE, CETA, PEF, and CONN) suggest losses between 0.4% and 3.4% of GDP (EMF14, 1994). Most notably, however, the GDP losses in all of our stabilization scenarios are rather small, compared to the scenario's increase of total GDP by a factor of 11 (from 1990 to 2100), which illustrates that atmospheric carbon concentration stabilization at 550 ppmv is possible at moderate costs.

5. Summary and conclusions

In this report, we have estimated future potentials of carbon capture and sequestration technologies (CCT) in the framework of global greenhouse gas emissions scenarios of economic, demographic, and energy demand development, where alternative policy cases lead to the stabilization of atmospheric CO_2 concentrations at 550 ppmv. In contrast to several other scenario analyses where technology costs and performance are assumed to stay constant over time, we have analyzed the future prospects of CCT technologies using a more dynamic representation of technology. In particular, we quantified a "learning curve" for CCT, which describes the relationship between specific cost reductions and the accumulation of experience in CCT deployment. To do this, we examined past experience with managing other major power plant emissions that may serve as a reasonable guide to technological progress in managing CO_2 emissions. In particular, we focused on the experience made over the past 30 years in the US and other countries with reducing emissions of sulfur dioxide (SO_2) using flue gas desulfurization (FGD) systems. This technology (commonly known as SO_2 "scrubbers") employs principles of operation that are similar to those employed in currently commercial CO_2 capture systems. These systems use chemical sorbents to remove CO_2 from gas mixtures, such as combustion products. For FGD systems, investment costs declined by 13% for each doubling of capacity worldwide, and this is therefore the value we used to quantify the learning curve for CCTs.

Part of the integrated assessment was to analyze the potential of CCTs in the context of other possible carbon mitigation technologies and measures. We did this by including (learning) CCTs into the energy supply optimization model MESSAGE-MACRO, in which carbon capture and sequestration have to compete with other mitigation measures such as fuel switching and price-induced conservation. Our analysis shows that the timing, costs, and contribution of carbon mitigation measures strongly depend on (1) the socioeconomic and technological assumptions included in the baseline scenario and (2) the assumed learning potential of carbon capture and sequestration technologies. Assuming that learning in CCT technology deployment proceeds at a similar pace as in SO_2 abatement technologies in the past, the long-term carbon emission reduction potential for CCTs is vast; in our scenarios ranging between 140 and 250 Gt C of cumulative CO_2 sequestration (from 1990 to 2100, assuming a stabilization target of 550 ppmv). This is particularly due to large-scale investments into CCT and the accumulation of experience, which leads to rapid cost decreases of these technologies. Even though their widespread deployment requires decades, CCTs gain much higher market shares in the case of learning, compared to scenario results with static CCT cost assumptions. At the end of the 21st century, almost all fossil power plants are equipped with CCT in the case of learning. Thus, we conclude that carbon capture and sequestration is one of the obvious priority candidates for long-term technology policies and enhanced R&D efforts to hedge against the risk associated with the high environmental impacts of climate change.

Our scenario analysis also showed that the capturing of carbon with subsequent sequestration might not be sufficient to meet a 550-ppmv stabilization constraint (in the year 2100), even in the case of learning and a very rapid market penetration for CCTs. In addition to carbon sequestration, reaching this goal must also include better energy efficiency and the increased use of low-carbon emitting energy sources, in particular fuel switching, primarily away from carbon-intensive coal to low or zero-carbon fuels.

Acknowledging the major differences between scenarios with learning CCTs and those with static cost assumptions leads us to two important conclusions. First, climate policy models should be capable of characterizing future changes in cost and performance resulting from technology innovation (learning). Second, climate policies need to be extended to include technology policies, in order to make the diffusion of environmentally sound technologies operational in the long run (as shown by our stabilization scenarios). This calls for early action to accomplish the required cost and performance improvements in the long term, including the creation of niche markets, the development of small-scale demonstration plants, and targeted R&D.

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Potentials of hydrogen and nuclear towards global warming mitigation—expansion of an integrated assessment model MARIA and simulations

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Abstract

This paper describes an extended version of an integrated assessment model called Multiregional Approach for Resource and Industry Allocation (MARIA) and how it was applied to assess the global and regional greenhouse gas (GHG) emission mitigation policies. The model has been developed to assess the potential contribution of fossil, biomass, nuclear and other energy technologies and land-use changes to future GHG emissions. In this paper, the MARIA model is extended to evaluate a new hydrogen production process through steam–methane reforming at a significantly lower temperature (300–500 °C) than that of conventional steam–methane reforming processes as a liquid fuel supplier under the long-term global warming strategies. Bern simple carbon cycle model is also included in the model to reflect the recent findings in climate science. The simulation results suggest that hydrogen with Fast Breeder Reactors could supply 5–8 GTOE of hydrogen in the second half of the 21st century when climate policy that stabilizes the atmospheric carbon concentration is introduced. Although biomass does not completely replace fossil energy sources, the simulations show that it effectively mitigates the marginal cost of carbon emission.

Keywords: Integrated assessment model; Climate change; Greenhouse gas (GHG) emissions; Hydrogen production

1. Introduction

It is now broadly recognized that the global warming issues may be a major barrier to world development, equity and sustainability. Intergovernmental Panel for Climate

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Change (IPCC) established in 1988 has summarized the scientific progresses in this field. In the IPCC Third Assessment Report (TAR), integrated assessment models (IAMs) contributed to evaluate the policy measures under the complex interrelationships among environment, energy, economy, technology, resource and societal issues. EMF-14 initiated organizing IAM developers and its successor EMF-19 activities have contributed to gather and investigate the ‘‘robust’’ model findings as well as IPCC conclusions. The recent activities of integrated assessment models are summarized in the special issue of *The Energy Journal* edited by Weyant (1999); Environment and Economics Policy Studies (2000) and the Chapter-2 of IPCC-TAR (2001a).

The MARIA, Multi-regional Approach for Resource and Industry Allocation, model utilized in this paper is developed to assess future greenhouse gas (GHG) reduction options and was used in the IPCC emission scenario activities (IPCC, 2000).

These research activities agree on the importance of low-carbon technologies and their development and implementation strategies. Among many energy technology options, hydrogen has been regarded as playing a ‘‘major role’’ in the future because of source flexibility as well as being carbon-free. Although many hydrogen production processes have been developed, hydrogen is used in only very limited area of energy systems due to the high cost. Recently, new technological options for hydrogen have been proposed in both demand side-fuel cells for automobiles and small residential buildings—and the supply side where hydrogen can be processed at lower temperature than the conventional process. Although they are not on the market yet, these lower temperature processes provide new opportunities to produce hydrogen based on nuclear heat, waste thermal heat, etc. The purpose of this paper is to assess these new hydrogen processes based on an integrated assessment model called MARIA. An extension of MARIA involving the Bern carbon circulation model Bern is also described.

2. Background of the MARIA model

The Multiregional Approach for Resource and Industry Allocation (MARIA), developed by the author aims at integrated assessment of global warming issues. MARIA aims at integrated assessment by generating international trade prices for fossil fuels as well as equilibrium prices for tradable carbon emission permits under certain constraints. The land-

Table 1
Regional Aggregation of MARIA-8

Region	Countries
NAM	USA, Canada
JPN	Japan
DC	Other OECD member countries in 1990
FSU	former USSR and eastern European countries
ANS	Indonesia, Malaysia, Philippines, Singapore, South Korea, Thailand, Taiwan
CHN	China
SAS	India, Bangladesh, Pakistan, Sri Lanka
ROW	Other countries

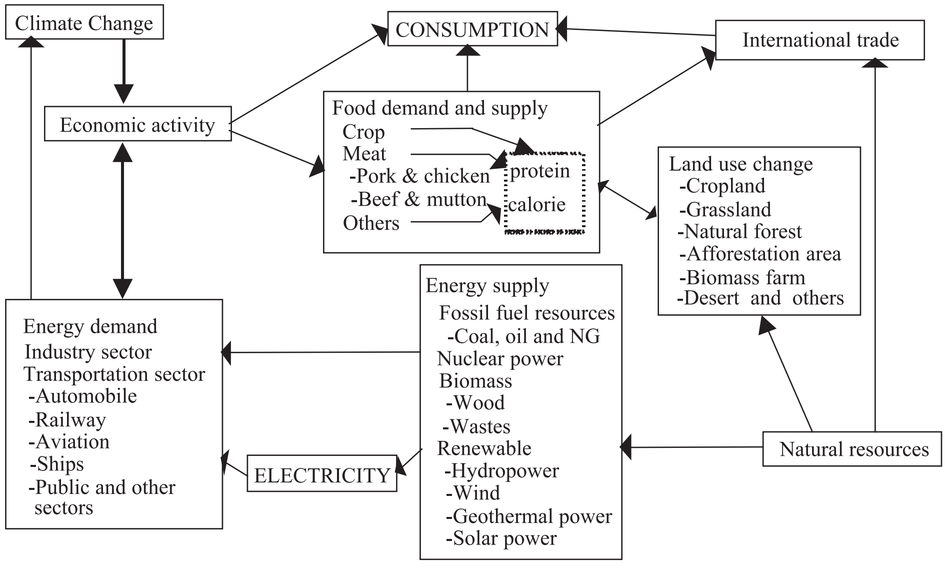

Fig. 1. Structure of the MARIA model (one region).

use subsystems and food demand–supply equations are also imposed to evaluate biomass energy resources under food supply constraints. The original MARIA incorporated the four world rgions (Mori and Takahashi, 1999) and currently has the eight world regions shown in Table 1. The basic structure of MARIA-8 follows MARIA-4, as is shown in Fig. 1.

MARIA includes carbon sequestration technologies as well as nuclear power technologies, e.g., once-through light water reactors (LWR), Plutonium thermal reactors (LWR-Pu), and fast breeding reactors (FBR). MARIA is formulated as an intertemporal nonlinear optimization model including around 18,000 variables and 15,000 constraints. The detailed parameters and formulations included in MARIA are documented in the other papers by the author (Mori, 2000a,b; Mori and Takahashi, 1999).

3. Expansion of MARIA—incorporating the Bern carbon circulation model

In the last decade, climate change researches have progressed through both theory development and model simulations. However, simulations of detailed climate models require the fastest super-computers. As the scale of the climate models and societal interest in global warming issue grow larger, on the other hand, the need for "simple" climate models as a policy evaluation tool has grown. MAGICC model (Wigley, 1993) which includes the radiative forcing of carbon and non-carbon GHGs is a famous pioneering work in this field. The Bern carbon circulation (Bern-CC) model (Joos et al., 1996) employed here is also developed for this purpose focusing on the carbon emission and concentration processes. The Bern model consists of an atmospheric carbon circulation block, carbon absorption by oceans and emissions and storage in the biosphere. The third feature enables

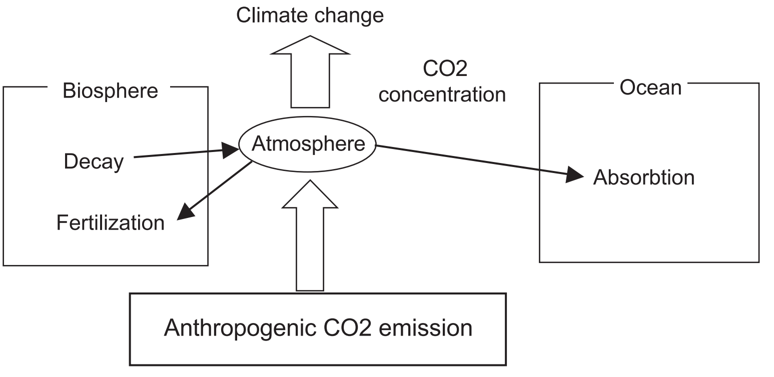

Fig. 2. Basic structure of Bern carbon cycle model.

us to evaluate the effects of CO_2 fertilization and land-use change. Although the formulation of the Bern model is simple, it follows the results of large GCMs well (IPCC, 2001b). Fig. 2 exhibits the basic structure of the Bern carbon circulation model. MARIA includes the Bern-CC model to reflect the new findings in climate science.

4. SER and palladium membrane process–low temperature hydrogen processes

Hydrogen is often expected to be a major fuel source in the future because of its low environmental impacts and flexibility of supply sources. Many industrial hydrogen production processes have been developed, which basically classified into three categories: electrolysis, steam reforming and hydrocarbon reforming. The first approach is simple but energy efficiency is low, while the second and the third ones require high temperatures.

Sorption-enhanced reaction (SER) is a new process being developed for the production of low-cost hydrogen through steam–methane reforming (Hufton et al., 1999, 2000). In this process, the reaction of methane with steam is carried out in the presence of a mixture of a catalyst and a selective adsorbent for CO_2. As a result, the reformation reaction occurs at a significantly lower temperature (300–500 °C) than that of conventional steam–methane reforming processes (around 800 °C) while achieving the same conversion of methane to hydrogen. According to Hufton, the hydrogen produced from the SER process is more than 99% pure while the conventional reactor provides only 70–75% purity. Fig. 3 exhibits the average gas composition of SER produced hydrogen (Hufton et al., 1999). According to them, the yield of hydrogen is high at 450 °C.

Shirasaki et al. (2001) also reports on a low temperature hydrocarbon reforming process using a palladium membrane for the selective separation of hydrogen. This system is, however, currently expensive and scale of economy does not likely appear due to the intrinsically high cost of palladium. Thin membrane synthesis technology would overcome this barrier.

The utilization of nuclear power for hydrogen production has recently been focused on, as can be seen in the proceedings of American Nuclear Society meeting in 2001 (ANS, 2001). It is not clear how and when their industrial marketability will appear although their

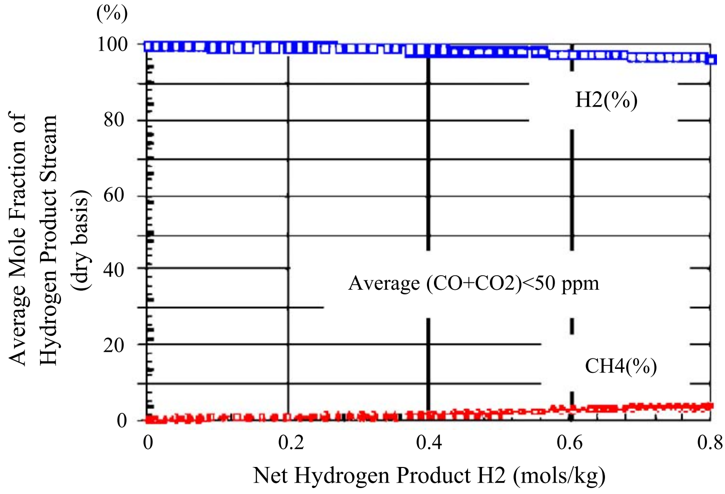

Fig. 3. Average product gas composition during a Sorption-Reaction Step with Initial H_2/Steam Pressurization as Measured on Lab-Scale SER#1 Unit; 6:1 steam/carbon feed, 1:1 adsorbent (HTC)/catalyst, 55 psig, 450 °C.

research feasibility has been demonstrated. However, when hydrogen production processes that operate under 500 °C are industrially realized, many opportunities for heat sources of them will be applicable, i.e., waste heat, gas turbine exhausts and FBR. In this paper, we focus on the possibility of FBR for electric power generation and SER hydrogen production process as well as the conventional electrolysis process using LWR, LWR-plutonium and FBR.

The fundamental chemical–thermal balances are the following:

Heat

$$CH_4 + H_2O = CO + 3H_2 - 206\ \text{kJ/mol}$$

$$CO + H_2O = H_2 + CO_2 + 41\ \text{kJ/mol}$$

$$CH_4 + 2H_2O = CO_2 + 4H_2 - 165\ \text{kJ/mol}$$

$$\text{Combustion of } H_2\ (\text{net}):\ +242\ \text{kJ/mol}\ (H_2)\ \text{or}\ 968\ \text{kJ/mol}\ (4H_2)$$

$$\text{Combustion of } CH_4:\ +803\ \text{kJ/mol}\ (CH_4)$$

Assuming 40% energy conversion efficiency in FBRs, the thermal heat of 1 GTOE-elec FBR and 12.167 GTOE methane generate 14.167 GTOE of hydrogen. Theoretically, this method can be applied to coal and other hydrocarbon-based processes.

It should be noted that these hydrocarbon-based processes are not carbon-free. However, carbon sequestration technologies are available if needed.

The cost assumptions are the keys to assess the potential contribution of FBR-based hydrogen production processes. However, the cost estimations have not been established yet since these processes are in the experimental stage. In this study, I set the parameters in the following manner:

(1) The production cost of hydrogen by electrolysis is assumed to be 4 Japanese yen per N m3 or, $129 per TOE in 1990 price.
(2) The electric power generation cost of an FBR is 10% higher than that of an LWR. If an FBR is used for hydrogen production, a power generation steam turbine unit is replaced by SER or palladium membrane reactor. The maximum additional cost of FBR–SER process to FBR power generation is assumed to be equal to the cost of hydrogen production via electrolysis case. The lowest additional cost is set to be 0. In other words, in this the cost of the steam turbine of the FBR is equal to the cost oh the SER reactor. Needless to say, this lowest cost is no more than an assumption for the simulations.
(3) The energy end-use cost of hydrogen should be also imposed. In the industry, transportation and other end-use sectors, 10% higher energy cost coefficients than those of natural gas are assumed.

5. Scenarios and simulations

5.1. Potential contribution of hydrogen

In this paper, I assess the contribution of the FBR–SER process with the MARIA model based on SRES-B2 scenario and 550 ppmv atmospheric carbon concentration case. The effects of the carbon tax are also evaluated according to the EMF-19 scenarios. Other model parameters are identical with existing MARIA assumptions (Mori, 2000a).

Fig. 4 compares the hydrogen consumption paths in seven simulation cases changing hydrogen process costs from the reference value, where hydrogen end-use costs are 10% higher than that of natural gas.

Fig. 4 suggests that there is no incentive to introduce FBR–SER under no-carbon control policies when the hydrogen end-use cost is higher than that of natural gas. Even in the carbon concentration control case, additional hydrogen process cost to the FBR power generation needs to be lower than the 12.5% of electrolysis process for it to become competitive. These findings with respect to the B2-marker are understandable since direct use of natural gas and FBR power generation is more energy efficient than FBR–SER under the no-carbon control policy cases. In the carbon control cases, the cost of hydrogen production is essential. When the hydrogen process cost is low, demand for FBR–SER grows rapidly and comes to 3.5–4.3 GTOE in the end of this century which is more than 14–17% of total final energy consumption as shown below.

When the end-use cost of hydrogen declines to those of natural gas in the case of zero additional hydrogen process cost to the FBR electric power generation cost, the demands for FBR–SER hydrogen increase rapidly as shown in Fig. 5.

Fig. 5 shows that the potential demand for the hydrogen in carbon control policy cases will come to around 6 GTOE which is around 24% of total final energy demand. Even in the no-carbon control policy cases, the case with no additional cost to FBR-power generation and to natural gas end-use cost employs FBR–SER

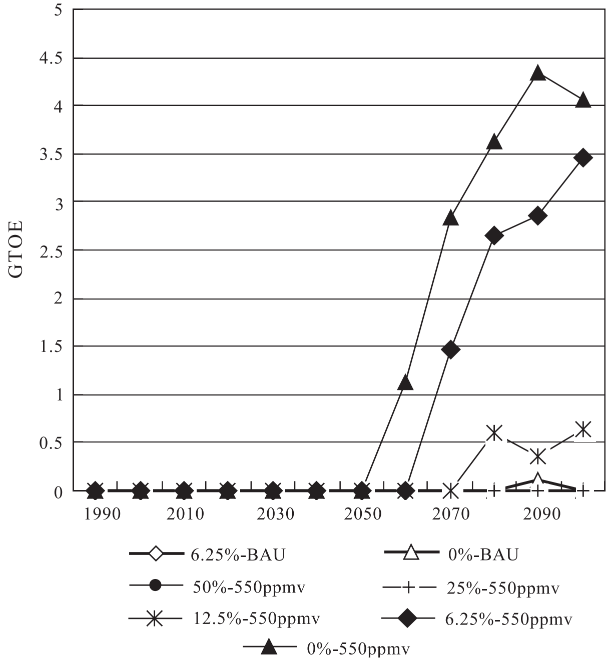

Fig. 4. Hydrogen consumption paths by changing hydrogen process costs in BAU and carbon control cases: 0%, 6.25%, 12.5%, 25% and 50% of the reference cost where hydrogen end-use cost is 10% higher than that of natural gas in all cases.

hydrogen in the second half of this century. However, its value diminishes in 2100. These findings suggest that potential of hydrogen production process is high but cost issues are critical.

Fig. 6(a and b) compares the world final energy flow profiles in B2-BAU scenario with reference hydrogen production and end-use cost and with zero additional production and end-use cost.

Fig. 7(a–c) shows the final demand profiles for hydrogen in the carbon concentration control cases. As the energy cost of hydrogen decreases, initial implementation of hydrogen becomes earlier and production increases.

Fig. 8 summarizes end-use hydrogen demand in the cases of (A) no additional hydrogen process cost to FBR-power generation and reference end-use cost and (B) no additional hydrogen process and end-use cost. Hydrogen input increases in all sectors uniformly. Unlike the B2-BAU cases, hydrogen is mainly input to industry and other sectors. Instead, biomass plays the main role in the transportation sector.

5.2. Effects of carbon tax options

Among various policy measures to mitigate carbon emissions, a carbon tax is still a major option since taxation institutions are already established well based on long tradition. Unlike carbon emission trading, carbon taxation does not guarantee meeting a

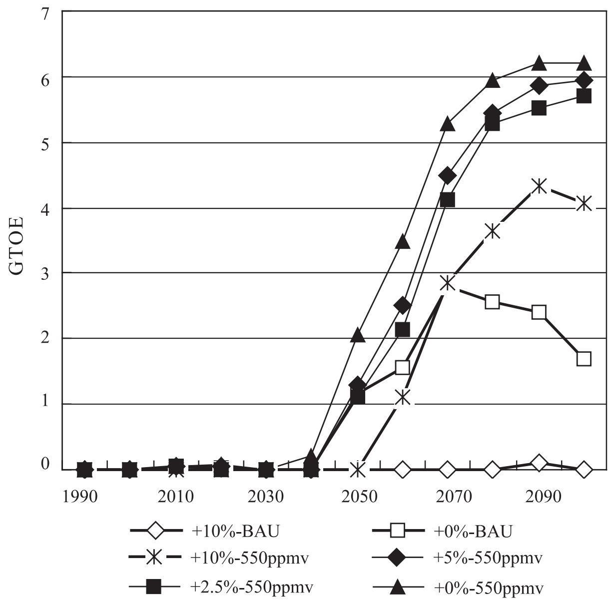

Fig. 5. Hydrogen consumption paths changing hydrogen end-use cost coefficients: 0%, 2.5%, 5% and 10% higher than those of natural gas where hydrogen additional process cost to the FBR power generation is set 0 in all cases.

carbon emission target. However, its revenue can be invested for the long-term R&D by public sector and tax reforming may be also expected. The short-term effects of such carbon taxes on the economy have been well investigated based on the CGE models as summarized in Chapters 8 and 9 of the IPCC-TAR-WG3 (IPCC, 2001a). The long-term

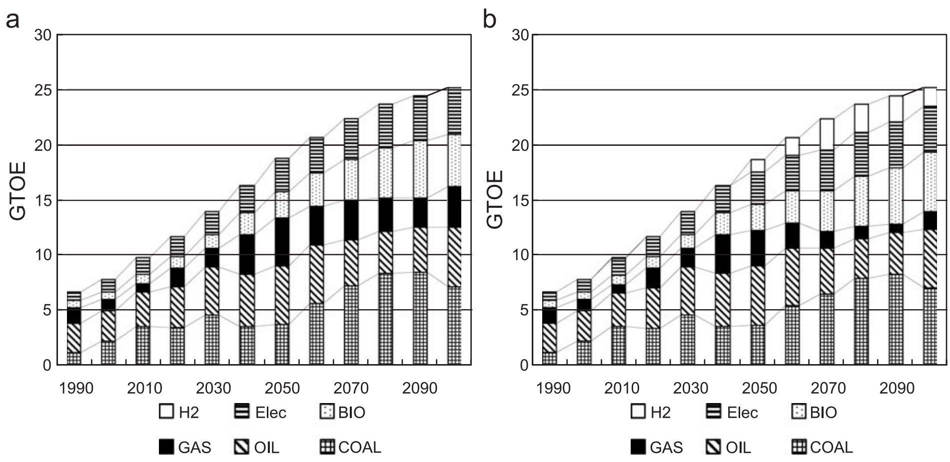

Fig. 6. (a) World final energy demand profiles in B2-Marker scenario with reference hydrogen production and end-use costs. (b) World final energy demand profiles in B2-Marker scenario with no additional hydrogen production and end-use costs.

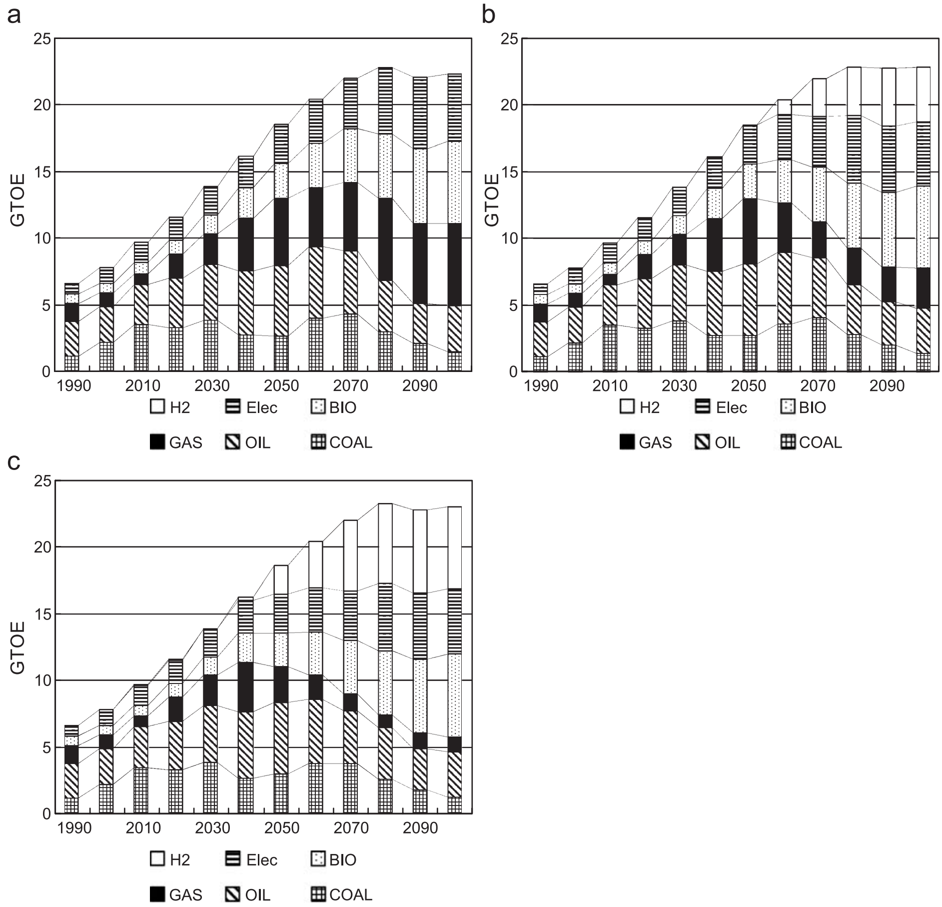

Fig. 7. (a) World final energy demand profiles in B2–550 ppmv control case with reference hydrogen production and end-use cost. (b) World final energy demand profiles in B2–550 ppmv control case with no additional hydrogen process cost to FBR-power generation and reference end-use cost. (c) World final energy demand profiles in B2–550 ppmv control case with no additional hydrogen process and no end-use cost.

impacts of carbon tax options have been discussed in the EMF-19 activities. In this paper, the following carbon tax scenarios provided by EMF-19 are evaluated.

(1) B2 Marker: business as usual (BAU) described in the previous section.
(2) WRE-550: carbon emission trajectory is set to stabilize the atmospheric carbon concentration at 550 ppmv following to the Wigley–Richels–Edmonds estimations.
(3) TAX-Low: increasing carbon tax $10 per carbon ton per decade which begins at $10 per carbon ton in 2010 and reaching $100 in 2100.
(4) TAX-High: increasing carbon tax $25 per carbon ton per decade which begins at $25 per carbon ton in 2010, reaching $100 in 2040 and staying at that level through 2100.
(5) TAX-100: constant carbon tax $100 per carbon ton which is implemented in 2010 and maintained at that level through 2100.

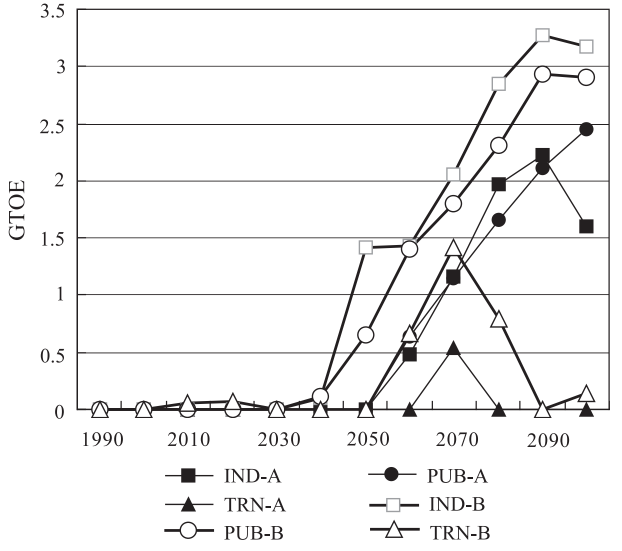

Fig. 8. Hydrogen end-use patterns for industry (IND), transportation (TRN) and public and other sectors (PUB) in B2–550 ppmv control cases under (A) no additional hydrogen process cost to FBR-power generation and reference end-use cost and (B) no additional hydrogen process and no additional end-use cost.

Fig. 9 shows the carbon emission trajectory of the above five scenarios. We can see that the WRE-550 trajectory is very similar to the TAX-High results. The constant carbon tax gives the largest carbon emission reduction in the first half of 21st century but emissions

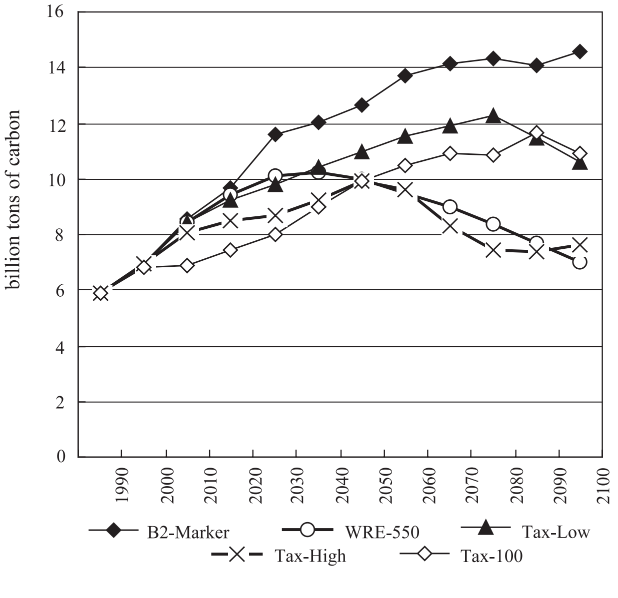

Fig. 9. Comparison of carbon emission trajectories of carbon tax options.

constantly increase. This suggests that the constant tax causes high net discounted emission reduction costs and fails to stabilize carbon concentrations.

Fig. 10 compares the nuclear power expansion results of the above scenarios. Although WRE-550 and TAX-High represent similar carbon emission trajectories, nuclear power in the latter is higher than that of the former. On the other hand, carbon sequestration is implemented in only WRE-550 case.

5.3. Interactions between nuclear and biomass

The previous sections suggest that the contribution of nuclear power is essential to stabilize the atmospheric concentration of carbon-dioxide. Although the nuclear power is the most cost-effective option, it is not indispensable as will be shown in this section. The B2−550 ppmv carbon control case with no expansion of nuclear power after 2010 leads to high biomass utilization. Carbon sequestration is also adopted at a 8.8-GtC in 2100 while it is at a 5.6-GtC rate in B2−550 ppmv case.

Fig. 11 shows that the loss of GDP where no nuclear expansion is assumed comes to more than 1.4% while that in B2−550 ppmv is no more than 0.6%. The potential expansion of biomass obviously mitigates the loss of GDP. Fig. 11 also shows that the lower carbon concentration target increases the maximum loss of GDP initially, but decreases it by the end of the century. This suggests that the social structure can adapt to the lower emission economy.

Fig. 12 provides similar results when one compares the trajectory of B2U450 with that of B2U550. These figures suggest that the impacts of the nuclear power saturation on the

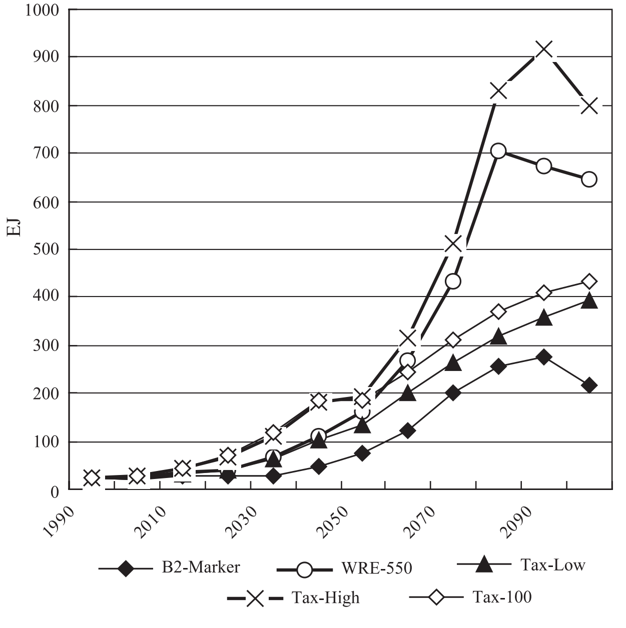

Fig. 10. Expansion of nuclear power of carbon tax options.

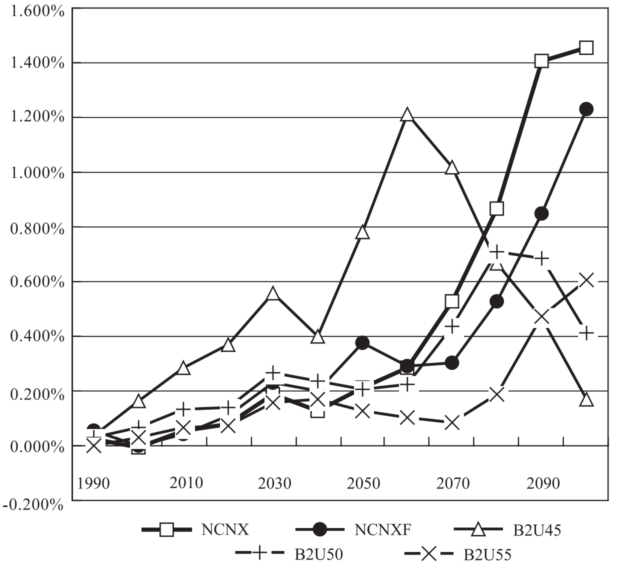

Fig. 11. Loss of World GDP when atmospheric carbon is stabilized. B2U45: 450 ppmv, B2U50: 500 ppmv, B2U55: 550 ppmv, NCNX: 550 ppmv no nuclear expansion, NCNXF/NCNX + increased potential biomass supply.

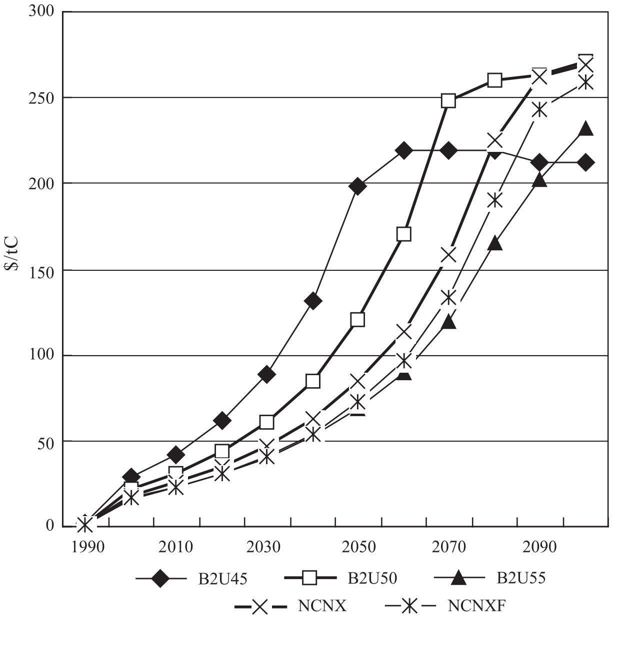

Fig. 12. Shadow prices of carbon emission. B2U45: 450 ppmv, B2U50: 500 ppmv, B2U55: 550 ppmv, NCNX: 550 ppmv no nuclear expansion, NCNXF/NCNX + increased potential biomass supply.

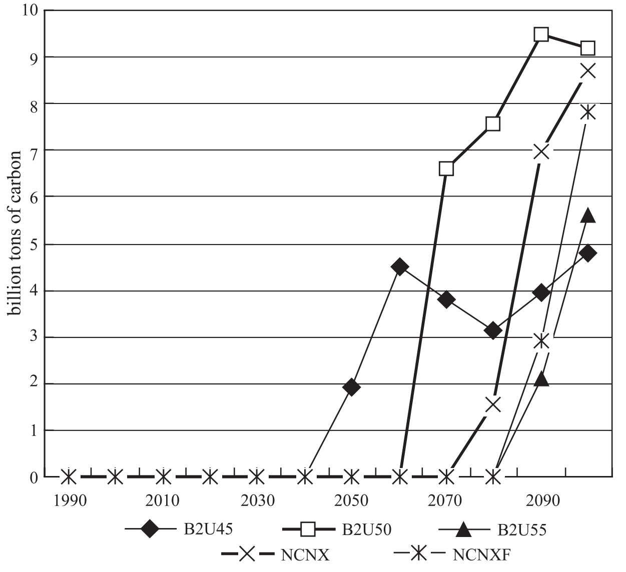

Fig. 13. Implementation of carbon sequestration. B2U45: 450 ppmv, B2U50: 500 ppmv, B2U55: 550 ppmv, NCNX: 550 ppmv no nuclear expansion, NCNXF/NCNX + increased potential biomass supply.

whole economy will be mitigated when the potential biomass supply increases. In the model, I assume that 10% of grassland and 5% of desert area can be converted to afforestation areas. Although the primary energy supply patterns do not change much, the loss of GDP and the shadow prices of carbon emission are apparently mitigated as are shown in Figs. 11 and 12.

Fig. 13 shows how carbon sequestration technologies are implemented. As the conditions become more stringent, earlier implementation of carbon sequestration is needed. The potential expansion of biomass supply mitigates the need for these options.

6. Conclusions

This study assesses the potential contribution of new hydrogen production processes utilizing FBRs using MARIA with the Bern-CC. Under a carbon concentration stabilization policy, FBR-based hydrogen can provide 6 GTOE in the second half of the century. However, the potential demand is sensitive to the supply cost. When additional process cost of hydrogen to FBR-electricity and additional energy cost to natural gas can be reduced, FBR-bases hydrogen can be implemented even in the no-carbon control case.

However, options with no nuclear power expansion policy are also possible under the carbon concentration control cases, where lower primary energy demand with around 1% additional GDP loss are observed. Higher carbon sequestration implementation is also required in this case.

The enhancement of biomass energy supply potential would mitigate the burden of carbon emission reduction as shown in the GDP losses and shadow prices of carbon emission figures, even if the primary energy supply profiles are not very different.

Low temperature hydrocarbon-based steam reforming processes are, however, applicable using heat sources other than nuclear heat. New heat cascading opportunities should also be evaluated as well as FBR-based processes. The assessments of these technologies should be the central in the future research.

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Responses to technology and taxes in a simulated world

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Abstract

A set of model experiments was performed to analyze the role of technology development on energy system responses to a global uniform carbon tax. The B2 baseline scenario as implemented by IMAGE 2.2 was used as the starting point for the analysis. Stabilization at a carbon dioxide concentration of 550 ppmv from this baseline was shown to be technically feasible at limited costs. In the first decades, improved energy efficiency and fuel switching play an important role in reducing greenhouse gas emissions. In the longer term, introduction of carbon-free options account for the bulk of the reductions. Technology development is demonstrated to play a crucial role for the mitigation costs (measured as the required level of the imposed carbon tax) by decreasing the gap between the (currently) more expensive low/zero carbon options and their fossil alternatives. For example, technology development, modeled as learning by doing, increases the global carbon reduction in 2030 as a result of a US$300/tC tax from nearly 40% to 60%. Three different aspects of technology development, i.e. technology development under baseline conditions, induced technology development and inertia caused by lifetimes of technologies were identified as important factors in explaining the different responses under different conditions. The relative importance of these factors is of crucial importance for the 'optimal' timing of abatement efforts. Finally, for long-term responses not only has technology development been shown to be important, but also other dynamic processes in the energy system, like depletion. They can sometimes work in the opposite direction.

Keywords: Technology development; Energy system; IMAGE 2.2

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1. Introduction

According to the latest report of the IPCC, the climate change observed over the 20th century was mostly caused by human activities (IPCC, 2001b). As further global warming is likely to result in increasing risks of negative impacts on both natural systems and human societies around the world, significant reductions of greenhouse gas emissions may be needed. The IPCC report also indicates that technologies for significantly reducing current emissions with respect to baseline development in the next 20 years are already available. However, reducing emissions on a large enough scale to prevent significant climate change using current technologies is seen in a number of studies to be costly. Therefore development of better technologies needs, certainly in the long run, to play an important role in providing a pathway to further reduce emissions at reasonable costs.

Several tools are used to study pathways to less greenhouse gas intensive futures and the role which might be taken by different (types of) technologies within these pathways (see, for instance, IPCC, 2001a for an overview). In the last few years, the focus on the role of technology development has significantly increased. Several concepts of technology development and its driving forces have been explored, including (descriptions of) autonomous improvement, R&D-driven improvement and improvement driven by use ('learning-by-doing'). The last category, in particular, has received considerable attention from modelers, both because of its empirical basis and as a way to endogenize technological progress within models (see, for instance, Grubler et al., 1999; Wene, 2000). Understanding the processes that determine technology development, and related to this, the potential of different technological options, is very important for developing mitigation strategies, both in terms of their costs and their timing.

In this paper, we will focus on the role of technology development within different mitigation scenarios and its possible consequences, e.g. for mitigation costs. More specifically, we will search for relevant dynamics within the system that could be important for the role that technological development may play, both in the long and medium terms. Such dynamics include, for instance, the relationship with capital turn-over rates (and inertia in the system), technology development already included in the baseline scenario, development induced by climate policies (both based on learning curves) and the influence of resource depletion. The relative contribution of these different processes is crucial in the debate on the timing of mitigation action.

The analysis was done with the TIMER model, part of the integrated assessment model IMAGE 2.2. The model was developed to study the long-term dynamics of the energy system, in particular, transitions to systems with low carbon emissions (De Vries et al., 2001; IMAGE-team, 2001). TIMER is a system-dynamic energy system model at a medium level of aggregation. The model uses learning curves for almost all its technologies. The position of TIMER within the integrated assessment framework of IMAGE also allows us to study such factors as environmental impacts and co-benefits—but also land use consequences of mitigation choices. Earlier, the model was used to explore pathways to reach a stabilization of 450 ppmv from the B1 scenario (van Vuuren and de Vries, 2001). In this paper, we will continue this type of analysis by looking at different mitigation scenarios that will bring the carbon concentration to 500–600 ppmv by the end-of-the century, starting from the B2 baseline scenario.[1]

We will first address several methodological issues, including some of the relevant processes of technological change in relation to climate policies, and the most relevant features of the IMAGE/TIMER model. Secondly, we describe how the B2 baseline scenario is implemented in IMAGE/TIMER, providing the context for our further analysis. Thirdly, we will look at the results of the various mitigation experiments explored. These are divided into three experiments. The first investigates how stabilisation of greenhouse gas concentration can be achieved starting from the B2 scenario. The second experiment looks into some of the relevant dynamics of long-term mitigation scenarios (until 2100). The last experiment looks in detail at the different processes relevant for medium-term energy system response to mitigation action. The last section deals with the main conclusions.

2. Theoretical background and methodology

The IMAGE 2.2 integrated assessment model and its energy system model TIMER (Alcamo et al., 1998; IMAGE-team, 2001; De Vries et al., 2001), used in the analysis, will be overviewed later in this section. First, we discuss some of the dynamic processes of particular importance for the influence of technology development (assuming the use of learning curves) on the response of the energy system to mitigation action. The modeling experiments are outlined at the end of the section.

2.1. Dynamic processes that influence technological development

The main focus here is the role of technology development on the costs of emission reductions in the medium and long term. The term technology development refers to changes in the portfolio of technologies used to supply energy to end-users. In stricter sense it refers to changes to the set of available technologies that change (improve) their performance either in terms of utility or costs. A method to explore the influence of technology development in an energy model is analysis of the response of the model through emission reductions to an externally applied carbon tax. Several authors have used such a method with progressively increasing taxes to develop so-called marginal-abatement cost curves, e.g. Criqui et al. (1999) and Ellerman and Decaux (1998).[2] We will use this information as a central element of our analysis—defining system response R, as indicated in Eq. (1). Here, E_{tax} represents the emissions after a tax has been applied and $E_{baseline}$ the emissions in the case of a baseline.

$$R = E_{tax}/E_{baseline} \tag{1}$$

[1] Both the B1 and B2 baseline scenarios are part of total set of six IPCC scenarios introduced in the Special Report on Emission Scenarios (Nakicenovic et al., 2000). B2 is a medium emission scenario in the total set. The scenario will be discussed in more detail later.

[2] The curves can be interpreted as marginal-abatement cost curves where the carbon tax is seen as an indicator of mitigation costs. A more general name for these curves is ‘system-response’ curves.

The focus in this paper is on changes in the system response R as a result of technological change at global level. The use of an energy-system model allows us to study these responses in the context of the (full) dynamics in the world energy system, including depletion and trade but also several technology-relevant processes. In fact, we recognize six dominant dynamic processes in models that are directly related to technological development—and directly influence the response to the model to external impulses. These are:

- switches between different technologies as a result of changes in relative costs;
- the technology development under baseline conditions;
- the induced technology development by applying a carbon tax;
- technology inertia, in particular inertia that due to limited capital turn-over rates;
- investments in research and development;
- impacts of technology-specific resource depletion.

Further on we will discuss these processes in the context of the modeling experiments that have been explored, indicating their importance for the total system response. Here, they are only briefly discussed:

- *Switches between different technologies as a result of changes in relative costs*. The most direct impact of a carbon tax is that it changes the relative costs of fuels/technologies and thus also their penetration. This leads to additional use of zero/low carbon fuels/technologies.
- *The influence of the technology progress already included in the baseline scenario*. In general, costs of new renewable (zero carbon) technologies such as solar/wind and biomass will, under the baseline, decrease more rapidly than the costs of more mature, fossil-based technologies (in a model, this process can be formulated in terms of learning-by-doing or alternatively by exogenous assumptions). As a result, the gap that climate policies need to bridge over time in enforcing the penetration of the more expensive zero carbon options (compared to the cheaper fossil options) decreases. A consequence of this is that, all other things being equal, later introduction of a tax, will meet with a stronger response (in terms of Eq. (1)) than the same tax introduced earlier in time.
- *The influence of technology progress induced by climate policies*. The learning-by-doing mechanism (see also Section 2.3) implies that further employment of renewable technologies in response to a carbon tax will cause further cost reductions of these technologies. These technologies would then become more attractive, and thus, all other things being equal, the response to a carbon tax would slowly increase over time.
- *The influence of technology inertia*. There is much inertia in the energy system. Particularly important is that capital is normally only replaced after its lifetime. This means that the response to a carbon tax only slowly precipitates into the system. The response of some energy demand sectors can be somewhat swifter than in other sectors as technical lifetimes of the technologies used are shorter than in energy production and, to some degree, behavioral changes and so-called good housekeeping measures may allow for almost immediate responses. Thus, as a result of inertia, the response to a carbon tax will slowly increase in time.

- *Investment in research and development (R & D)*. Another important process that could stimulate technology development is investing in research and development. There is some discussion whether this process can be seen as a separate process for technology development ('learning-by-searching'), or whether it should be seen in conjunction with learning-by-doing. If seen as a separate process, investments into R&D can bring down costs of more expensive low carbon options without applying these technologies first, increasing the response to a carbon tax in time.
- *The influence of depletion*. Indirectly, the use of a carbon tax also changes the depletion dynamics of different forms of energy. Important in this context is that different fuels/technologies have their own depletion characteristics.

It is interesting to see that these different processes are strongly related to the earlier discussion on the timing of mitigation action. The second process (learning in the baseline) leads to the conclusion that it is better to wait for technologies to develop before implementing strict climate policies. This argument was forcefully presented in (Wigley et al., 1996) in their discussion on timing of mitigation action. In contrast, the third process enforces the argument that climate policies should be seen as a lever with which to bring about climate-friendly technical innovation and diffusion, favoring an early-action type of approach (Wene, 2000; Azar and Dowlatabadi, 1999; van Vuuren and de Vries, 2001). The fourth process translates into an argument that no climate policy should result in premature replacement of capital. This argument was used by Wigley et al. (1996) as a reason for later abatement being cheaper. However, others have argued that after including fully all system inertia, this argument actually gives preference to early action to make the transition as smooth as possible (Ha-Duong et al., 1997; Grubb, 1997). The fifth process might, in turn, favor a strategy in which first strong investments into R&D are made, followed latter by large-scale employment of available technologies (once they have become competitive). Finally, the influence of the sixth process is ambiguous. A crucial question from a final decision on timing is how important these processes are in relation to each other.

In an earlier publication, we looked into how the total set of processes could work out in a scenario with very positive assumptions on technology development and low energy use (the SRES B1 scenario) (van Vuuren and de Vries, 2001). We found early action to be a more favorable strategy than delayed response for a discount rate of 4% and lower, as postponing measures foregoes the benefits of learning-by-doing. Using higher discount rates would favor a delayed response approach.

2.2. Modeling framework

In this study we used the TIMER energy system model and the integrated assessment framework IMAGE 2.2.[3] IMAGE 2.2 was developed to assess the impact of global environmental problems, in particular, climate change. It actually consists of a set of linked and integrated models collectively describing the chain of global environmental change from population and economic change to impacts on ecosystems and agricultural systems.

[3] An abbreviation of Integrated Model to Assess the Global Environment.

The models operate on two geographical scales. Most of the drivers of change (population, economy, agricultural demand, energy use, emissions) are calculated for 17 world regions. In addition, a large number of the environmental parameters are calculated at the grid level of $0.5^\circ \times 0.5^\circ$. The IMAGE 2.2 scenarios cover the 1970–2100 period. In 2001, the model was used to re-implement the IPCC SRES scenarios (base year updated to 1995) (see IMAGE-team, 2001).

2.2.1. TIMER

TIMER is an energy-system model describing the demand and supply of 12 different energy carriers for 17 world regions (Fig. 1). A full description of the model can be found in (De Vries et al., 2001). The main objective of the TIMER model is to analyze the long-term trends in energy demand and efficiency and the possible transition towards renewable sources. The model particularly focuses on several dynamic relationships within the energy system, such as inertia, learning-by-doing, depletion and trade among the different regions. This makes the model very suitable to study some of the long-term dynamics related to technology development discussed in Section 2.1.

The demand submodel of TIMER determines demand for fuels and electricity in five sectors (industry, transport, residential, services and other) based on structural change, autonomous and price-induced change in energy intensity ('energy conservation') and price-based fuel substitution. The demand for electricity is fulfilled by fossil-fuel based thermal power, hydropower and two other non-thermal alternatives, i.e. nuclear power and

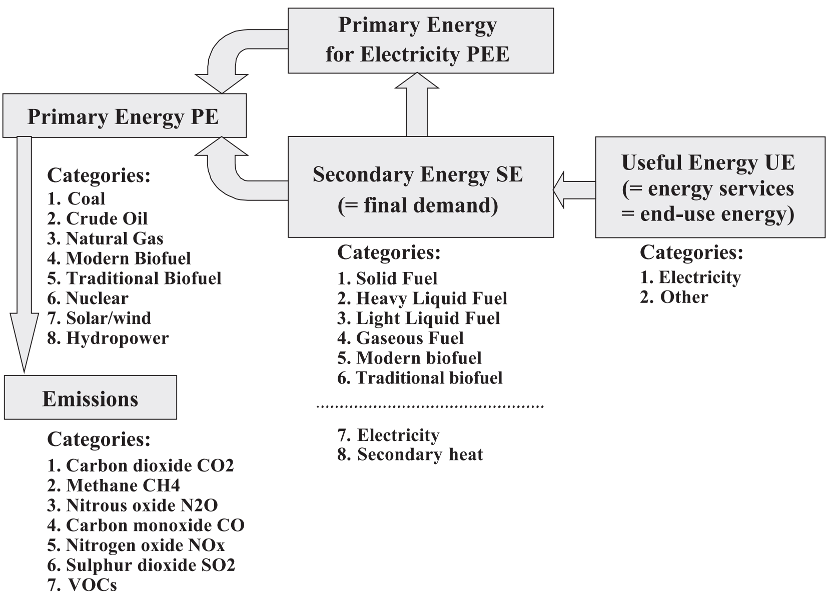

Fig. 1. Overview of the TIMER model.

solar/wind. The option 'solar/wind' describes a renewable electricity option with characteristics of both solar and wind power. Both nuclear power and solar/wind penetrate the market based on relative costs. The thermal power option consists of four alternative options: coal based, oil based, natural-gas based and biomass based which are fully intercompetitive. The exploration and exploitation of fossil fuels (either for electricity or direct fuel use) is described in terms of depletion and technological development. Biofuels can be used in place of fossil fuels, and are on their turn also assumed to be subject to technological development and depletion dynamics.

Below we will describe those processes in TIMER that directly relate to the dynamic processes discussed in Section 2.1.

2.2.2. Technology development

An important aspect of the TIMER model is the endogenous formulation of technological development on the basis of 'learning-by-doing'. This phenomenon has been investigated in detail and for a variety of products and processes. More recently, the concept received great interest as a meaningful representation of technological change in global energy models (Grubler et al., 1999; Azar and Dowlatabadi, 1999; Wene, 2000). Its general formulation is that a cost measure y tends to decline as a power function of an accumulated learning measure, x:

$$y = \alpha^* Q^{-\pi} \tag{2}$$

where π is the learning rate, Q the cumulative output and α a constant. Often, the learning rate, π, is expressed by the progress ratio ρ, which indicates the factor with which the costs measure, y, decreases with the doubling of experience, x. It is easily seen that $\rho = 2^{-\pi}$. Many illustrations of this law have been found and published. The progress ratio in almost all cases investigated has been found to be between 0.65 and 0.95, with a median value of 0.82 (e.g. Argotte and Epple, 1990).

In the TIMER model, the learning factor influences the costs of coal, oil and gas production, the investments of renewable and nuclear energy and the decline of the energy conservation cost curves. The value of the learning rate ρ varies from a high of 0.7 to 1.0 based on historic ρ values for the different technologies. The choice of these values depends on the technologies and scenario setting. First of all, the learning rates of solar/wind and biomass have been set lower than those for fossil-based technologies, based on observed historic trends (e.g. Wene, 2000). There is strong evidence that in the early stages of development ρ values for learning-by-doing curves are lower (thus faster learning) than for technologies that have already been in use for long-time periods. Some have tried to explain this by other factors, which may contribute to learning in these early phases, such as a relatively high investment in research and development (Grubler et al., 1999; Wene, 2000). In TIMER all ρ values are time-dependent with ρ values going to 0.9 or higher before 2100 for all technologies. The development of the learning rates is also related to the storyline of the scenario (e.g. high technological progress or not). Table 1 gives the ρ values used in the B2 scenario of TIMER.

An interesting question is whether learning curves should be applied at the level of regions or for the world as a whole. On the one hand, technologies developed in one

Table 1
Progress ratios used in the B2 scenario as implemented in TIMER

Technology	Progress ratio 1995	Progress ratio 2100
Coal production	0.90–0.94	0.95–0.96
Oil production	0.85	0.92
Natural gas production	0.86–0.93	0.90
Efficiency	0.85–0.9	0.92
Nuclear	1.00	0.96
Solar/wind	0.80	0.90
Biomass	0.88	0.92

region will, in most cases, also be available in other regions. On the other hand, a significant part of cost reductions is actually representative of the experience gained by applying the technology. In TIMER, the learning curves are applied at the level of separate regions; however, to model the influence of technology transfer, we assume that all other regions will partly benefit from the additional knowledge gain of the forerunner (see Vries et al., 2001).

2.2.3. Depletion

Depletion plays a different role for different technologies. Depletion is described in terms of long-term supply curves (related to cumulative production) for the fossil fuel technologies and nuclear energy. These curves are derived from (Rogner, 1997) and the World Energy Assessment (WEA, 2000). For renewable sources, in contrast, depletion is described as a function of production. This formulation assumes that at higher production levels less attractive sites or technologies will have to be used. Specific investment costs and the maximum production levels for renewable energy have been derived from various sources, as indicated in the model documentation (De Vries et al., 2001). These derived values include, in particular, the resource estimates of the World Energy Assessment and calculations made using the IMAGE 2.2 land use model (WEA, 2000, Hoogwijk et al., 2000). A specific form of 'depletion' is found within the electricity sector—where it is assumed that only a limited share of renewable electricity options can be adopted free of costs—after which additional investments need to be made into the system to assure sufficient reliability (e.g. storage or grid extensions). These additional costs are assumed to come into play where the share of solar/wind in total electricity production is above 20%.

2.2.4. Substitution between different technologies

Substitution among energy carriers and technologies is described in the model with the multinomial logit model (Edmonds and Reilly, 1985):

$$\mathrm{IMS}_i = \exp(-\lambda^* c_i)/\sum_j \exp(-\lambda^* c_j) \tag{3}$$

IMS_i is the indicated share in total investments of production method i, λ the so-called logit parameter determining the sensitivity of markets to price changes and c_i the costs or the price of production method *i*. The latter may include other factors such as premium factors, additional investment costs and cost increases as result of a carbon tax. The multinomial logit model used here indicates that the share of a certain technology (or fuel type) depends on its relative costs to its competitors. The cheapest option gains the largest market share. However, it does not get the full market share as we assume heterogeneity within the market, creating specific niches for technologies with higher average costs (but lower costs than its alternatives within this specific niche). The multinomial logit mechanism is used within TIMER to describe substitution among end-use energy carriers, different forms of electricity generation (coal, oil, natural gas, solar/wind and nuclear) and substitution between fossil fuels and biofuels. It should be noted that the mechanism is actually used to determine shares in new investment, which implies that actual market shares respond much slower.

2.3. Modeling experiments

In order to learn more about the possible role of different technology pathways, we performed three different model experiments, starting from IMAGE implementation of the SRES B2 scenario, i.e.:

(a) A scenario aimed at stabilization of atmospheric carbon dioxide concentration at 550 ppmv;
(b) A series of three model runs in which a US$100/tC carbon tax is introduced: (i) immediately going from zero to US$100/tC between 2000 and 2010; (ii) increasing at US$25/tC per decade in the first 40 years after 2000—and staying constant at US$100/tC after 2040 and (iii) increasing at US$10/tC per decade for the whole 2000–2100 period (see Fig. 5);
(c) A series of model runs in which different levels of carbon taxes are applied in 2000, 2010, 2020 and 2030, with the response recorded 10–30 years afterwards.

In the first experiment, we looked at the types of technologies chosen by the model to achieve the required level of mitigation. Some attention was paid to possible consequences of this action, for instance, in terms of reduction of other greenhouse gasses and impacts on energy-exporting regions. In the second set of experiments, a carbon tax was introduced in three different modeling runs, in all cases reaching a level of US$100/tC (see Fig. 5), but the rate of introduction varied between the different experiments. The aim of this experiment was to find out whether technology dynamics within the system would result in different responses to these taxes in the long term. Specifically, one may expect that the run reaching the final US$100/tC tax level early in the simulation would benefit more from the induced technology development than any of the other runs. The last set of experiments took place in a much shorter time frame and searched specifically for the different contributions to the overall system in its response to a carbon tax of induced technological learning where learning forms part of the baseline and inertia.

It is important to note that the model applied in this study does not take into account physical carbon sequestration (removing carbon from the energy system for underground/underwater storage) or options to reduce land-use related emissions.

3. Baseline scenario

The IPCC SRES B2 scenario has been developed within a total set of six baseline scenarios, none of which includes explicit climate policies (Nakicenovic et al., 2000). The IPCC SRES scenarios are based on the development of narrative ‘storylines’ and the quantification of these storylines using six different integrated models from different countries. For each scenario, the elaboration by one specific model has been chosen as being characteristic for that particular storyline, the so-called marker scenario. Elaboration of the same storyline by other models needs to fulfil certain harmonization criteria before they can be indicated as a fully harmonized elaboration. The B2 storyline describes a regionalised world with a focus on environmental and social values. The marker implementation of the B2 scenario strongly emphasizes the ‘dynamics-as-usual’ results that could play a role in this scenario (Riahi and Roehrl, 2000). The IMAGE 2.2 implementation, in contrast, has put slightly more emphasis on the original storyline—although the implementation still fully complies with the harmonization criteria (IMAGE-team, 2001). As a result, the IMAGE B2 scenario has slightly lower emissions than the original marker but can still be regarded as a medium emission scenario with global greenhouse gas emissions increasing from 10 GtC-eq in 2000 to about 15 GtC-eq in 2020—and finally stabilizing at 17 GtC-eq from 2040 onwards (see Fig. 2). In terms of sectors, energy use remains responsible for the larger share of emissions. Driven by the increasing emissions, the atmospheric carbon dioxide concentration in the B2 scenario increases from 370 to 605 ppmv in 2100 (or 425 ppmv CO_2-eq to 820 ppmv CO_2-eq), more than double pre-industrial levels. The global temperature increase is found in the range of almost 3° above 1970 levels (using a central estimate of climate sensitivity).

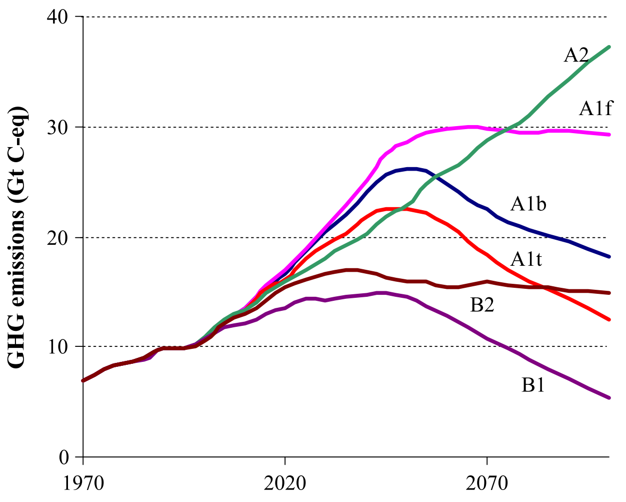

Fig. 2. Global greenhouse gas emissions in the IMAGE 2.2 implementation of the SRES scenarios (all Kyoto gases and all sources) (IMAGE-team, 2001).

4. Mitigation experiments

The results of the experiments described in Section 2.3 are outlined below.

4.1. Stabilization at 550 ppmv

Reaching a profile that stabilizes the atmospheric carbon dioxide concentration at 550 ppmv from the IMAGE B2 scenario requires a reduction of cumulative emissions in the 2000–2100 period of about 25%. Such reduction could be regarded as a relatively modest one.[4] If we introduce a uniform carbon tax (across regions and sectors) in TIMER, we need a tax slowly rising to US$190/tC to achieve such a reduction (no carbon tax is applied to land-use-related carbon emissions). The profile of the required carbon tax is shown in Fig. 5.

In total, the required carbon tax reduces global primary energy use by about 10–15%. This decrease is unequally divided among the different energy carriers. Cumulative use of coal declines by almost 50%. The cumulative consumption of natural gas and oil declines by about 10%, respectively (the decline in natural gas is slightly higher than for oil, as natural gas experiences considerable competition from non-fossil energy carriers in the electricity market). Other, low/zero carbon, energy carriers gain market share such as modern biomass (+14%) and nuclear and renewable power electricity (in total 36% gain).

In Fig. 3, we attributed the reduction in carbon emissions from B2 to B2-550 to the different changes within the system.[5] In the first two decades, the lion's share of the reductions comes from energy efficiency improvement and fuel-switch from coal to other fossil fuels. By 2030, the other options start to become important: using biofuels instead of fossil fuels and non-thermal electricity modes (solar/wind and nuclear power) instead of fossil-based electricity.[6] The largest reductions are likely to occur in the electrical power sector. This result can easily be understood if one looks at generation costs of the two fully competitive non-fossil power options compared to those of thermal power (Fig. 4). In the baseline, from 2000 until around 2030 there is still a very clear gap between the generation costs of these options in favor of fossil-fuel based options; solar/wind is still around a factor 2–3 times more expensive, while the difference with nuclear power is somewhat smaller. In time, by learning-by-doing, the costs of solar/wind power and nuclear power slowly decline and around 2050 generation costs become nearly equal. As solar/wind power at that time gain a considerable market share, cost reductions start to be offset by the

[4] The reduction is in size of the same magnitude as the reduction that is required for achieving stabilisation at 450 ppmv of carbon dioxide in the atmosphere starting from the B1 baseline scenario that we described earlier (van Vuuren and de Vries, 2001). Further in this section we compare the results to those of the B1 450 ppmv analysis.

[5] The actual size of each option depends somewhat on the order of attribution. We first determined the total contribution from efficiency improvement, next from penetration of solar/wind and nuclear power and biofuels, then from biofuel penetration and finally for a fuel-switch among the different fossil fuels.

[6] We have allowed additional use of nuclear power as a mitigation option in these calculations. In fact, as the cost of this option is lower in the baseline than the solar/wind power option, it represents the most attractive alternative in terms of a first response. The 'learning' capacity of this option is, however, assumed to be lower than for solar/wind power. It should be noted that generation costs for fossil-based electricity is in fact calculated in the model through a weighted average of coal, oil and natural gas generation costs.

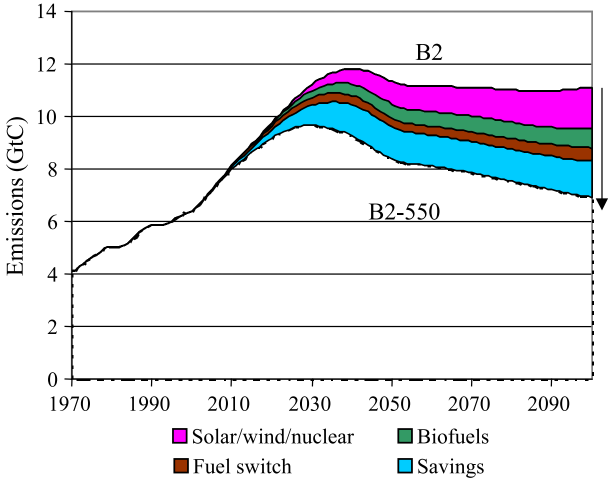

Fig. 3. Allocation of carbon dioxide emission reduction going from B2 to a 550 ppmv stabilization scenario.

fact that the best production sites are already occupied and the further penetration requires higher storage and/or distribution costs. As a result thermal-based electricity remains the cheapest of the supply options throughout the century in the baseline. If a carbon tax is introduced into this system, it easily shifts the costs of the thermal options above the alternative costs for nuclear and solar/wind. This induces in the model a strong penetration of these options into the power generation system, allowing for a sharp reduction of carbon dioxide emissions.

The strongest impact of the carbon tax is on coal use. Hence, the largest changes in terms of energy use will occur in regions with relatively high coal consumption and production rates. This includes China, India, South Africa and the USA. Impacts on oil use and trade are much smaller—in view of the relatively modest taxes required to reach 550 from the B2 scenario (also note that trade levels in B2 are somewhat lower than in other SRES scenarios). Middle East oil exports, for instance, decrease in terms of the ratio of export revenues and GDP from 11.6% to 11.1% in the 2000–2050 period (Table 2).

Table 2
Volume of fuel trade as % of GDP in selected regions (2000–2050) (net imports are negative; net exports are positive)

	Oil export (% GDP)			All energy export (% GDP)		
	B2	B2-550	Diff.	B2	B2-550	Diff.
USA	– 0.75	– 0.71	0.04	– 1.36	– 1.41	– 0.04
South America	1.09	1.02	– 0.07	2.44	2.70	0.26
Western Europe	– 0.57	– 0.52	0.05	– 1.14	– 1.12	0.02
FSU	3.37	3.01	– 0.36	10.44	10.97	0.53
Middle East	11.64	11.13	– 0.51	13.58	13.11	– 0.47
South Asia	– 2.07	– 1.93	0.14	– 3.54	– 3.53	0.00
East Asia	– 0.70	0.67	0.03	– 1.11	– 1.22	– 0.11
Japan	– 0.66	– 0.63	0.03	– 1.28	– 1.25	0.03

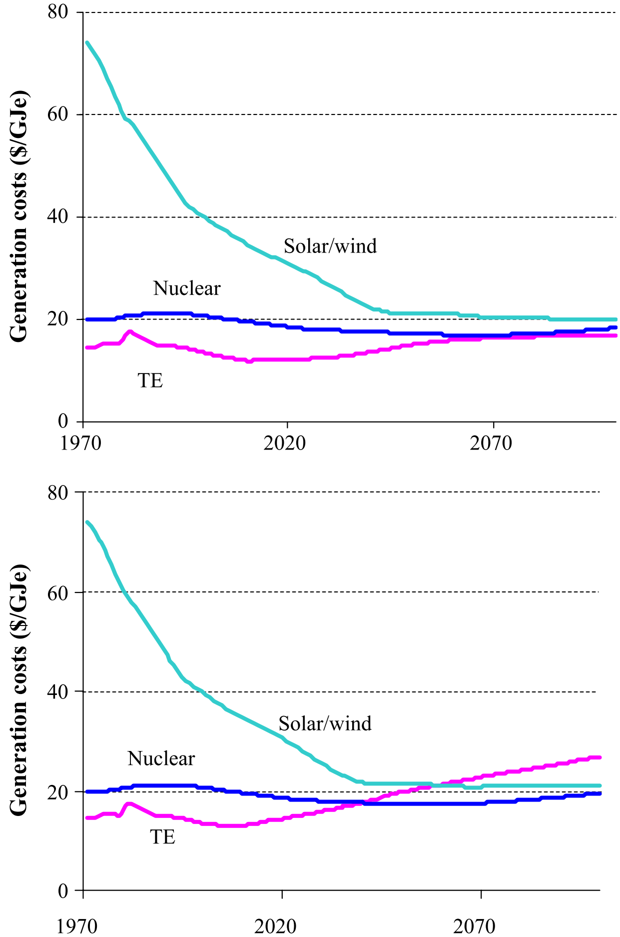

Fig. 4. Generation costs of non-thermal options (solar/wind and nuclear) versus electricity from thermal-power plants (mostly fossil-fueled, but including biofuels; TE) electricity generation in the B2 baseline (top) and the 550 stabilization scenario (bottom).

Impacts in regions with slightly higher production costs, such as the FSU, could be larger in relative terms. A number of other import regions could benefit from reduced oil imports, around 2050 in particular China and India. Interestingly, changes in the trade of other fuels can cause a different picture for total energy export as percentage of GDP. The Former Soviet Union, for instance, is suffering in the long-run (2030–2060) from reduced oil exports. The exploitation from this region's oil resources, very competitive by that time under the baseline, is subject to a carbon tax that by that time already reaches a level of US$100/tC. In contrast, in the medium term (2010–2030) this region benefits significantly from increased natural gas exports to Western Europe and Japan. Also, South America sees some losses in oil exports—but these are offset as the region captures its experience in producing biofuels and becoming an important exporter of these fuels. Finally, for China, the reduction in oil exports is offset by an equally sharp increase in natural gas and later biofuels imports (van Vuuren et al., 2003).

The reduction of energy/industry-related cumulative carbon dioxide emissions are about 20%, following a 20% in 2050 and a 40% in 2100 (the equivalent of 4.3 GtC/year). As a result of the induced changes in the energy system to the carbon tax (more energy crops to produce biofuels, thus less land for new forest), land-use emissions increase slightly by about 0.4 GtC (a form of carbon leakage that could be reduced by additional policies oriented to land-use related emissions). The carbon tax does not directly tax non-carbon dioxide greenhouse gasses either. However, as the carbon tax induces changes in the energy system, the emissions of other energy-related gasses are reduced. For instance, energy-related methane emissions are reduced by about 10% compared to baseline (a 60% increase of emissions instead of a 70% increase)—with corresponding advantages in terms of greenhouse gas concentrations. Sulfur emissions are also reduced by about 10% compared to baseline. The latter gives rise to important co-benefits of climate policies in terms of reduction of both urban and regional air pollution (van Vuuren et al., 2003).

The B2-550 stabilization scenario developed here results in a rise of global average temperature of 2.6 °C vis-à-vis a temperature increase of 2.9 °C in the B2 baseline scenario. The gains from reduction of the radiative forcing of carbon dioxide are, in particular in the first decades, somewhat offset by a decrease in the negative forcing of sulfur aerosols.

If we compare the results for stabilizing the carbon concentration at 550 ppmv from the B2 scenario to our earlier analysis, we see that the required efforts and consequences are very comparable. Stabilizing the carbon concentration at 450 ppmv from the B1 scenario required a US$200–230/tC carbon tax by the end of the century (depending on the timing), versus the US$190/tC used here. Responses in terms of the contribution of different technologies also seems to be comparable—although reducing coal use is slightly more important in this B2-550 analysis in view of the higher shares of coal use in total energy use. In contrast, impacts on the oil trade are smaller—most probably due to the more fragmented oil market in the B2 scenario.

4.2. Responses to different US$100/tC taxes

In the second set of experiments, a carbon tax is introduced that reaches a level of US$100/tC—but is introduced at three different rates (see Fig. 5). Fig. 6 shows that carbon dioxide emissions are reduced the fastest in the scenario that has already reached the US$100 level in 2010 (1); followed by the second and third scenario. As a result, by 2100 the first scenario has a considerably lower carbon dioxide concentration than the third. We can also compare the relative reductions for the same tax levels. These are not always similar; apparently, model dynamics do play a role here. However, the expected effect (see Section 2) of a sharper 2100 emission reduction in the first scenario compared to the others, due to a longer period of induced learning, is not visible. There are four important reasons inherent in the model for this:

- *Learning slows down with knowledge gained*. The learning curve describes technical progress as a function of the logarithm of cumulative production. This means that a

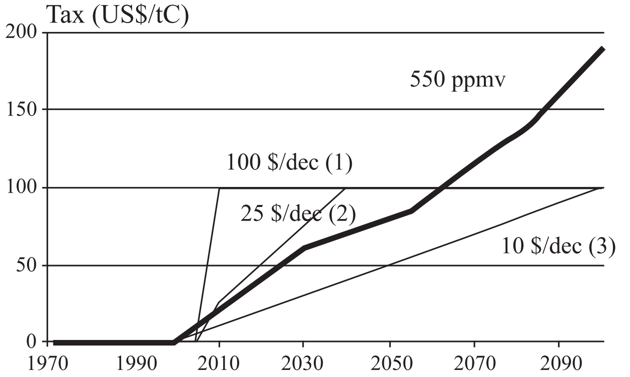

Fig. 5. Overview of the different taxes applied.

similar improvement in production costs can be realized for each doubling of cumulative production, as explained in Section 2. Production itself cannot keep 'doubling' its production rates throughout the century, thus cost reductions slow down in time. The scenario that reaches the US$100/tC as early as 2010 benefits from fast learning early in the scenario—but also experiences the consequences of slower learning afterwards.

- *High production rates for renewables are costly*. We assume that depletion for renewable technology option is directly related to production rates (see Section 2): high production rates imply that less favorable options (e.g. less favorable sites for wind power) have to be chosen. The early tax scenario results in higher production rates of these options—and thus experiences higher depletion.
- *High shares of renewables induce costs*. Most of the renewable energy options have lower reliability in terms of their electricity production than fossil-fuel options. Therefore, total electricity production can only take up a certain percentage of renewable electricity options (we assumed 20%) before requiring additional investments into the system to improve its reliability (e.g. storage or grid extensions that enlarge the system). This dynamic element has similar results to the one for depletion described above.
- *Some cheap oil and gas are still there*. Finally, the competitive fossil-based alternatives will have slightly lower production costs in the first scenario than in the second and third scenario as less depletion of cheap resources will have taken place.

In conclusion, in addition to 'learning-by-doing' there are also other technology-relevant dynamic processes, some of which may work in the opposite direction to the expected gains for early action scenarios of 'learning-by-doing'. Under the B2 model assumptions in TIMER, these processes completely offset the gains of early action in terms of costs by 2100. On the other hand, it should be noted that the early action benefited from lower costs for solar/wind during most of the simulation (see Fig. 7). The environmental impacts of these three scenarios are certainly not similar (see carbon dioxide concentration in Fig. 6).

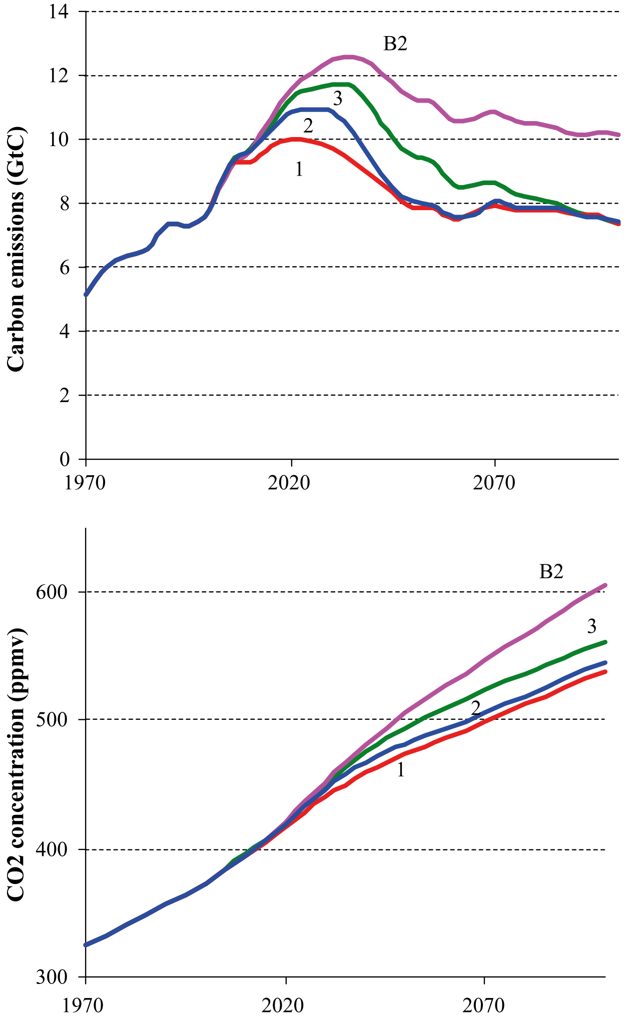

Fig. 6. Global carbon dioxide emissions (top) and carbon dioxide concentration (bottom). Note: the numbers correspond to the different tax profiles of Fig. 5.

4.3. Responses to carbon tax with and without learning

In the last set of experiments, we took a shorter time horizon (2000–2030) and investigated whether we could identify the role of different relevant dynamics to determine response to a carbon tax as defined in formula (1). We assumed that some of the dynamics discussed in the previous section were of less importance on this medium-term time scale, in particular those related to depletion. The three types of dynamics of particular importance for the medium-term response are technology development under baseline, induced technology development and system inertia.

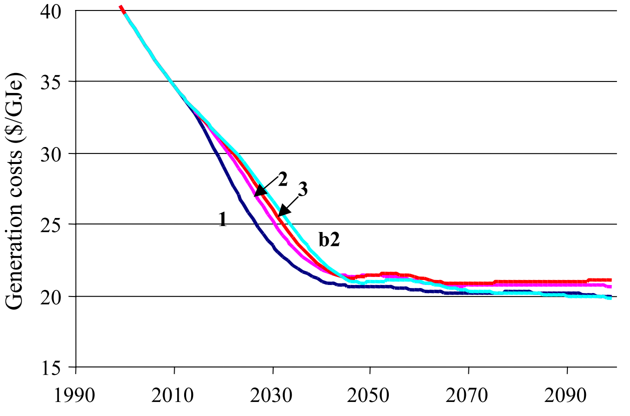

Fig. 7. Costs of solar/wind power generation in TIMER. Note: the numbers correspond to the different tax profiles of Fig. 5.

We tried to get an idea of the influence of the three processes through a set of experiments in which we recorded the system response as a function of the year of introduction (t_{in}), the year in we measure the system response (t_{rec}) and the level of the tax (T). For both t_{in} and t_{rec}, values were applied in 5-year steps between 2000 and 2030. The level of the carbon tax varied between US$0 and 600/tC.

In the first experiment we focused on the recording year (t_{rec}). We introduced a carbon tax into the TIMER model in the year 2000 (t_{in}) of US$10/tC ($T$) and recorded its immediate impact in 2000, and its impact in 2010, 2020 and 2030 (t_{rec}), after 10, 20 and 30 years, respectively. This experiment was repeated for the different tax levels between US$10 and 600/tC in steps of US$10/tC. This process is very similar to experiments in which modelers record the response of their model to carbon taxes in order to derive so-called Marginal Abatement Curves (MAC). However, in contrast to the normal MAC experiments, we looked at how the system response develops over time in the period after introduction of the carbon tax. Fig. 8a shows the results of this experiment. The recordings have resulted in four system-response curves that indicate the reduction in global carbon emissions in four different years. All of the curves show the typical form of a MAC, in which the response increases along with the level of the tax but with decreasing additional gains. Fig. 8a shows the response to the carbon tax increasing with time. A US$300 tax introduced in 2000, for instance, has only a very limited response in 2000 itself but causes a 30% reduction of global carbon emissions after 10 years—and reduces global emissions by more than 50% after 30 years. ‘Baseline learning’, ‘induced learning’ and ‘inertia’ all contribute to this increasing response in time.

In a second experiment we bring in the time of introduction of the tax (t_{in}). What happens if the tax is not introduced in 2000, but in 2010 or 2020? We recorded the impact in 2030 (t_{rec}) of three different series of taxes introduced in 2000, 2010 and 2020, respectively (Fig. 8b). The results are fairly similar to the previous experiment. A tax introduced in 2000 has the largest response, benefiting again from both baseline and induced learning processes, and having sufficient time to overcome the existing inertia. The 2030 response to a tax introduced in 2020 is significantly smaller. Interestingly, this

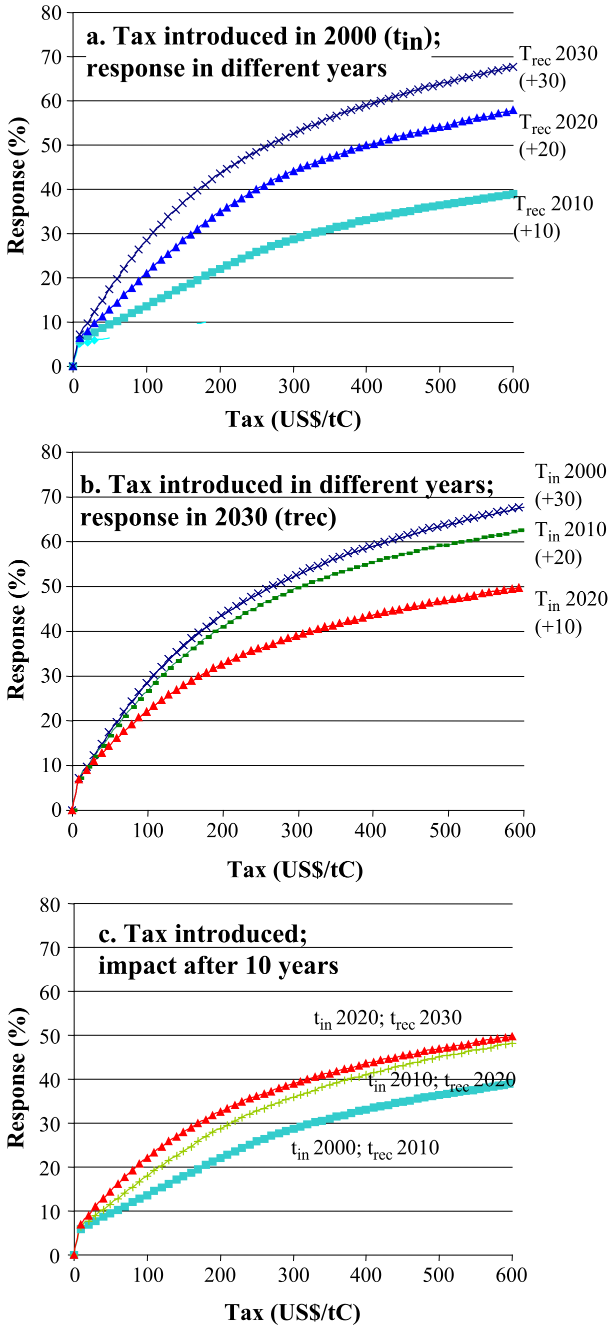

Fig. 8. Response to a carbon tax, (a) introduction year 2000; different recording years. (b) Recording year 2030; different introduction years. (c) Recording year 10 years after introduction year.

curve lies some 10% above the curve in Fig. 8a of the 2010 response of tax introduced in 2000 (both curves are included in Fig. 8c). In terms of time elapsed after the tax was introduced these cases are similar as both curves show the situation 10 years after the tax was introduced. Assuming that the role of inertia and induced learning will therefore be comparable, in particular technology development under the baseline can be identified as an important process explaining these differences. Fig. 8c shows all three curves, recorded 10 years after the introduction of the tax.

We continue this line of thinking by now considering the introduction time t_{in} and the recording time t_{rec} as two independent axes on one graph. In this graph we show for a given tax level T (in this case US$300/tC) all possible responses as a function of combinations of t_{in} and t_{rec}, in 5-year steps. The surface that is created in this way obviously shows the strongest response in the lower right corner, as this depicts the situation of an early introduction of the tax (2000) and late recordings (2030). The diagonal from the left low corner ($t_{in}=2000$, $t_{rec}=2000$) to the right upper corner ($t_{in}=2030$; $t_{rec}=2030$) represents all points in which response is recorded immediately after the introduction of the tax—and responses along this diagonal are therefore small. All points going to the left upper corner from this diagonal are zero by definition (recording time before the introduction of the tax). This representation allows for a comparison in different directions. Horizontal and vertical lines through the graph show the influence of changes in recording time and introduction time, respectively, while diagonals compare cases with a constant time between t_{in} and t_{rec}. The highlighted diagonal in the graph, for instance, shows all cases with a 20-year time period between introduction of the tax and recordings for the 2020–2030 period.

We will first look at the results of this graph in the normal model mode (Fig. 9; left upper graph). A US$300/tC tax gives a maximum response of almost 60% reduction of global CO_2 emissions if introduced in 2000 and recorded in 2030 (right low corner). An important observation is that the graph is not symmetrical in its response to the two different time axes. The cause of this is mainly the ‘learning under the baseline’ that creates different starting situations for our experiments.

In the model, we can now step-by-step switch off different dynamics. First, the additional ‘learning-by-doing’ induced by a carbon tax is completely switched off (learning is equal to baseline), resulting in Fig. 9 (upper right graph). Instead of reaching a maximum reduction near 60% in the maximum reduction is now 40–50% (right low corner). Thus, induced learning between 2000 and 2030 to a US$300/tC tax creates an additional 10% response under the B2 assumptions to the response that would be obtained if no induced learning was included in the model. Interestingly, the difference between the first and second graph becomes less for the cases with a shorter period between the year of introduction and the recording time. This result can be understood, as this also decreases the period in which induced learning can take place.

In the last experiment, we also switched off all learning that had already occurred in the baseline—leaving all technology frozen at its 2000 level[7] (Fig. 9; lower left). This means that now mainly system inertia determine our results. Again, taking out the process of

[7] Obviously, this also changes the baseline itself in terms of emissions. However, as we are interested in relative responses, this does not create major obstacles for comparing the different cases.

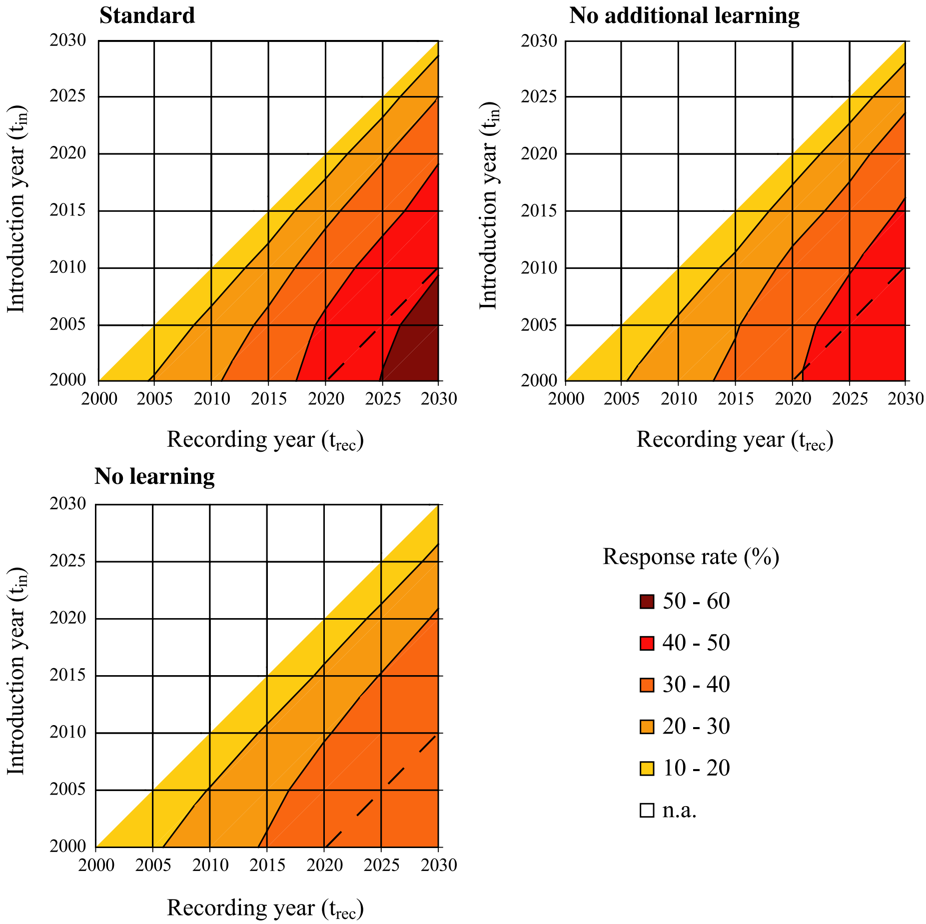

Fig. 9. Global carbon response rate (in % reduction compared to baseline) to a US$300/tC tax as a function of introduction and recording year. The introduction year represent the year the tax is introduced, the recording year the year that the response to the tax is recorded. The dashed line indicates, as example, all points in which the response is recorded 20 years after the introduction.

technological development has reduced the response of the system to the carbon tax. The maximum response is now around 35% for the 2000 introduction, and 2030 as recording year (right low corner), thus again a loss of about 10% in terms of carbon emission reduction. A second observation is that the graph has become more symmetrical. This complies to our explanation that the asymmetric response in first two graphs of Fig. 9 is at least partly related to learning under the baseline. The remaining asymmetry is caused largely by depletion of fossil fuels in time (weakening the competitive position of fossil-fuel based technologies).

This set of experiments shows the importance of (assumptions about) technology development for the effectiveness of reducing carbon dioxide emissions—and for the abatement costs, if we take the level of the carbon tax as a proxy of costs. In our experiments, we have more-or-less untangled the different roles of technology development in the baseline, induced technology development and inertia. Both induced technology development and technology development in the baseline contributed to 10% more reduction of carbon dioxide emissions in case of a US$300 tax introduced in 2000 and recorded in 2030. Inertia is very important as well, and on its own it causes a difference between a 10% reduction of global emissions after 5 years and a 35% reduction after 30 years. It should be noted that these results reflect the full dynamics in the (simulated) world energy system, including depletion and trade.

5. Discussion and main conclusions

We have studied a set of different mitigation experiments, with a particular focus on the role of technologies in terms of mitigation response to a carbon tax.

In interpreting the results of these experiments, we obviously need to realize the model characteristics and assumptions. TIMER is an energy system model with a strong focus on relevant dynamic relationships among the various mitigation options but without macroeconomic feedbacks. A second point refers to the baseline and the options that were used in our mitigation scenarios. The IMAGE B2 baseline, used as a baseline for our analysis, should be regarded as a medium- to low-emission scenario. As a result, most of the reductions that have been studied here can be regarded as reductions with a medium level of ambition (e.g. a 40% reduction of carbon emissions by 2100 is required to reach stabilization at 550 ppmv). On the other hand, the TIMER 1.0 version does not include all available mitigation options, in particular, carbon sequestration, neither by means of capture and storage or by means of sinks enhancement.

Using an energy-model in the context of an integrated assessment model allows us to study some indirect changes of climate policies as well. First of all, the changes in the energy system in response to the carbon tax not only change carbon emissions but also other greenhouse gases and sulfur emissions. We have shown in this paper that the environmental effectiveness—certainly in the short term—is limited as a result of a reduction in the aerosol cooling effect. Secondly, using integrated analysis can show some of the trade-offs between reducing energy-related carbon dioxide emission by using biofuels and its impact on land-use emissions. In our current results, biofuel use has a net mitigation effect, but some of the mitigation is offset by the additional demand for agricultural land, which increases land-use emissions.

The results, above all, indicate *how important technological improvement is for climate mitigation strategies*. This is shown, for instance, by cost reductions in solar/wind technology in the case of the first two experiments. This is shown the clearest with the results of the last set of experiments. Leaving out all forms of technology development reduces the response to a US$300/tC carbon tax in 2030 from a 60% reduction to only 30% (both compared to baseline). Partly as a result of these technology developments, stabilization of 550 ppmv from the IMAGE B2 baseline appears feasible at relatively low costs by introducing a uniform carbon tax and the variety of measures induced by this tax. Interestingly, the costs and measures taken in going from B2 to 550 stabilization are more-or-less comparable to those found earlier for going to 450 ppmv stabilization from the B1 baseline (van Vuuren and de Vries, 2001). This shows how important baseline assumptions can be for the costs of reaching different stabilization levels; in particular, the sustainable development orientation and the strong technology development assumed in the B1 baseline can allow for reaching lower stabilization levels at bearable costs when compared to other baseline scenarios.

Breaking down the results for the B2-550 stabilization scenario shows improved efficiency to be the single most important factor in the first decades in terms of the mitigation response, followed by fuel-switching among the fossil fuels (in particular from coal to natural gas). However, from 2030 onwards, introduction of carbon-free supply options provides the bulk of the required reductions. As a result, the changes in global energy intensity remain near the upper end of the historically observed range, whereas decarbonization rates go the levels above historical rates for the whole century. In terms of energy carriers the sharpest reductions take place for coal: a 50% reduction in cumulative coal use. This implies that the greatest changes take place in regions with high shares of coal consumption or production. Alternatively, these regions might need to develop carbon storage (excluded in our experiments). In terms of fuel trade, carbon-tax induced oil trade changes appear to be modest. Changes in trade of other energy carriers may be of the same order of magnitude and, depending on the region, work in the same direction as changes in oil trade or completely offset them. The latter is, for instance, the case for the Former Soviet Union, where one could see how natural gas and biofuels exports offset the losses in oil exports.

Technology development needs to be studied in the context of other dynamic processes important in the world energy system. In our simulated B2 world of the TIMER model, early-action type of scenarios results in accelerated technology development on the short and medium term. In the long run, however, there are a number of processes that may work in the opposite direction, such as the maximum share of renewable technologies that can be absorbed in the electric power system without additional costs, and the impacts on depletion of both fossil fuels and renewables. The exact results depend on the different assumptions made. In the current runs, scenarios with early carbon taxes still have lower carbon dioxide concentrations in 2100; however, these scenarios show a similar emission reduction in 2100 as the scenarios with a slower introduction of the same carbon tax. It is important to study the role of these processes in more detail.

Three technological processes that have a direct influence on the mitigation response to carbon taxes are the *technology development in the baseline, induced technology development as a result of climate policy and inertia*. The relative importance of these different processes is directly related to the discussion on timing of mitigation action. In our analyses, we have indicated how these processes all play a role. Learning that is part of the baseline indeed makes a 2030 response to a 2020 tax, 5–10% larger than a 2010 response to a 2010 tax. However, the other two processes that work in the opposite direction are at least as strong. Induced learning results in 10% more reduction to a US$300/tC tax in 2030; and without learning, inertia results in a difference a 10% reduction of global emissions after 5 years and a 35% reduction after 30 years. Taken together, in this very short time period of evaluation, the processes that would support an early action response seem to dominate over the processes that favor a delayed response approach—at least, if no discount rate is applied. In any case, the dynamics behind different technological process have been found to be very important. Providing sufficient pressure to stimulate technology development in the direction of low-carbon energy systems seems to be crucial. Sufficient resources for research and development and climate policies can help the developments in this direction.

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The impact of learning-by-doing on the timing and costs of CO_2 abatement

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Abstract

A particular ceiling on atmospheric CO_2 concentrations can be maintained through a variety of emission pathways. Over the past decade, there has been considerable debate over the characteristics of a least-cost pathway. Some have suggested that a gradual departure from the emissions baseline will be the most cost-effective because it reduces the pressure for premature retirement of the existing capital stock, and it provides valuable time to develop low-cost, low-carbon-emitting substitutes. Others counter that a major flaw in analyses that support this line of reasoning is that they ignore learning-by-doing (LBD).

In this paper, we examine the impact of LBD on the timing and costs of emissions abatement. With regard to timing, we find that including learning-by-doing does not significantly alter the conclusions of previous studies that treated technology cost as exogenous. The analysis supports the earlier conclusion that for a wide range of stabilization ceilings, a gradual transition away from the "no policy" emissions baseline is preferable to one that requires substantial near-term reductions. We find that the major impact of including learning-by-doing is on the costs of emission abatement. Depending upon the sensitivity of costs to cumulative experience, LBD can substantially reduce the overall costs of emissions abatement.

Keywords: MERGE; Climate policy; Technology

1. Introduction

The issue of learning-by-doing (LBD) has become an integral part of the climate debate. LBD is the process by which the costs of new technologies decline as a function of

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cumulative experience. Although a number of studies have addressed the potential role of learning-by-doing in the context of climate policy, the effect of LBD on the timing and costs of emissions abatement remains unclear (Grubb, 1996; Tol, 1996; Grubler and Messner, 1998; Grubler et al., 1999; Goulder and Mathai, 2000; Kypreos, 2000; Manne and Barreto, 2002; Miketa and Schratenholzer, 2004). The objective of this paper is to help clarify the role of LBD as it relates to the choice of emissions abatement strategy.

The ultimate goal of the UN Framework Convention on Climate Change (UNFCCC) is "the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (Intergovernmental Negotiating Committee for a Framework Convention on Climate Change, 1992). Although what constitutes "dangerous" has yet to be determined, for most concentration ceilings, there is likely to be flexibility in terms of the emissions pathway for achieving stabilization. This is because future CO_2 concentrations are determined more by cumulative emissions rather than year-by-year emissions (Houghton, 1996).

Although little attention is placed on abatement costs in the selection of a concentration ceiling, cost-effectiveness does come into play in determining how to meet a prescribed target. In particular, the UNFCCC states that "...policies and measures to deal with climate change should be cost-effective so as to insure global benefits at the lowest possible cost" (Intergovernmental Negotiating Committee for a Framework Convention on Climate Change, 1992). Hence, once a concentration ceiling has been chosen, the issue then becomes one of how to stay beneath the ceiling in a cost-effective manner.

Some have suggested that the least-cost emissions pathway is one that departs only gradually from the emissions baseline (Wigley et al., 1996). A gradual departure avoids premature obsolescence of the existing capital stock, and it provides more time to develop low-cost, low-carbon-emitting substitutes. These analyses are based on models that typically treat the decline in technology costs as a function of time, ignoring the potential contribution of learning-by-doing.

The exclusion of LBD has led others to question the conclusions of such models (Grubb, 1997). They argue that an effective way to reduce abatement costs is to accelerate learning-by-doing. This can be accomplished through mandating a sharp near-term departure from the emissions baseline. This would raise the price of energy from existing carbon-intensive technologies. Currently uneconomical technologies would then become attractive. As their costs drop, so would the overall costs of emissions abatement.

Still, others suggest that learning-by-doing has an ambiguous impact on the timing of emissions abatement (Tol, 1996; Goulder and Mathai, 2000). LBD reduces the costs of future abatement. This suggests delaying abatement activities. However, there is added value to current abatement. It contributes to cumulative experience and hence helps reduce the costs of future abatement. It is unclear which of these two effects dominates.

In evaluating the desirability of one emissions pathway over another, we need to consider both the near-term costs to the economy and also the benefits of having low-cost substitutes earlier than might otherwise be the case. The near-term costs will be determined, in large part, by the inertia in the energy system. Much of the existing capital stock is long lived (buildings, power plants, and motor vehicles). This places constraints on the rate at which new technologies can be introduced. The switch to a less carbon-intensive economy cannot happen overnight. Tight near-term constraints can accelerate the process, but at a cost. Whether these near-term costs are warranted will depend upon how the costs of low-emitting substitutes respond to learning-by-doing.

Before turning to the analysis, some caveats are in order. First, this paper focuses exclusively on learning-by-doing. Another important channel for inducing technical change is R&D. Because knowledge is not fully appropriable, private markets probably underinvest in R&D. For purposes of the current analysis, we assume that any market failures that lead to an underinvestment in R&D are overcome (most likely through public sector intervention). To the extent that this fails to be the case, the benefits from LBD are likely to be diminished. For a discussion of the role of R&D in providing low-cost substitutes to high-carbon emitting technologies, see Tol (1996), Goulder and Mathai (2000), Nordhaus (1997), Goulder and Schneider (1997), and Carraro et al. (2002). For a general overview of the issue of induced technical change, see Clarke and Weyant (2002).

Second, the focus of the current work is on the timing and the costs of emissions abatement required in order to meet a given concentrations target. We do not address the issue of how the potential impacts attributed to climate change might be affected by choosing one emission pathway over another when complying with a prescribed concentration ceiling. Previous work has suggested that the differences in terms of temperature increase and sea level rise may be small (Wigley et al., 1996). Nevertheless, analysis to date has been rudimentary, and further work is required. To the extent that the choice of emissions pathways differs in terms of its impacts on climate change, these differences need to be considered.

Finally, consistent with UNFCCC, we have assumed that once a concentration ceiling is adopted, the goal is to achieve it in a cost-effective manner. If we were conducting a cost-benefit rather than a cost-effectiveness analysis, the reduction in abatement costs brought about by learning-by-doing would lead to more abatement in the future relative to that which might take place in the absence of LBD (Goulder and Mathai, 2000).

2. The model[1]

In this section, we provide a brief overview of a model for evaluating regional and global effects (MERGE) of greenhouse gas reductions. MERGE is an intertemporal general equilibrium model of the global economy, which incorporates perfect foresight. Although we will focus on global results, the underlying model is based on a world divided into nine geopolitical regions: (1) the USA, (2) Western Europe (OECDE), (3) Japan, (4) Canada, Australia, and New Zealand (CANZ), (5) Eastern Europe and the Former Soviet Union (EEFSU), (6) China, (7) India, (8) Mexico and OPEC (MOPEC), and (9) the rest of the world (ROW). MERGE is calibrated to the year 2000. Future

[1] For a detailed description of MERGE and its key assumption, see our website: http://www.stanford.edu/group/MERGE/.

periods are modeled in 10-year intervals. Hence, the Kyoto Protocol's first commitment period (2008–2012) is represented as 2010 (Conference of the Parties, 1997). Economic values are reported in US dollars of constant 1997 purchasing power.

MERGE provides a bottom-up perspective of the energy supply system. A distinction is made between electric and nonelectric energy. Table 1 identifies the alternative sources of electricity supply. The first five technologies represent sources in operation during the base year, 2000. The second group of technologies includes candidates for serving electricity needs in 2010 and beyond.

Previous versions of MERGE have included two electric "backstop" technologies: ADV-HC and ADV-LC. These refer to advanced high- and low-cost, carbon-free electricity generation, respectively. The low-cost variant is not available until well after the high-cost one. Their distinguishing characteristic is that once introduced, they are available at a constant marginal cost. Any of a number of technologies could be included in these categories: wind, solar, advanced nuclear, biomass, coal-based generation with carbon capture and sequestration, and others. Given the enormous disagreement as to which of these technologies or combination of technologies will succeed in terms of economic attractiveness and public acceptability, we refer to them generically rather than attempt to pick specific winners.

In the current version of the model (MERGE 4.5), we continue to refer to these technologies generically but follow a somewhat different approach. We assume that the decline in the cost of backstops will be a function of cumulative experience.[2] To do this, we have replaced ADV-LC with learning-by-doing, electric (LBDE). Its total costs are initially identical to ADV-HC (95 mills/kWh), but its learning costs decline by 20% for every doubling of cumulative experience (McDonald and Schrattenholzer, 2002). The potential for reducing costs through learning-by-doing, however, is limited. Given the uncertainties, we explore two alternatives. For a pessimistic case (LBDE-HC), we assume that costs can be reduced to 55 mills/kWh through learning-by-doing. For our optimistic case (LBDE-LC), we assume that these costs can be reduced to 35 mills/kWh.[3] In addition, we assume that due to autonomous technical progress, the time-dependent electricity-generating costs decline at the rate of 0.5% per year.[4]

Fig. 1 illustrates how the LBDE costs might decline in the absence of a carbon constraint. The top two lines are based upon the two alternative assumptions about learning-by-doing.[5] We also show how the costs of COAL-N might change over time in two different regions. Due to coal transportation costs, the costs of coal-fired electricity are higher in OECD Europe (OECDE) than in the United States. As a result, OECDE begins investing in LBDE-LC and LBDE-HC in 2010 and 2030, respectively. Our cost curves reflect the assumption

[2] See Manne and Barreto (2002) for a description of the approach used in this study. A heuristic is employed to deal with the problem of isolated, local optima.

[3] We also note that even at 95 mills/kWh there may be some "niche" markets where these technologies are already competitive. To the extent that this is the case, the rate of learning will be accelerated.

[4] The 0.5% per year decline applies to the static component of the LBDE technologies as well.

[5] Assumptions regarding learning-by-doing, nonelectric (LBDN) remain the same in both cases. Because of its high initial costs, this technology does not begin to play a significant role (i.e., providing 10% of nonelectric energy supply) until 2070.

Table 1
Electricity generation technologies available to the United States[a]

Technology name	Identification/examples	Earliest possible introduction date	Costs in 2000[b] (mills/kWh)	Potential cost reduction due to learning-by-doing (mills/kWh)	Carbon emission coefficients (billion tons per TWH)
HYDRO	Hydroelectric and geothermal	Existing	40.0		0.0000
NUC	Remaining initial nuclear	Existing	50.0		0.0000
GAS-R	Remaining initial gas fired	Existing	35.7		0.1443
OIL-R	Remaining initial oil fired	Existing	37.8		0.2094
COAL-R	Remaining initial coal fired	Existing	20.3		0.2533
GAS-N	Advanced combined cycle	2010	30.3		0.0935
GAS-A	Fuel cells with capture and sequestration—gas fuel	2030	47.7		0.0000
COAL-N	Pulverized coal without CO_2 recovery	2010	40.6		0.1955
COAL-A	Fuel cells with capture and sequestration—coal fuel	2040	55.9		0.0068
IGCC	Integrated gasification and combined cycle with capture and sequestration—coal fuel	2020[c]	62.0		0.0240
ADV-HC	Carbon-free technologies; costs do not decline with learning-by-doing	2010	95.0		0.0000
LBDE-HC[d]	Carbon-free technologies; costs decline with learning -by-doing (high cost)	2010	95.0	40.0	0.0000
LBDE-LC[d]	Carbon-free technologies; costs decline with learning-by-doing (low cost)	2010	95.0	60.0	0.0000

[a] Introduction dates and costs may vary by region.

[b] Except for oil and gas costs and the learning by doing component, we assume that the costs of all technologies decline at a rate of 0.5% per year beginning in 2000. Note that this column is used to calculate the autonomous learning component. The earliest possible introduction date is specified in the previous column.

[c] IGCC is currently available however without capture and sequestration.

[d] For the LBDE technologies, it is necessary to specify an initial quantity. We assume that the cumulative experience prior to 2000 is only 0.2 tkWh global.

that learning-by-doing is based on global diffusion. That is, experience in one region will reduce the costs of a technology in all regions. Notice that those technologies that do not benefit from learning-by-doing, for example COAL-N, still experience some decline in costs due to autonomous technical progress.

Table 2 identifies alternative sources of nonelectric energy within the model. Notice that oil and gas supplies for each region are divided into 10 cost categories. The higher cost groups have been added to reflect the potential use of nonconventional sources. With regard to carbon-free alternatives, the choices have been divided into two broad categories: low-cost renewables such as ethanol from biomass (RNEW) and high cost backstops such as hydrogen produced through photovoltaics and electrolysis

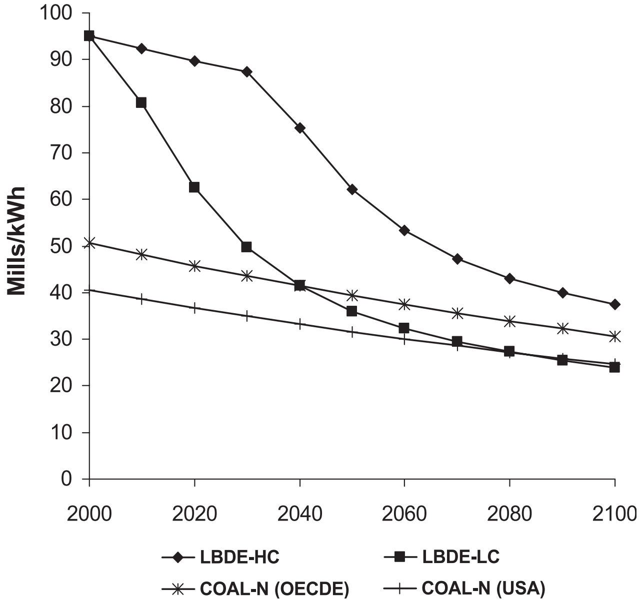

Fig. 1. Electricity generating costs for three technologies in the absence of a carbon constraint.

(NEB-HC). The key distinction is that RNEW is in limited supply, but NEB-HC is available in unlimited quantities at a constant but considerably higher marginal cost. As in the case of electric energy, we have added a new category of technologies. This is termed learning-by-doing, nonelectric (LBDN). As with its counterpart in the electric sector, costs are a function of cumulative experience. In essence, LBDN adds a learning component to NEB-HC. In addition, all nonelectric technologies enjoy autonomous technical progress.

Typically, the energy-producing and -consuming capital stock is long lived. In MERGE, introduction and decline constraints are placed on new technologies. We assume that the production from new technologies in each region is constrained to 1% of the total production in the year in which it is initially introduced and can increase by a factor of three for each decade thereafter. The decline rate is limited to 2% per year for new technologies, but there is no decline rate limit for existing technologies. This is to allow for the possibility that some emission ceilings may be sufficiently low to force premature retirement of the existing capital stock.

Turning from the supply to the demand side of the model, we use nested production functions[6] to determine how aggregate economic output depends upon the inputs of capital, labor, electric, and nonelectric energy. In this way, the model allows for both price-induced

[6] These production functions represent an additional opportunity for induced technical change. As the cost of carbon-emitting technologies changes, there will be interfuel substitution between electric and nonelectric energy. Similarly, as the price of energy changes, there will be substitution between energy and capital–labor.

Table 2
Nonelectric energy supplies available to the United States[a]

Technology name	Description	Cost in 2000 ($/GJ)[b]	Potential cost reduction due to learning-by-doing ($/GJ)	Carbon emission coefficients (tons of carbon per GJ)
CLDU	Coal—direct uses	2.50		0.0241
OIL-1—10	Oil—10 cost categories	3.00–5.25		0.0199
GAS-1—10	Gas—10 cost categories	2.00–4.25		0.0137
RNEW	Renewables	6.00		0.0000
NEB-HC	Nonelectric backstop	14.00		0.0000
LBDN[c]	Carbon-free technologies; costs decline with learning-by-doing	14.00	6.00	0.0000

[a] Costs may vary by region.

[b] Except for the learning by doing component, we assume that the costs of all technologies decline at a rate of 0.5% per year beginning in 2000.

[c] We assume that the cumulative global experience prior to 2000 is only one GJ.

and autonomous (nonprice) energy conservation and for interfuel substitution. Because there is a "putty-clay" formulation, short-run elasticities are smaller than long-run elasticities. This increases the costs of rapid short-run adjustments. The model also allows for macroeconomic feedbacks. Higher energy and/or environmental costs will lead to fewer resources available for current consumption and for investment in the accumulation of capital stocks.

It is assumed that there can be international trade in emission rights. This allows regions with high marginal abatement costs to purchase emission rights from regions with low marginal abatement costs. There is also trade in oil, gas, and energy-intensive goods. Each of the model's nine regions maximizes the discounted utility of its consumption subject to an intertemporal budget constraint. Each region's wealth includes not only capital, labor, and exhaustible resources but also its negotiated international share in global emission rights.

3. The effect of learning-by-doing on reference case emissions

We begin the analysis by examining how CO_2 emissions might grow in the absence of policy intervention. We explore three scenarios. In the first, there is no learning-by-doing. The costs of all technologies are specified exogenously. The second and third scenarios incorporate learning-by-doing but differ in their potential for cumulative experience to lower costs.

Fig. 2 illustrates how the inclusion of learning can affect baseline projections of CO_2 emissions over the 21st century. The top line shows the "no LBD" baseline. That is, neither the costs of the ADV-HC nor of NEB-HC decline as a function of cumulative experience. Their costs depend only on the passage of time. The other two trajectories

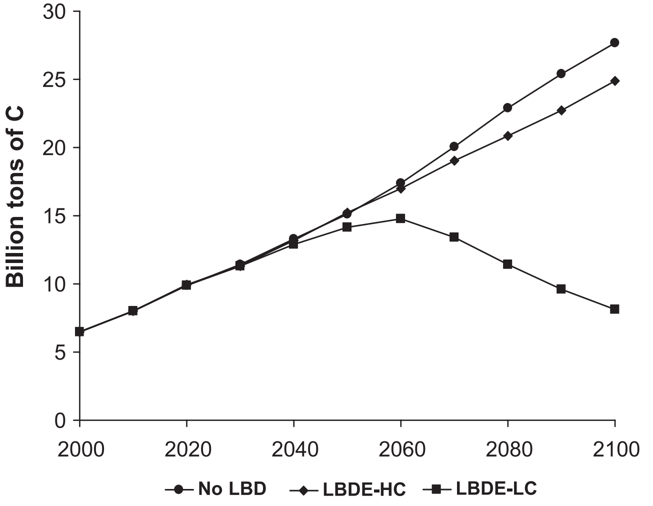

Fig. 2. Global carbon emissions—no carbon constraints.

incorporate learning-by-doing. They differ however with regard to the potential for cost reductions in the electric sector.[7]

Under the assumptions adopted in the present analysis, learning-by-doing has a negligible effect on the baseline during the first half of this century. However, the effect can be substantial in the second half. In the absence of a carbon constraint, the transition to a low-carbon economy is governed by the exhaustion of conventional oil and gas resources, the relative cost and availability of each technology, and the inertia in the energy system.

With LBDE-LC, the technology's ultimate cost is sufficiently attractive so that there is an incentive to start the learning-by-doing process early. For this case, global emissions peak in the middle of the century and then turn downward—even in the absence of a carbon constraint. Concentrations eventually stabilize in the range of 650 ppmv. Conversely, with LBDE-HC, the relatively high cost provides little incentive for its introduction prior to 2040. As a result, we observe little change from the "no LBD" baseline throughout the time horizon under study.

Fig. 3 illustrates the importance of the expansion constraints. Suppose, for example, that there is no constraint on the rate at which the LBDE technologies can enter the energy system. In the case of LBDE-LC, the percent of global electricity generation increases. This is a reflection of the technology's ultimate economic attractiveness. Conversely, the expansion constraint has little impact on the rate of introduction of the LBDE-HC technology. Even after allowing for learning effects, this technology has a high cost and is unattractive in most regions.

[7] Assumption regarding LBDN (learning-by-doing, nonelectric) remain the same in both cases. Because of its high initial cost, this technology does not begin to play a significant role (i.e., providing 10% of nonelectric energy supply) until 2070.

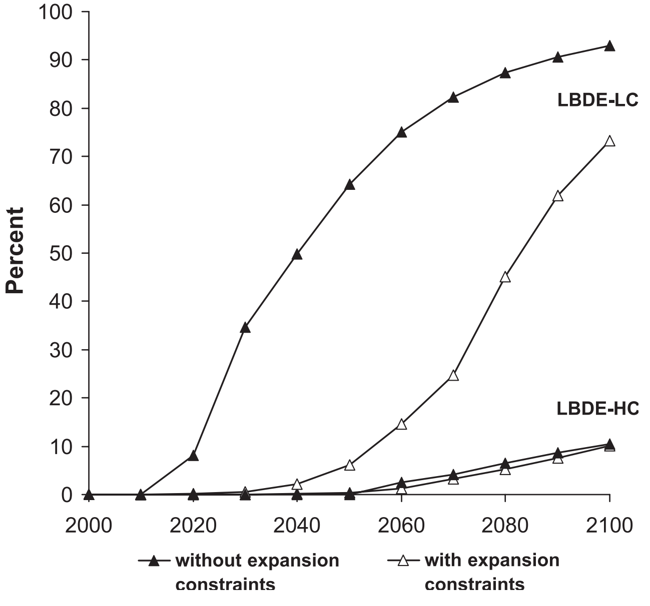

Fig. 3. Percent of global electricity generation supplied by LBDE—no carbon constraints.

These results highlight the potential importance of learning-by-doing in determining the baseline. If learning-by-doing can lead to technologies that are both low carbon emitters and economically competitive, then it can substantially reduce the need for external intervention. Carbon emissions will decline naturally in response to market forces.[8]

4. The effect of learning-by-doing on least-cost abatement pathways

We now examine the impact of learning-by-doing on the timing and costs of emission abatement policies. Two types of constraints are explored: those on ultimate concentrations and those on year-by-year emissions. The former is more in the spirit of the UNFCCC. The latter is more nearly consistent with the Kyoto Protocol. It prescribes a constraint on emissions in each commitment period.

We are far from reaching agreement on what might constitute "dangerous anthropogenic interference with the climate system". This will likely be the subject of intense scientific and political debate for some time to come. For illustrative purposes, this section is based on the goal of stabilizing atmospheric CO_2 concentrations at 550 ppmv (SCC-550). We also assume that the criterion is to achieve this concentration target in an economically efficient manner.[9] To do this will require full "where" and "when" flexibility. That is, emissions are

[8] Again, we note the assumption that the market failures leading to underinvestment in R&D by the private sector are succesfully addressed, most likely through public sector intervention.

[9] We stress, however, that to the extent that "command and control" approaches are chosen over "market mechanisms", abatement costs will be higher.

reduced both where and when it is economical to do so. This is apart from the issue of who pays the bill. If there is full international trade in emission rights, equity, and efficiency, issues may be separated.

There are three distinct phases in the transition to a low-carbon energy system. Fig. 4 suggests that with full "where" and "when" flexibility, the least-cost abatement trajectory stays very close to the baseline through 2020. This is true both with and without learning-by-doing. Roughly speaking, a concentration ceiling places a limit on the cumulative amount of carbon that can be emitted into the atmosphere. But how do we allocate this carbon budget over time? Not surprisingly, the least-cost emissions pathway involves dependence on inexpensive high-carbon emitting technologies in the early years, and a gradual shift to lower-carbon emitting technologies in the future once their decline in costs makes them more economically attractive.

In the case of LBDE-LC, future costs are sufficiently low to warrant some early investment, although it is presently uneconomical. However, the inertia in the energy system limits how quickly the LBDE-LC technologies can expand. In the case of LBDE-HC, learning-by-doing in the early years results in a less dramatic reduction in future costs. As a result, there is less inducement for early investment.

In the second phase (2020–2060), incorporating learning-by-doing has what initially appears to be a counterintuitive influence on the least-cost pathway. Fig. 5 compares the three emission profiles for stabilizing CO_2 concentrations at 550 ppmv. Although all three cases eventually show a substantial reduction in emissions, note that emissions are lower in phase II in the "no LBD" case. This is because, based upon the assumptions about technology cost and availability, there is no concern about locking into technologies that will soon prove to be economically inferior. With LBD, however, investors are reluctant to commit to low-cost, low-carbon-emitting substitutes when even lower cost, lower carbon-emitting substitutes will soon be available. For example, in the "no LBD" case, COAL-A

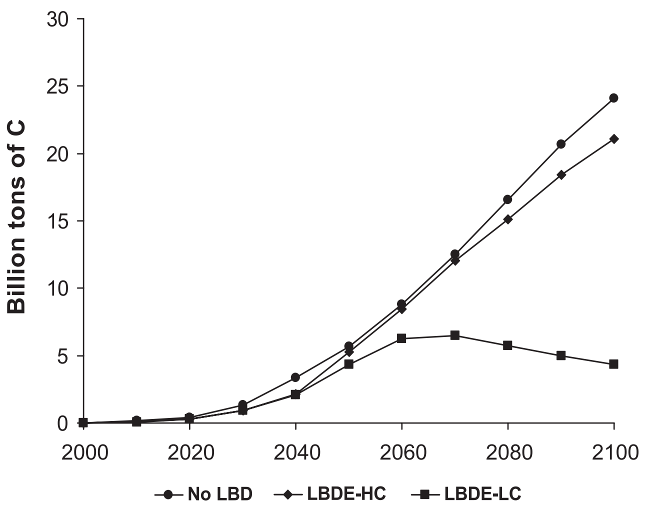

Fig. 4. Global emission reductions required to stabilize concentrations at 550 ppmv.

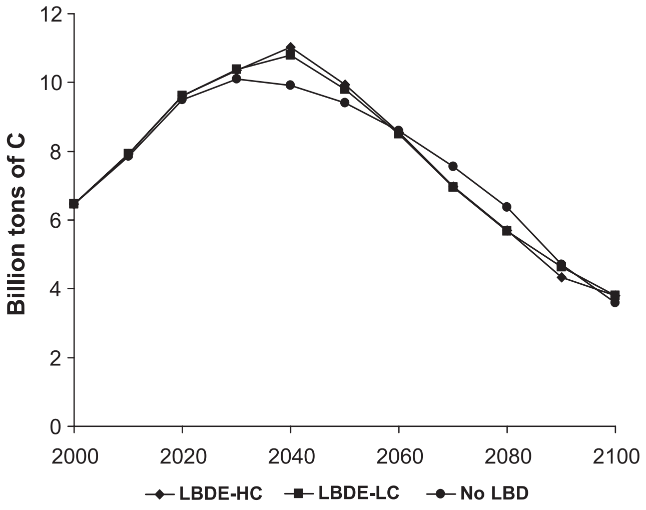

Fig. 5. Global carbon emissions—SCC-550.

(e.g., the solid oxide fuel cell) becomes available in 2040 and is the technology of choice. However, when we incorporate learning-by-doing, the LBDE technologies win out although their costs remain noncompetitive for another decade or so. The final phase (2060–2100) is the time frame in which the LBDE technologies have a clear economic advantage over all other electric technologies.

Although learning-by-doing has little impact on the timing of near-term emission reductions, it has a major impact on costs. Fig. 6 shows cumulative discounted global abatement costs for stabilizing concentrations at 550 ppmv, assuming full "where" and "when" flexibility. Compared with no LBD, the LBDE-HC and LBDE-LC scenarios show a reduction in costs by 42% and 72%, respectively. Although learning-by-doing has

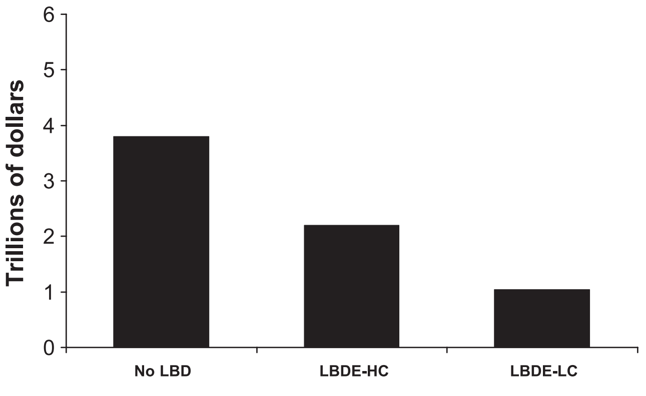

Fig. 6. Cumulative discounted global abatement costs for stabilizing concentrations at 550 ppmv (discounted at 5% from 2000–2100).

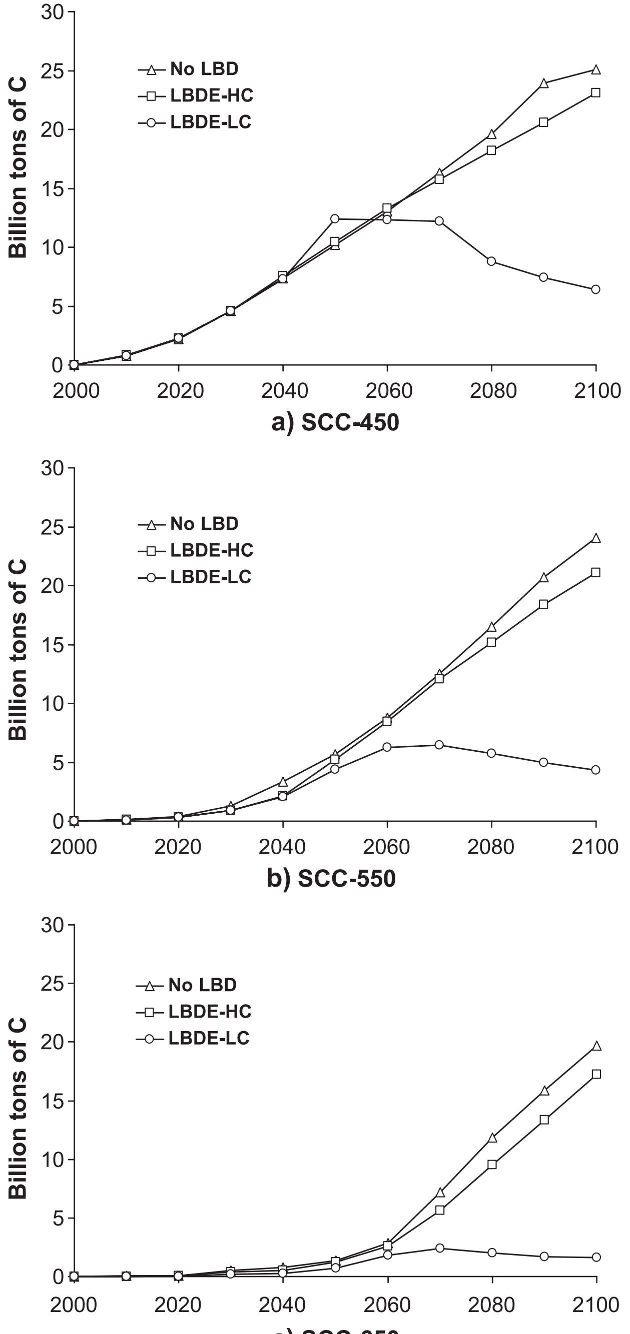

Fig. 7. Global emission reductions from the baseline for three alternative stabilization ceilings.

little impact on the timing of emission reductions during the early decades of the 21st century, it has a major impact on total abatement costs.

5. Some additional sensitivity analysis

5.1. The impact of learning-by-doing under alternative concentration targets

Up to this point, we have assumed that the goal was to stabilize atmospheric CO_2 concentrations at 550 ppmv. Now let us consider alternative concentration targets: 450 and 650 ppmv. Fig. 7 compares the least-cost stabilization pathway for these ceilings. With a target of 450 ppmv, we see an immediate departure from the emissions baseline—regardless of the LBD assumption. With such a tight ceiling, it is necessary to introduce major near-term changes in the energy system if we are to stay below the prescribed concentration level. The incremental value of carbon emission rights rises high enough to induce sufficient fuel switching and price-induced conservation to stay on the least-cost trajectory (see Table 3). The implicit tax is roughly an order of magnitude higher than that required for a ceiling of 550 ppmv or above. For a ceiling of 650 ppmv, very little is required in the early decades, hence the implicit tax is negligible.

Fig. 8 shows the implications for discounted abatement costs over the 21st century. As one would expect, the costs are highest with a 450 ppmv target. The benefits from learning-by-doing will come too late to offset these increases in near-term costs.

5.2. The impact of learning-by-doing on a Kyoto-type target

We now turn to a case closer to that suggested by the Kyoto Protocol. There is not "when" flexibility, nor is there complete "where" flexibility. This scenario is designed to achieve approximately the same level of concentrations in 2100 as SCC-550 but is more aggressive in terms of emission reductions in the early decades of the present century. We refer to this case as the "Kyoto plus" (Kyoto+).

Specifically, we assume that all Annex B countries (with the exception of the United States) adopt the Protocol during the first commitment period. Furthermore, with an intertemporal general equilibrium model like MERGE, it is necessary to make assumptions about requirements for emission reductions in subsequent commitment periods. Here, for illustrative purposes, we assume that Kyoto will be followed by subsequent protocols in which all Annex B countries agree to reduce emissions by an additional 10%

Table 3
Incremental value of carbon emission rights ($ per ton of carbon) for alternative stabilization ceilings

	No LBD		LBDE-HC		LBDE-LC	
	2010	2020	2010	2020	2010	2020
450 ppmv	75	134	70	126	72	129
550 ppmv	9	16	7	12	6	11
650 ppmv	2	4	0	2	0	0

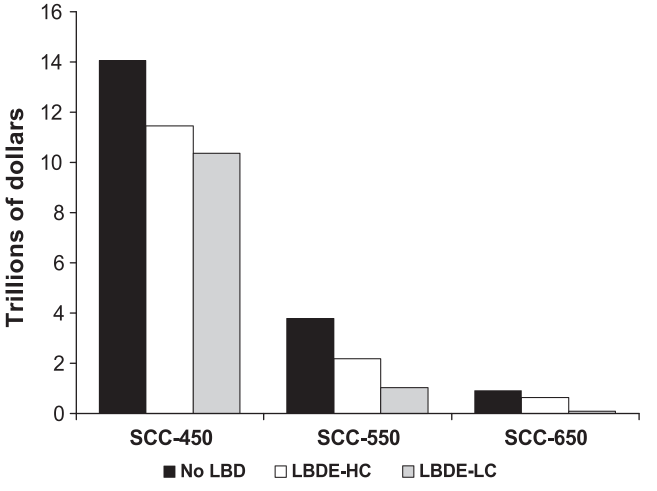

Fig. 8. Cumulative discounted global abatement costs (discounted at 5% from 2000–2100).

per decade starting in 2020. For the United States, this constraint in 2020 is assumed to be the same as if it had eventually adopted the Kyoto Protocol. Finally, we assume that all countries adopt binding targets and timetables by 2050. Clearly, the nature and timing of these future constraints are highly speculative, and they need to be subjected to extensive sensitivity analysis. The one adopted here provides an alternative emissions pathway to stabilization at 550 ppmv in 2100.

Fig. 9 shows that regardless of the assumption about learning-by-doing, Kyoto+ results in an immediate departure from the baseline. In order to induce sufficient reductions, the

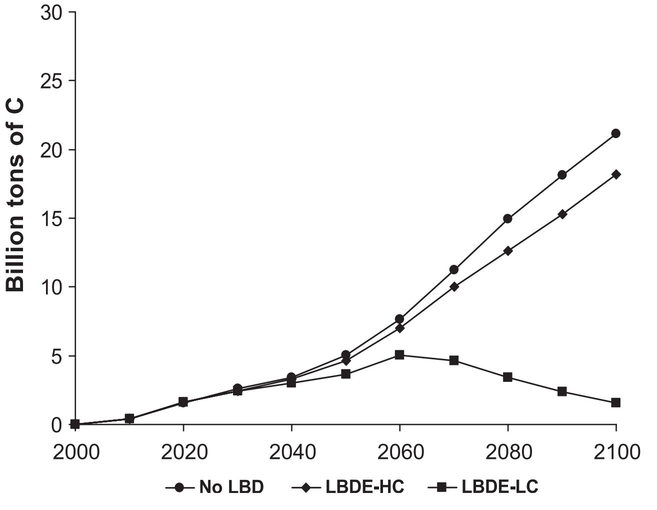

Fig. 9. Global emission reductions required under Kyoto+.

Table 4
The incremental value of carbon emission rights ($ per ton of carbon) for two alternative emission pathways for a ceiling of 550 ppmv

	No LBD		LBDE-HC		LBDE-LC	
	2010	2020	2010	2020	2010	2020
550 ppmv	9	16	7	12	6	11
Kyoto +	99	164	101	168	102	170

incremental value of carbon emission rights must again be an order of magnitude higher than that associated with a 550 ppmv ceiling with complete "where" and "when" flexibility (see Table 4).

Finally, Fig. 10 compares cumulative discounted abatement costs for SCC-550 and Kyoto+. In all cases, Kyoto+ represents a substantial increase in the overall costs relative to SCC-550.

6. Concluding comments

A particular concentration target can be achieved through a variety of emission pathways. Over the past decade, there has been considerable debate over the characteristics of a least-cost pathway. Some have suggested that a gradual departure from the emissions baseline will be the most cost-effective, because it avoids premature retirement of the existing capital stock, and it provides valuable time to develop low-cost, low-carbon-emitting substitutes. Others counter that a major flaw in this line of reasoning is that it ignores learning-by-doing. In this paper, we examine the impact of LBD on the timing and costs of emissions abatement.

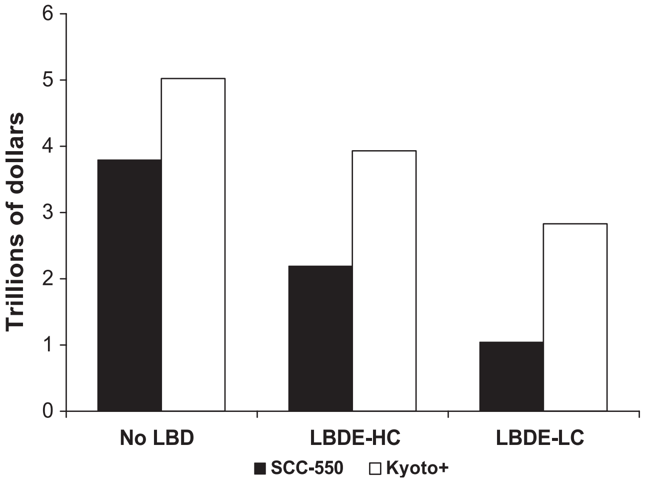

Fig. 10. Cumulative discounted abatement costs for SCC-550 and Kyoto+ (discounted at 5% from 2000–2100).

We find that including learning-by-doing does not alter the conclusions of earlier studies that focused on the timing of emission reductions. For ceilings of 550 ppmv and above, a gradual near-term departure from the emissions baseline is still preferred. For concentration targets in the neighborhood of 450 ppmv, a more rapid near-term departure is still required—with or without LBD.

Although learning-by-doing may not accelerate the timing of the transition to a less carbon-intensive infrastructure, it can have a major impact on the overall costs of the transition. This is particularly so for concentration ceilings of 550 ppmv and above. Cumulative discounted abatement costs are substantially lower relative to the ''no LBD'' case. However, for a 450 ppmv ceiling, most of the costs are associated with premature retirement of the existing capital stock. LBD can do little to reduce these costs.

We emphasize that a gradual departure from the baseline is not a ''do nothing'' or ''wait and see'' strategy. The emissions baseline incorporates considerable technical progress on both the supply and demand sides of the energy sector. We also assume that to the extent that there are ''no regrets'' options, they will be incorporated in both the reference case and the policy case. For example, we do not need climate policy to take advantage of efficiency improvements that make sense in their own right.

Finally, although emissions abatement represents immediate action, the choices are not confined to emissions abatement. The response to the threat of climate change suggests a portfolio of responses. These include: (1) emissions abatement, (2) adaptation, (3) reducing scientific uncertainty, and (4) the development and deployment of low-cost substitutes. The issue is not one of ''either–or'' but what constitutes the right balance. This paper examines the interaction between two of the options in the portfolio: emissions abatement and technology development and deployment, and it examines their relative contributions over time.

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Learn-by-doing and carbon dioxide abatement

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Abstract

There are inherent difficulties in solving earn-by-doing (LBD) models. Basic to such models is the idea that the accumulation of experience leads to a lowering of costs.

This paper is intended to explore some of the algorithmic issues in LBD modeling for carbon dioxide abatement. When using a standard algorithm for nonlinear programming, there is no guarantee that a local LBD optimum will also be a global optimum. Fortunately, despite the absence of guarantees, there is a good chance that one of the standard algorithms will produce a global optimum for models of this type—particularly if there is an artful selection of the starting point or of the terminal conditions. Moreover, there is a new procedure named BARON. In the case of small models, a global optimum can be recognized and guaranteed through BARON.

Eventually, it should be possible for BARON or a similar approach to be extended to large-scale LBD models for climate change. Meanwhile, in order to check for local optima, the most practical course may be to employ several different starting points and terminal conditions.

Keywords: Learn-by-doing model; Carbon dioxide abatement; BARON

1. Introduction

There are inherent difficulties in solving learn-by-doing (LBD) models. Basic to such models is the idea that the accumulation of experience leads to a lowering of costs. This idea goes back to the model of Arrow (1962)—and even earlier to empirical estimates of airframe production costs. Within the context of global climate change, it has been applied by Goulder and Mathai (2000), Gritsevskyi and Nakicenovic (2000), Kydes (1999),

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Kypreos et al. (2000), Kypreos (2000), Mattsson and Wene (1997), Messner (1997), Seebregts et al. (2000), TEEM (1999) and Van der Zwaan et al. (2002).

This paper is intended to explore some of the algorithmic issues in LBD modeling for carbon dioxide abatement. When using a standard algorithm for convex nonlinear programming, there is no guarantee that a local LBD optimum will also be a global optimum. Fortunately, despite the absence of guarantees, there is a good chance that one of the standard procedures will produce a global optimum for models of this type—particularly if there is an artful selection of the starting point or of the terminal conditions. Moreover, there is a new algorithm named BARON. In the case of small-size LBD models, a global optimum can be recognized and guaranteed through BARON.

For a general idea of what is involved, see Fig. 1. There are just two decision variables, x_1 and x_2. The feasible set consists of a convex polygon: all points within the shaded area ABCD. If the minimand is strictly concave, it can happen that point A is a local optimum. That is, it has lower costs than the adjacent extreme point B, but it has higher costs than the distant extreme point C. This is illustrated by the two dashed iso-cost lines. The curved line going through A indicates higher system costs than the curved line going through C. In any case, the minimum system cost lies at one of the extreme points (the vertices)—*not* between them. (For a rigorous treatment of this proposition, see Hirsch and Hoffman (1961).) Moreover, there may be only a small difference in costs between the extreme points.

In connection with the debate over global climate change, a small example of LBD will be examined in this paper. We will show that occasionally one of the standard algorithms fails, but that BARON is successful in producing a global optimum. Simultaneously with this effort, we are applying some of these ideas to a larger, more realistic model known as

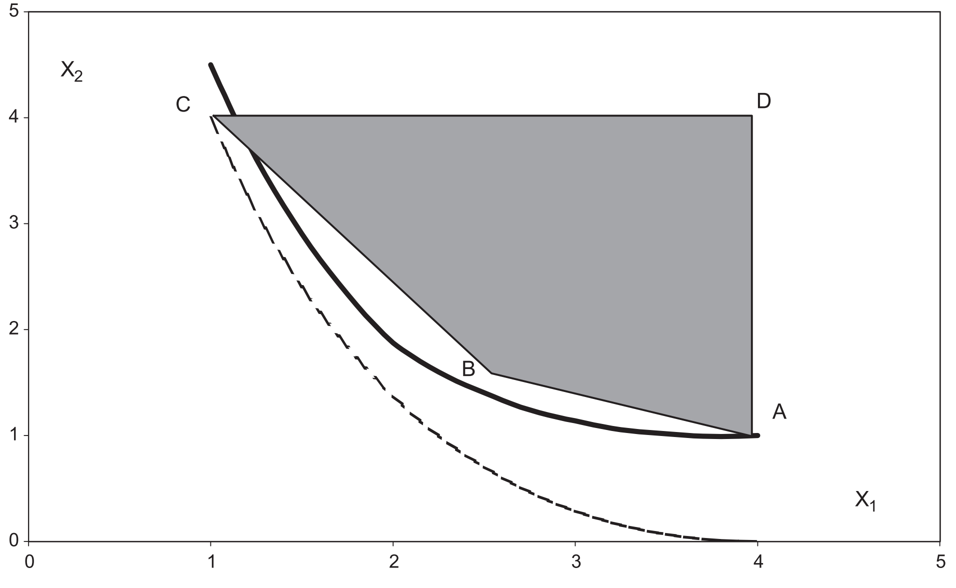

Fig. 1. Two-dimensional example of a local optimum.

MERGE. Here the standard algorithms produce plausible solutions, but we have to take any steps that we can to ensure that these represent a global rather than a local optimum.

2. The BARON algorithm

For details on BARON, see Sahinidis (2000) and http://archimedes.scs.uiuc.edu. According to: http://www.gamsworld:

> BARON is a computational system for solving non convex optimization problems to global optimality. Purely continuous, purely integer, and mixed-integer nonlinear problems can be solved with the software. The Branch And Reduce Optimization Navigator derives its name from its combining interval analysis and duality in its reduce arsenal with enhanced branch and bound concepts as it winds its way through the hills and valleys of complex optimization problems in search of global solutions.

BARON is a tool that allows for the identification of globally optimal solutions. It combines range reduction techniques with an enhanced branch and bound algorithm. This combination gives the name to the algorithm: Branch and Reduce. The Branch and Bound algorithm is applied to a (generally convex) relaxation of the original non-convex problem. In each node, a relaxed version of the original problem is solved. If this is a minimization, its solution provides a lower bound for the original non-convex problem. Using this solution as the starting point (or, if available, a better starting point can be used), the original problem is solved and an upper bound for the global optimal solution is found. If the gap between the upper and lower bounds is not small enough, the feasible region is divided in parts. A new relaxed problem is solved for each subdivision and new lower and upper bounds for the global optimum are computed.

The range reduction techniques help to restrict the search space and reduce the relaxation gap. They are applied to every sub-problem of the branch-and-bound search tree in pre- and post-processing steps, helping to improve the performance of the bounding procedure at every node of the tree. Different types of reduction tests can be applied according to the form of the problem. Optimality- and feasibility-based range reduction tests are possible. Optimality-based range reduction uses the optimal (dual) solution of the relaxed problem to reduce the range of constraints and variables. Feasibility-based range reduction uses heuristic procedures to generate constraints that eliminate infeasible portions of the solution. These constraints approximate the solution of optimization problems that generate improved bounds for the problem variables.

3. The LBD perspective

For an example of LBD, see Fig. 2, copied from International Energy Agency (2000). This reports average unit costs (1990 ECU per kilowatt-hour) for a series of alternative electricity producing technologies in the European Union, 1980–1995. The vertical axis refers to unit costs; the horizontal axis refers to cumulative electricity production at

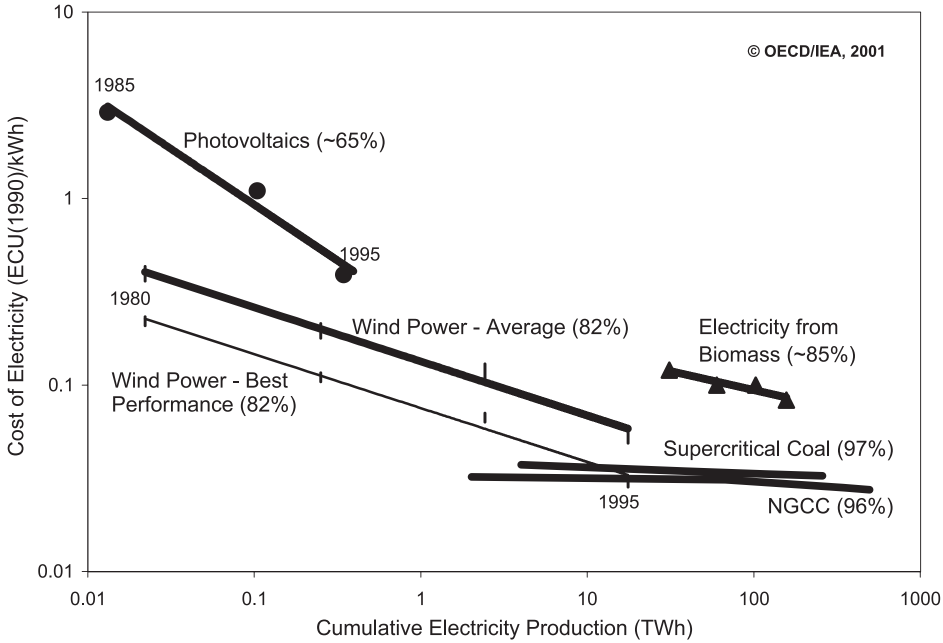

Fig. 2. Electric technologies in EU 1980–1995.

successive dates. With greater "experience" (cumulative production), there is a pronounced tendency for a decline in the unit costs of novel technologies such as photovoltaics and wind power, but there is no obvious decline in the unit costs of more conventional methods such as supercritical coal and NGCC (natural gas—combined cycle). Significantly enough, nuclear power is *not* plotted on this diagram. If it were plotted, it would almost surely illustrate an increase in unit costs with additional experience—and with additional concerns about reactor safety.

In Fig. 2, note that the newer technologies tend to be higher in unit costs than the conventional ones. If investors based all their decisions on immediate costs, there would be little tendency to support the newer technologies that are currently more expensive. Their cumulative experience is too small, and they could be "locked out" permanently. This is the rationale for public intervention in the market. LBD entails the acceptance of high near-term costs in return for an expected lowering of future costs. It is an investment choice, and it depends critically upon the rate of discount.

Associated with each technology, Fig. 2 shows a "progress ratio" entered in parentheses. This measures the percentage decline in unit costs that is associated with a doubling of experience. In the case of wind, for example, this parameter is shown as 82%. That is, $2^{\mathrm{lrn}} = 82\%$. Therefore, the exponent $\mathrm{lrn} = -0.29$. This exponent is one of the essential parameters that is entered into an LBD model.

So far, so good. The next analytical issue is the measurement of cumulative experience. Should this be limited to the European Union (as in Fig. 2)? Or should it also take account of efforts elsewhere—in Japan, the USA, etc.? This is not an easy question to answer. In a global economy, technological experience diffuses widely. It is quite possible that there is a more rapid flow of information between the European and US branches of a given company than between the European branches of different companies.

The geographical range of diffusion is one issue. Another is the measurement of cumulative experience associated with the leftmost point along each curve. If, for example, there is no experience with wind power reported before 1980, how do we measure the cumulative experience at this initial date? The initial cumulative experience is an estimate that must be made thoughtfully, and there are no easy answers. Even in the year 2000, the production of wind and solar electricity provides just a small percentage of the total.

4. A small-scale model of electricity choices

In order to develop a small-scale model of electricity choices, consider the options that are available to the world as a whole. It will be supposed that the world plans to meet the total electricity demands implied by the "reference case" of MERGE. This is a multi-region, multi-technology model for estimating the costs of regional and global greenhouse gas reductions. It is based upon a bottom-up view of energy supplies and a top-down view of energy demands. For details on MERGE, see the website: http://www.stanford.edu/group/MERGE.

To meet the reference case demands, suppose that there are just three technologies available:

1. defender: the average type of unit on line in the year 2000; a predominantly fossil mix of technologies, but also includes hydroelectric and nuclear; it is not subject to LBD.
2. challenger: the initial challenger—the average type of carbon-free technology available in 2000; this is high cost and subject to learning along the lines of the LBD model; and
3. advanced: an advanced challenger—the average type of carbon-free technology that might become available in 2050; this is lower-cost and also subject to the endogenous type of learning.

Let the decision variables $X_{j,t}$ denote the quantity of electric energy (trillion kilowatt-hours) produced by technology j in period t (where the time periods refer to successive decades during the 21st century). Together, the three technologies must meet the projected electricity demands. If one is not concerned about carbon accumulation, one could meet these demands solely through technology 1 (the low-cost, predominantly fossil-based option). If one is concerned about reducing carbon, there will be a role for the higher-cost carbon-free technologies. The earlier one has the advantage of being available immediately, but the later one has the advantage of being potentially lower in costs. It might, for example, represent nuclear or fusion. Or it might represent advanced developments of wind or of photovoltaic solar—or fossil fuel plants with carbon capture and sequestration.

To express the condition that total demands must be met by a combination of these three technologies, there is first the supply–demand balance constraint:

$$X_{1,t} + X_{2,t} + X_{3,t} \geq E_t, \tag{1}$$

where E_t denotes the demands in decade t.

Next, there are the constraints that none of these technologies may expand too rapidly. To illustrate this idea concretely, suppose that a new technology cannot supply more than 1% of the market during the first decade in which it is introduced, and that it cannot expand much more rapidly than a factor of four during subsequent decades. We then have:

$$X_{j,t+1} \leq .01E_t + 4X_{j,t} \qquad (\text{for all } j,\ t) \tag{2}$$

Similarly, to ensure that technologies are not replaced too rapidly, we impose a maximum annual decline rate of 3% per year. For intervals of a decade, this works out as follows:

$$X_{j,t+1} \geq (1/1.03)^{10} X_{j,t} \qquad (\text{for all } j,\ t) \tag{3}$$

In order to keep track of cumulative carbon emissions from the electric power sector, we take the average of emissions at the beginning and the end of each decade. Cumulative emissions through decade t are represented by the decision variable. CARB_t. They are proportional to the output of technology 1 (the predominantly fossil fuel defender):

$$\text{CARB}_{t+1} = \text{CARB}_t + 5\ \text{cec}(X_{1,t} + X_{1,t+1}) \tag{4}$$

where cec represents the average carbon emission coefficient during the year 2000. Under a ‘‘business-as-usual’’ scenario, the cumulative emissions would be roughly 700 billion tons during the 21st century. To illustrate a low-carbon scenario—but one in which there is no immediate need for abatement—we impose an upper bound of 400 billion tons on the terminal year cumulative emissions, CARB_T.

It is assumed that learning costs depend upon the cumulative production experience for each of the technologies. Let the decision variables $Y_{j,t}$ represent this experience. Basing these variables upon an average of the production at the beginning and end of each decade, we have:

$$Y_{j,t+1} = Y_{j,t} + 5(X_{j,t} + X_{j,t+1}) \qquad (\text{for all } j, t) \tag{5}$$

The objective function is expressed as one of minimizing the present value of costs—subject to meeting the supply–demand constraints (1), the expansion and decline constraints (2) and (3), the cumulative carbon constraints (4), the cumulative production experience (5), and both upper and lower bounds on individual variables. In order to employ a market-oriented criterion, we let pv_t (the present value factor for period t) be based upon a 5% real rate of return on capital. This is intended to be net of inflation, and represents a before-tax rate of return. Let the decision variable PVC denote the present value of costs throughout the 21st century. For each time period and each technology, we

Table 1
Illustrative values of the cost parameters

Technology j	1	2	3
	Defender	Challenger	Advanced
Static cost coefficients, cost_j, \$ per thousand kWh	40	30	30
Initial learning cost coefficients, inlc_j, \$ per thousand kWh	0	50	10
Initial accumulated experience, acc_j, trillion kWh	1	1	1
Learning exponent, lrn_j	n.a.	– 0.2	– 0.2

then have two cost components. The first may be termed "static" and the second "dynamic".

$$\text{PVC} = \sum_t \text{pv}_t \left\{ \sum_t \text{cost}_j X_{j,t} + \sum_j \text{incl}_j X_{j,t} \left[\frac{Y_{j,t}}{\text{acc}_j} \right]^{\text{lrn}_j} \right\} \tag{6}$$

That is, the static terms are proportional to the cost_j factors. These provide a lower bound on the average cost of each technology. The dynamic terms depend upon the cumulative learning experience. This in turn depends upon the $Y_{j,t}$ decision variables—and also upon three parameters: the initial learning cost coefficient inlc_j, the initial experience acc_j, and the learning exponent lrn_j. Table 1 shows illustrative values of these individual parameters. In this case, the costs of the fossil fuel defender remain constant over time—at \$40 per thousand kWh. The learning exponent is "n.a." (not applicable) in this case. Initially, the first challenger's costs are twice the level of the defender: 30 + 50=\$80 per thousand kWh. These costs decline over time with cumulative experience. The advanced challenger has lower initial costs, but does not become available until 2050.

Note that the initial accumulated experience parameters acc_j must be chosen with care. Over time—with cumulative experience—the costs of all three technologies will decline toward the limits imposed by the static cost factors. The parameters acc_j must be checked for their comparability with the values of the cumulative production variables $Y_{j,t}$ during the initial decades of the 21st century.

The reader could experiment with other parameters. From earlier work, for example, we know that the optimal solution is highly sensitive to the learning exponent, lrn_j.

Just as in the two-dimensional example (Fig. 1), the constraint set of this problem is a convex polyhedron. The minimand is concave. A solution must therefore lie at one or another of the extreme points of the polyhedral constraint set. However, it is not sufficient to check *adjacent* extreme points. One must somehow be able to verify that distant extreme points are also handled. This is the role played by BARON.

5. Numerical results from the small-scale model

Fig. 3 shows the percentages supplied by each of the three technologies in the global, minimum-cost solution to this problem. Each technology follows a unimodal path. That is, there is at most one maximum point for its deployment. There are distinct phases in which one or another expansion/decline constraint is active. The first challenger is not introduced

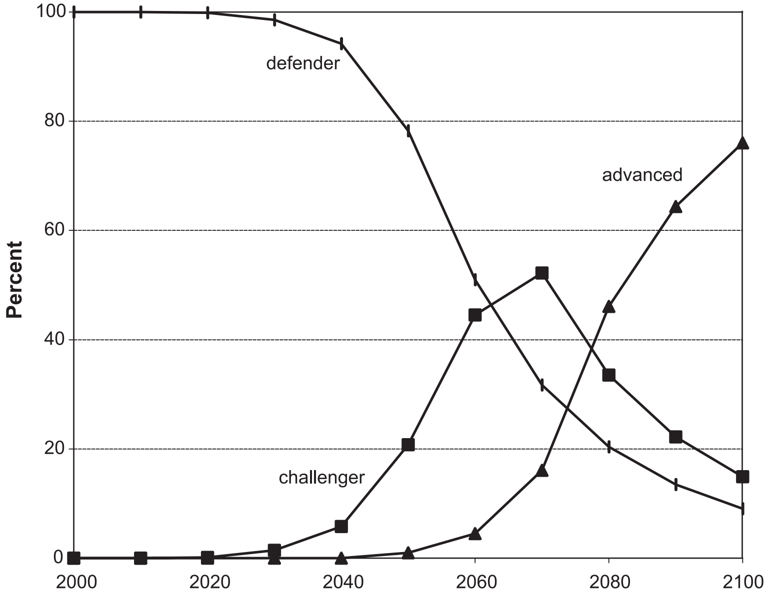

Fig. 3. Percentages of demand supplied by alternative technologies.

immediately in 2010. With a cumulative carbon constraint of 400 billion tons, there is enough slack in the system so that the challenger does not need to enter until 2020. Thereafter, it expands at a maximum rate until 2050. The fossil defender begins to decline after 2040. In 2050, the advanced challenger begins to enter at its maximum rate, and after 2070, the earlier challenger begins its decline.

Along with these introduction patterns, there is a distinct pattern of learning costs. To see how the average unit learning costs change with cumulative experience, see Fig. 4. There, results are reported for two alternative values of the accumulated initial learning experience parameter. When $acc_j = 1.0$, we obtain the upper experience curve. In this case, it is optimal to wait until 2020 before introducing the challenger. Alternatively, if $acc_j = 0.1$, this provides a more attractive initial point for the challenger. The same unit costs are attained with less experience. In turn, this creates an incentive for more rapid deployment of the challenger—and an earlier date at which costs begin to be lowered.

Each of the experience curves is determined by the three dynamic LBD parameters listed in Table 1. The vertical distance of the 2000 value is the initial learning cost coefficient, $inlc_j$. The horizontal distance of the 2000 value is the initial accumulated experience, acc_j. And the slope of the experience curves (on a log-log scale) is given by the learning exponent, lrn_j. The rate at which we progress down the experience curve is determined by the endogenous learning process. The less expensive the challenger, the more rapidly it is deployed.

To put things into perspective, it is useful to examine Fig. 5. This shows the total of the static plus the dynamic learning costs for the challenger. Both cost curves begin at the same point in 2000—at twice the level of the defender technology—but they diverge thereafter. Throughout the 21st century, there is no date at which the upper curve lies

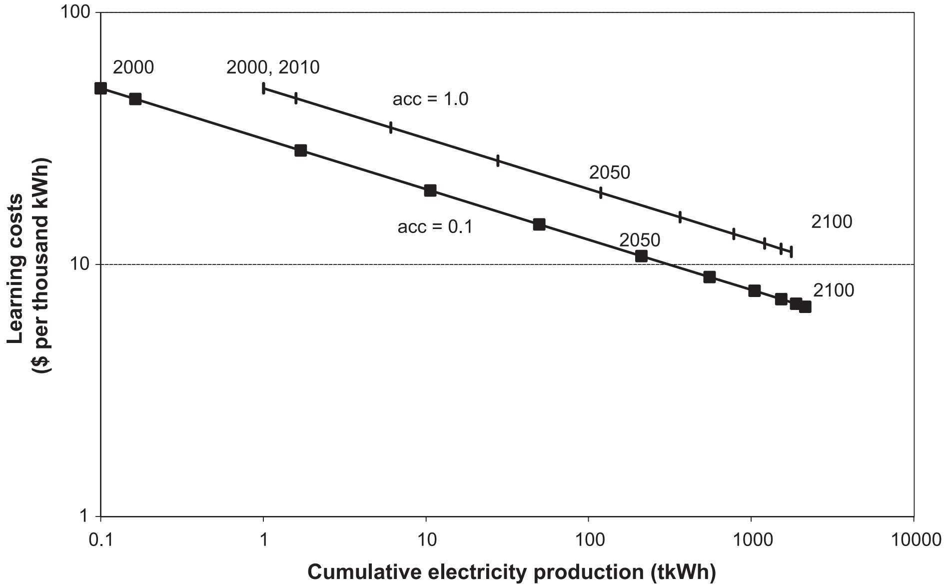

Fig. 4. Experience curves for challenger—alternative values of initial experience, acc.

below the costs of the defender ($40 per thousand kWh). Without a carbon constraint, there would be no rationale to introduce the challenger. With the lower curve, however, the challenger's costs lie below those of the defender from 2050 onward. Under these

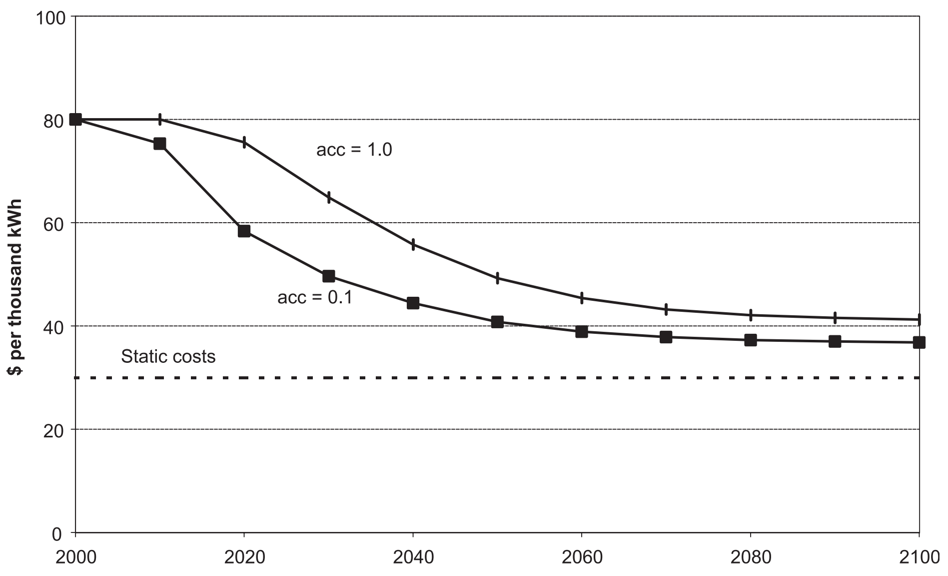

Fig. 5. Static + learning costs for challenger.

circumstances, the challenger is introduced at the maximum rate from the earliest date that it becomes available, and the 400 billion ton carbon constraint becomes inactive.

These projections should not be taken literally, but they do indicate that this type of LBD model has a tendency toward "bang-bang" behavior. That is, a technology may not be introduced immediately when it becomes available. When it is introduced, however, it tends to enter at a maximum growth rate, and eventually to be phased out at a maximum decline rate.

When $acc_j = 1.0$, the results of BARON are duplicated by two standard convex nonlinear programming algorithms: CONOPT3 and MINOS5. There is a coincidence between the local and the global optimum. How often does this occur? Not always. For example, when we take the same model but eliminate the carbon constraint, we obtain two different solutions. CONOPT3 generates the same global optimum as BARON, but MINOS5 generates a very different local optimum.

Without a carbon constraint, the global optimum is one in which the defender supplies all of the demands through 2040. From 2050 onward, the advanced low-cost challenger then expands at the maximum rate. The locally optimal solution is one in which the defender supplies the world's demands throughout the entire horizon. The other two technologies are both locked out. With a different starting point, MINOS5 produces still a different solution, but again one that is not a global optimum. In all the sensitivity analyses that we have conducted, CONOPT3 has duplicated the same globally optimal solution as BARON, but MINOS5 has produced a number of local optima.

Caveat: These experiments are not conclusive. To our knowledge, there is no theoretical reason for the superiority of one or another of these standard methods when the minimand is concave. Eventually, it should be possible for BARON or a similar approach to be extended to large-scale LBD models. Meanwhile, in order to check for local optima, the most practical course is to resort to heuristics. One possibility would be to apply several different nonlinear programming algorithms—and several different starting solutions with each of them.

6. An alternative approach—terminal conditions

Another possibility is to experiment with alternative terminal conditions. This is the approach that has been applied at a large scale in connection with the MERGE model. To see how this works, consider Fig. 6. This is based on the small-scale numerical model described in this paper, but the inlc parameter for the advanced technology has been increased to $20/MWh to provide a clearer example.

For the initial challenger, the cumulative experience through 2100 is shown on the vertical axis, Y(chl,2100). The cumulative experience for the advanced challenger is shown on the horizontal axis, Y(adv,2100). Both of these variables are expressed in trillion kilowatt-hours. The *feasible* combinations of these two variables are shown within the shaded polygon. The lower edge of this area is the 45° line determined by the cumulative carbon emissions constraint. The upper edge is implied by equalities in the supply–demand balances, constraints (1). Again this is a 45° line. The leftmost edge is governed by the lower bound constraint on Y(adv,2100), and the rightmost edge by the combined effect of the expansion and decline constraints.

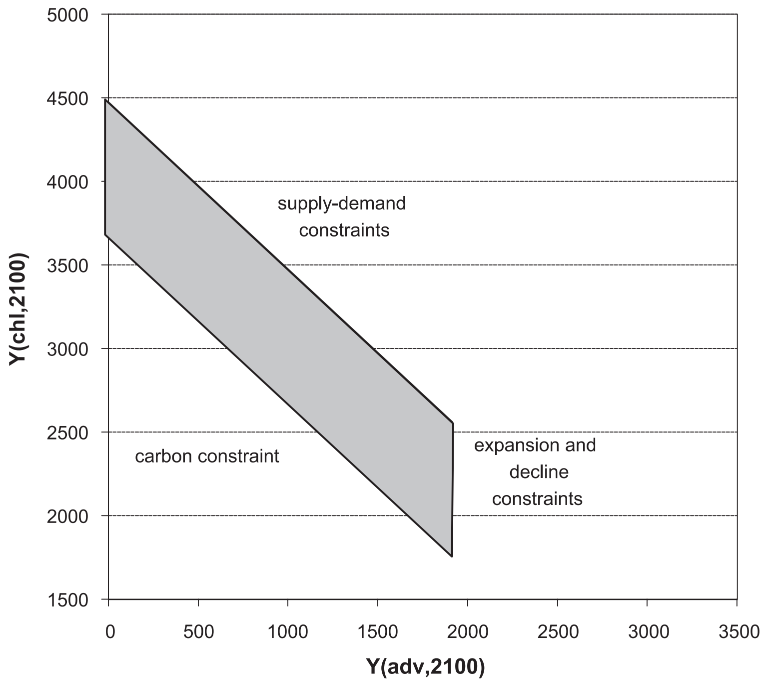

Fig. 6. Feasible combinations of the two cumulative experience variables.

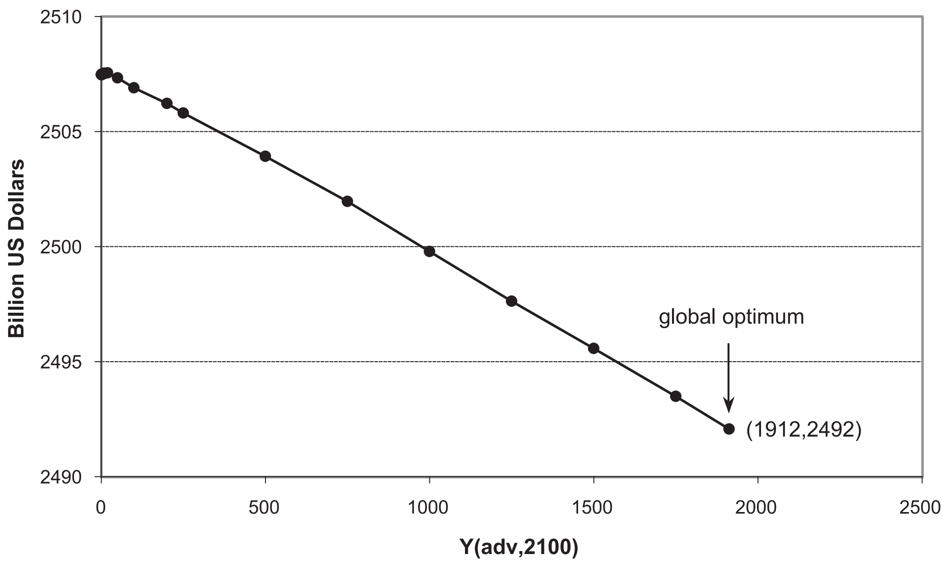

Fig. 7. Present value of costs (inlc(adv) increased to $20/MWh).

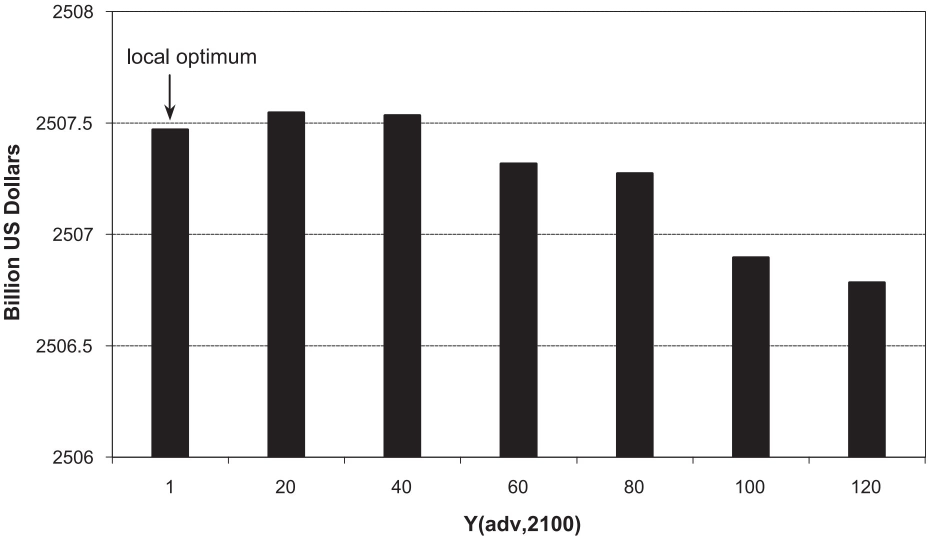

Fig. 8. Present value of costs—a closer look (inlc(adv) increased to $20/MWh).

Now turn to Fig. 7. This shows how the minimum present value of costs varies when we alter the terminal value of the cumulative experience with the advanced technology. It *looks* as though there is no local minimum. This appears to be a monotone decreasing function, and the global minimum occurs when the advanced technology is brought in at a maximum level. However, when we take a closer look at the left-hand portion of this diagram (the stacked column graph shown in Fig. 8), there is a second local minimum. This occurs at the lowest admissible value of *Y*(adv,2100). To avoid this local minimum, all that we need to do is to introduce an arbitrary lower bound on this decision variable. For example, with a lower bound of 20, we rule out the local solution at 1, and the nonlinear solver CONOPT3 proceeds directly to the global optimum at the maximum value of 1912 (again see Fig. 7).

A similar procedure has been applied to MERGE, and it seems to work well. Caveat: In MERGE, there is only one LBD technology for the electric sector and one for the nonelectric sector. With several LBD technologies, these arbitrary bounds would have to be selected with greater care. There would then be considerable value in developing an algorithm such as BARON—one which is guaranteed to find a global optimum. Until such a procedure is developed, it will be useful to employ the terminal conditions heuristic.

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Assessment of global warming mitigation options with integrated assessment model DNE21

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Abstract

We developed an integrated assessment model, DNE21, composed of three sub-models: an energy systems, a macro economic and a climate change model. DNE21 is an optimization model, and its energy supply system is formulated in bottom-up fashion with about 50 kinds of technologies. This paper first describes the model and then presents simulation results. The results indicate that the optimal mitigation strategy against global warming should be comprehensive implementation of the various options, among which energy saving in the end-use sectors is important throughout the 21st century, and CO_2 sequestration is after the middle of the century.

Keywords: Global warming; Carbon dioxide; CO_2 sequestration; Integrated assessment model; Energy system

1. Introduction

Strategies for global warming mitigation should be conceptualized broadly due to the scope and potential magnitude of the global climate change issue. In order to conduct transparent and consistent analyses of this complicated issue, it is highly desirable to use integrated assessment models, whose components are usually an energy systems model, a climate change model and a macro economic model. We have developed an integrated

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assessment model for evaluation of global warming mitigation options based on the DNE21 model (Dynamic New Earth 21; see e.g., Fujii and Yamaji, 1998) with updated model data.

DNE21, which we have developed as an integrated assessment model, is a full integration model which hard-links a macro economic model to a combined model of a 10-region world energy systems model and a climate change model through a nested CES production function which has four energy sectors, and is appropriate for detailed world-wide assessments of global warming mitigation options including economic impact assessments.

In the following sections the outline of the Integrated Assessment Model DNE21 is described together with several major assumed data, and simulation results are presented including discussions on key technological options for CO_2 emissions reduction.

2. Integrated assessment model DNE21

2.1. Framework of integrated assessment model DNE21

The Integrated Assessment Model DNE21 basically seeks the optimal trajectory of global energy systems development for the global warming mitigation by maximizing the cumulative discounted present value of the world macro economic consumption over the given time range. This model consists of three sub-models: an energy systems model, a macro economic model and a climate model (see Fig. 1).

The model covers the time range over the 21st century with the representative time points of 2000, 2010, 2020, 2030, 2040, 2050, 2075 and 2100, and is formulated as a multi-

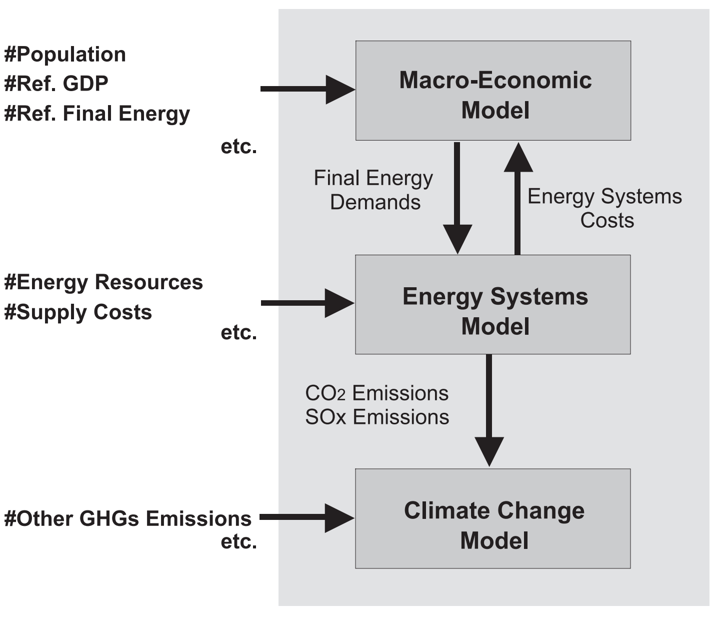

Fig. 1. An overview of the integrated assessment model DNE21.

region model, and the whole world is geopolitically divided into 10 regions: (1) North America, (2) Western Europe, (3) Japan, (4) Oceania, (5) Centrally Planned Economy Asia, (6) South and East Asia, (7) Middle East and Northern Africa, (8) Subsaharan and Southern Africa, (9) Latin America and (10) Former USSR and Eastern Europe.

2.2. Energy systems model

The energy systems model, which is the main component of DNE21, is a so-called process-engineering model, or a bottom-up type model. The assumed configuration of energy conversion processes in the model is shown in Fig. 2.

Primary energy sources of eight types are explicitly modeled: natural gas, oil, coal, biomass, hydro and geothermal, photovoltaics, wind and nuclear. The biomass energy is further disaggregated into 13 types of energy sources: energy crops, wood residues, cereal harvest residues, etc. Natural gas, oil, coal, methanol, hydrogen and biomass fired power plants, hydro and geothermal, wind, photovoltaics and nuclear power plants are taken into account for electricity generation, and IGCC with CO_2 recovery is also formulated in this model. In addition, various types of energy conversion technologies, such as coal gasification and methanol synthesis, etc., are explicitly modeled as technological options. As for CO_2 recovery, both of chemical absorption from flue gas of thermal power plants and physical absorption from outlet gas of fossil fuel gasification plants are explicitly modeled. In connection with CO_2 recovery, two major CO_2 sequestration measures, ocean sequestration and subterranean sequestration, are explicitly formulated. Subterranean CO_2 sequestration is further divided into three types: (1) sequestration in aquifers, (2) storage in depleted natural gas wells, and (3) injection into oil wells for EOR operation. All these sequestrations are important elements of the energy systems model in this study and their future practice is assessed for each region of the world. In addition, de-sulfurization processes are also explicitly handled in the model. This modeling is necessary for taking into account the cooling effect of SO_x emissions which accompanies CO_2 emissions from coal/oil burning. In total about 50 kinds of technologies of energy supply side are explicitly modeled.

The end-use sector of the model is disaggregated into the following four types of secondary energy carriers: (1) gaseous fuel, (2) liquid fuel, (3) solid fuel and (4) electricity. The liquid fuel demand is further decomposed into demands of three types of oil products: gasoline, light fuel oil and heavy fuel oil. Electricity demand is expressed by daily load duration curves having three kinds of time periods: peak period, intermediate period and off-peak period. The future energy demand in case of no climate policy is exogenously provided by energy type, region and year as the reference scenario.

The world 10 regions in this model are linked to each other by interregional trading of seven items: coal, crude oil, synthetic oil, methane, methanol, hydrogen and CO_2.

2.3. Climate model

DNE21 model has a simple climate change model as an integrated part. The climate model is based on MAGICC (Model for the Assessment of Greenhouse gas Induced Climate Change) which was developed by Wigley et al. (Wigley, 1991; Wigley and Raper,

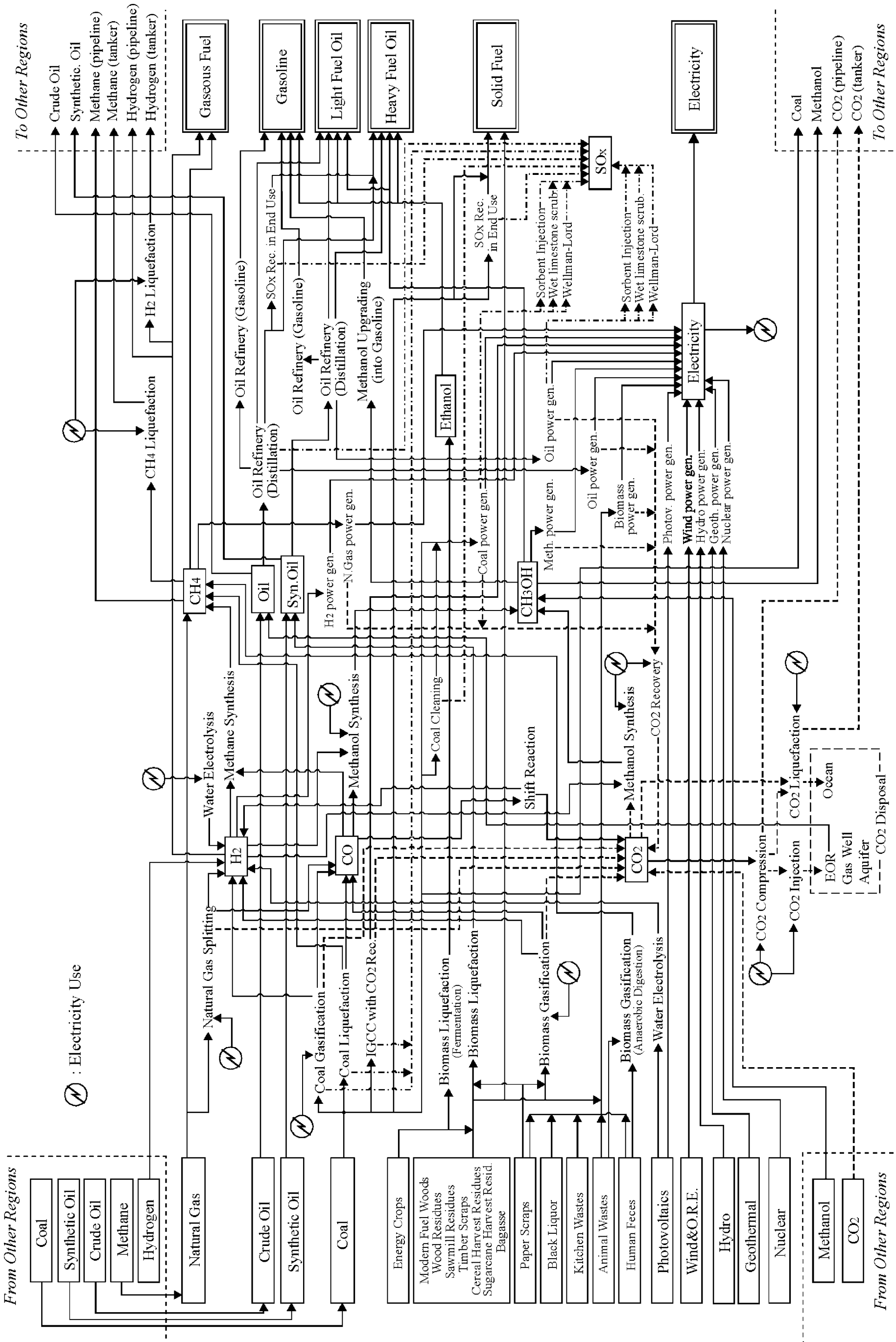

Fig. 2. Energy conversion processes in DNE21.

1992; Houghton et al., 1996). DNE21 takes into account various green house gases such as carbon dioxide, methane, nitrous oxide and halocarbons. In addition, cooling effects of sulfate aerosols are formulated in the model. The future time profiles of the atmospheric concentrations, the radiative forcings of various GHGs, the global mean temperature and the sea level change can be calculated with this model. Linking of the energy systems model and climate change model is conducted through linear approximation of the input–output relations of the climate change model, and described in Fujii and Yamaji (1998).

2.4. Macro-economic model

The formulations of the macro economic model in the Integrated Assessment Model DNE21 are shown in Eqs. (1)–(3), which are expressed by a production function of CES (constant elasticity of substitution) type. Although the formulations are similar to those in ETA-MACRO (Manne and Richels, 1992), DNE21 has four energy sectors in end-use while ETA-MACRO has only two.

$$Y = \left\{ a(K^{\alpha}L^{1-\alpha})^{\rho} + \left(\sum_{i=1}^{4} b_i \mathrm{ED}_i^{\mu} \right)^{\frac{\rho}{\mu}} \right\}^{\frac{1}{\rho}} \tag{1}$$

$$\frac{\mathrm{d}K}{\mathrm{d}t} = \mathrm{IV} - \zeta \times K \tag{2}$$

$$Y = \mathrm{EC} + \mathrm{CS} + \mathrm{IV} \tag{3}$$

where

Y is GDP, K is capital stock, L is population, ED_i is ith final energy demand ($i=1$: Gaseous fuel, 2: Liquid, 3: Solid, 4: Electricity), IV is capital investment, ζ is annual depreciation rate (=5%/year), CS is consumption, EC is energy systems cost, ρ, μ are exogenous parameters for elasticity a, α, b_i are determined using the reference scenario of Y, K, ED_i and the shadow prices of K and ED_i.

Partial derivative of Y with respect to K should be equal to SP_K of the shadow price of K

$$\frac{\partial Y}{\partial K} = Y^{1-\rho}\alpha\, a\, L^{(1-\alpha)\rho}K^{\rho\alpha-1} = \mathrm{SP}_K \tag{4}$$

Partial derivative of Y with respect to ED_i (ith kind of energy) should be equal to $\mathrm{SP}_{\mathrm{ED}i}$ of the shadow price of ED_i.

$$\frac{\partial Y}{\partial \mathrm{ED}_i} = Y^{1-\rho} \left(\sum_{n=1}^{4} b_n \mathrm{ED}_n^{\mu} \right)^{\frac{\rho}{\mu}-1} b_i \mathrm{ED}_i^{\mu-1} = \mathrm{SP}_{\mathrm{ED}_i} \qquad (i = 1,\cdots,4) \tag{5}$$

The specific values of shadow prices SP_K and $\mathrm{SP}_{\mathrm{ED}i}$ are obtained through the optimization of the reference case. We have six parameters a, α, b_i ($i=1,\ldots,4$) to be determined, and Eqs. (1), (4) and (5). Thus, a, α, b_i are uniquely determined.

Future scenarios of population, reference GDP and reference final energy demands are derived from IPCC SRES (Nakicenovic et al., 2000; see Section 3.3).

2.5. Objective function

The objective function in DNE21 is expressed by Eq. (6), where the macro economic consumptions between the two representative time points are linearly interpolated.

$$J = \sum_{n=1}^{N} \sum_{t=0}^{T-1} \left\{ \int_{\mathrm{year}_t}^{\mathrm{year}_{t+1}} \frac{\mathrm{CS}_{n,t} \times (\mathrm{year}_{t+1} - \tau) + \mathrm{CS}_{n,t+1} \times (\tau - \mathrm{year}_t)}{\mathrm{year}_{t+1} - \mathrm{year}_t} e^{-\gamma(\tau - 2000)} \mathrm{d}\tau \right\} \quad (6)$$

where

γ	Discount rate (=5%/year)
$\mathrm{CS}_{n,t}$	Consumption of region n in period t
Year_t	The year of period t ($\mathrm{year}_0 = 2000$)

3. Model assumptions

3.1. Assumed primary energy potentials and costs

Assumed fossil fuel resources and production costs are derived from the estimations by Rogner (1997). The amounts of the world conventional and unconventional oil resources are about 300 and 2340 Gtoe, respectively. Those of world conventional and unconventional natural gas resources are about 390 and 19,590 Gtoe, respectively. The unconventional gas includes methane hydrate resource. However, none of our model simulation results call for methane hydrates before 2100 in this study. Fig. 3 shows the fossil fuel production costs for the entire world.

Table 1 shows the assumed unit supply costs and world annual supply potential of renewable energy (e.g., Nakicenovic, 1993). The supply costs of hydro and geothermal, wind power and photovoltaics are expressed as nonlinear functions of their annual production amounts for each of the regions. The biomass energy potentials of 13 types are estimated with a spreadsheet model which is a simplified form of GLUE Model (Global Land Use and Energy Model; Yamamoto and Yamaji, 1997).

3.2. Assumptions on technologies

3.2.1. Electricity generation

The assumed parameters on electricity generation such as unit plant costs, annual expense rates, usage rates and conversion efficiencies are shown in Table 2 (e.g., OECD/IEA, 1998; Ishitani and Johansson, 1996). The upper limit is placed on the nuclear power capacity of each region, paying due consideration to the public acceptance issue. The upper limit of the world total is 920 GW in 2050 and 1450 GW in 2100.

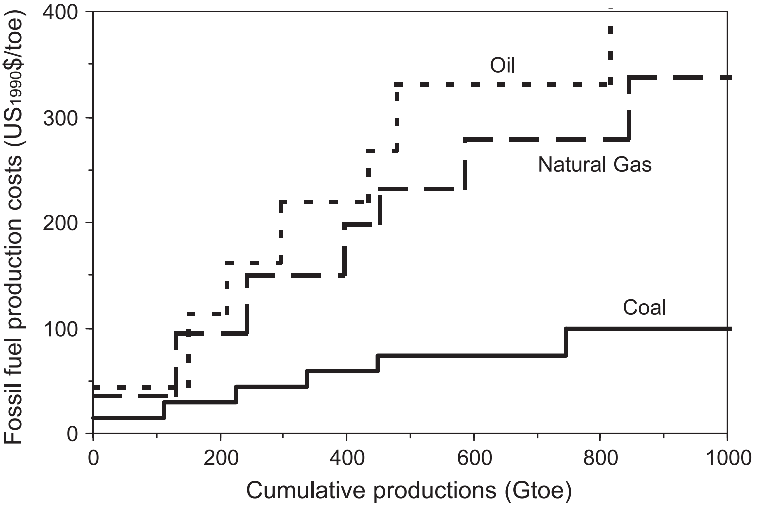

Fig. 3. Fossil fuel production costs.

3.2.2. CO_2 recovery and sequestration

CO_2 recovery parameters, i.e., unit costs of CO_2 recovery plants and required energy consumption are assumed as in Table 3 (e.g., Steinberg and Cheng, 1984), and costs and capacities of CO_2 sequestration are assumed as in Table 4 (e.g., Ishitani et al., 1993).

3.3. Population, GDP and final energy demands

Future scenarios of population, reference GDP and reference final energy demands are derived from B2 Marker Scenario of IPCC SRES (Nakicenovic et al., 2000; UN, 1998). We made, however, some modifications on the original scenario data so as to keep consistency with the historical data (IEA, 2001a,b; World Bank, 2001) and with DNE21

Table 1
Assumed unit supply costs and world annual supply potential of renewable energy

	Unit supply costs	World annual production potential
Hydro and geothermal	10–180 (US_{1990}\$/MWh)[a]	15000 (TWh/year)
Wind power	70–340 (US_{1990}\$/MWh)[a b]	7900 (TWh/year)
Photovoltaics	180–361 (US_{1990}\$/MWh)[cd]	286,400 (TWh/year)
Biomass (plantation)	120–1200 (US_{1990}\$/toe)[e]	1300–4400 (Mtoe/year)[f]
Biomass (residues)	– 550–390 (US_{1990}\$/toe)[e]	2100–5800 (Mtoe/year)[f]

[a] The range depending on the amount of annual supply.
[b] The unit supply cost is assumed to reduce by 1%/year until 2050.
[c] The range depending on the regions.
[d] The unit supply cost is assumed to reduce by 2%/year until 2050.
[e] The range depending on the amount of annual supply and kinds of biomass.
[f] The range depending on the time points.

Table 2
Assumed parameters for electric power plants

	Plant costs (US_{1990}\$/kW)	Annual expense rate (%)	Usage rate (%)	Conversion efficiency (LHV %)[a]
Coal fueled power	1300–1950[b]	17	85	31.7–50.0
Oil fueled power	850–1275[b]	17	85	34.3–52.0
N. gas fueled power	750–1125[b]	17	85	36.7–55.0
IGCC with CO_2 rec. unit	2050	17	85	37.3–41.5
Biomass fueled power	1500	17	85	30.0–40.0
Methanol fueled power	1450	17	85	44.9–55.0
Hydrogen fueled power	1100	17	85	51.4–60.0
Nuclear power	2000–3000[b]	19	80	–
Electricity storage	1000–1500[b]	13	85	70.0–75.0

[a] Conversion efficiencies are assumed to vary depending on the region in 2000 and to converge gradually at the upper values by 2100.

[b] Plant costs are assumed to vary depending on the region in 2000 and to converge gradually at the lower values toward 2100.

region division. Fig. 4 shows the procedure to generate assumed data of the population, reference GDP and reference final energy demands of four kinds of fuels, where the growth rates are utilized rather than the absolute values of the SRES scenario data. The assumed reference GDP by region and reference final energy demands by fuel are shown in Figs. 5 and 6, respectively. On this assumption, the world population reaches 10.4 billion in 2100, the gross world product reaches 217 trillion US_{1990}\$/year and the world final energy demands 19.7 Gtoe/year.

4. Model simulation results

4.1. Simulation cases

Three simulation cases—no climate policy case, a CO_2 concentration stabilization case and a carbon tax case—as shown in Table 5, are studied and their simulation results are presented to help assess global warming mitigation options. Maximum limits are assumed on sulfur emissions based on the sulfur emission scenario of SRES B2 Marker (Nakicenovic et al., 2000) for all the three simulation cases.

A discount rate of 5% was adopted throughout the study.

Table 3
Assumptions for CO_2 recoveries

CO_2 recovery options	Plant cost (US_{1990}\$/(tC/day))	Energy requirements (MWh/tC)[a]
Chemical Absorption from flue gas	56,500	2.130–1.368
Physical Absorption from gasification plant	14,500	0.902–0.496

[a] Energy requirements are assumed to reduce gradually and stay at the lower values by 2050.

Table 4
Assumptions for CO_2 sequestrations

CO_2 sequestration options	CO_2 sequestration costs[a] (US_{1990}\$/tC)	CO_2 sequestration capacity (GtC)
Oil Well	87–125[b]	9.2
Depleted Gas Well	46	8.2[c]
Aquifer	10–150	499.0
Ocean	25[d]	–

[a] Costs of recovery and transportation excluded. The value depending on the amount of cumulative sequestration in a region.
[b] The proceeds from recovered oil excluded.
[c] The initial value in 2000, and the capacity increases a natural gas consumption.
[d] The costs of CO_2 liquefaction and the sequestration facilities on ocean.

4.2. Simulation results

4.2.1. Overview of carbon mitigation options

First, resulting world carbon emission trajectories are shown for the three simulation cases in Fig. 7. The emissions from fossil fuel combustion in 2100 are approximately 24 GtC/year in the Reference Case, 20 GtC/year in the Tax + 10\$/tC Case and 4 GtC/year in the 550 ppmv Case. The atmospheric CO_2 concentration in 2100 is projected to be 760 ppmv in the Reference Case, and 700 ppmv in the Tax + 10\$/tC Case. Effects of the carbon taxation of the latter case cause relatively small reductions in carbon emissions. The shadow price of carbon reductions in the 550 ppmv Case is about 8 US_{2000}\$/tC in 2010 and about 720 US_{2000}\$/tC in 2100.

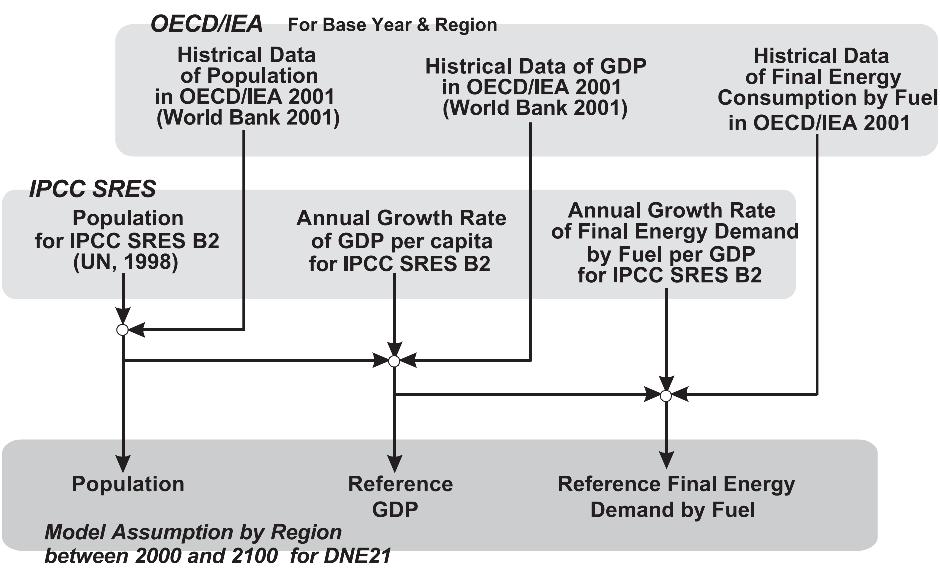

Fig. 4. Procedure to generate assumed data of population, reference GDP and reference final energy demand.

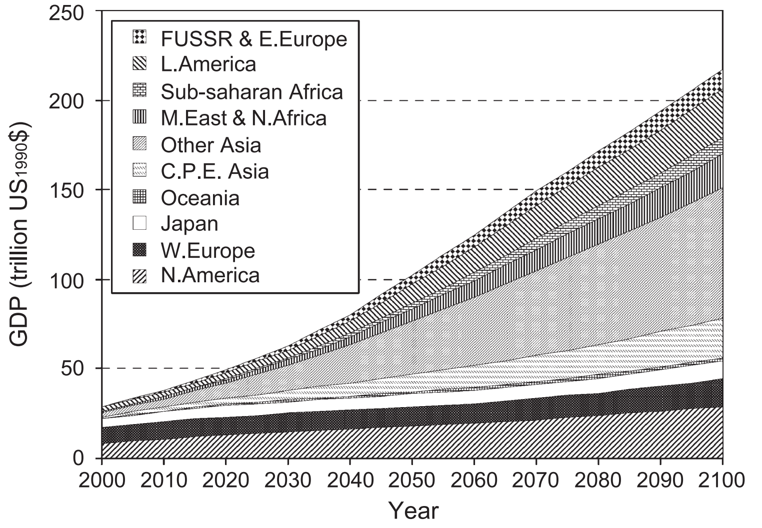

Fig. 5. Assumed reference GDP.

Table 6 shows the key indicators and their effects on carbon emissions and reduction using what is now called the Kaya identity (Kaya, 1989). The determinants of net carbon emissions growth from the energy systems are broken down first into four components, the growth of population, the growth of GDP per capita, the growth of energy intensity and the growth of carbon intensity, and then the growth of energy intensity and the growth of carbon intensity are each further divided into two sub-categories. While the growth rate of net carbon emissions is 1.61%/year for 2000–2020, 1.53%/year for 2020–2050 and

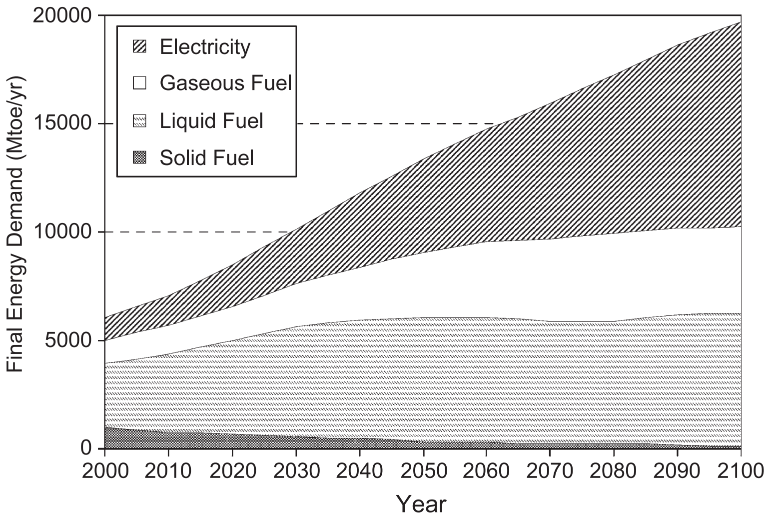

Fig. 6. Assumed reference final energy demands.

Table 5
Model simulation cases

(1) Reference Case	No climate policy
(2) 550 ppmv Case	Atmospheric CO_2 concentration is stabilized at 550 ppmv by 2100
(3) Tax + 10$/tC Case	Carbon tax increases by 10 $US_{2000}$$/tC per decade, starting with 10$/tC in 2010

1.03%/year for 2050–2100 in Reference Case (no climate policy), that of 550ppmv Case is 1.44%/year for 2000–2020, 0.90%/year for 2020–2050 and −1.99%/year for 2050–2100, indicating that larger carbon reductions are required for the later periods of time to achieve stabilization at 550 ppmv and that the required reductions are quite large for the second half of the century, as shown in Fig. 7. As shown in Fig. 7, the growth rate of net carbon emissions in the Tax + 10$/tC Case is close to that of Reference Case.

The growth rate of GDP per capita is clearly smaller in the 550 ppmv Case than in the Reference Case and the GDP loss in the 550 ppmv Case is about 5% in 2100 as compared with the Reference Case. However, differences in the growth rate of GDP per capita are very small among the three cases and the values of growth rates are all positive for all the time periods, indicating that the world can achieve 550 ppmv stabilization while continuing GDP growth with an acceptance of a small economic loss as long as the cost of mitigation options are optimized.

In the Reference Case the major driving forces to increase the net carbon emissions are the growth of GDP per capita throughout the century and the population growth up until 2020. After 2020 the population growth is relatively small as compared with the net emissions growth. In the meantime the energy intensity, of which to be improved is the final energy consumption per GDP, is to be improved, contributing to the reduction of net carbon emissions for all the time periods but the carbon intensity does not improve. It is quite natural, since there exists no economic incentive for carbon intensity improvement in the case of no climate policy.

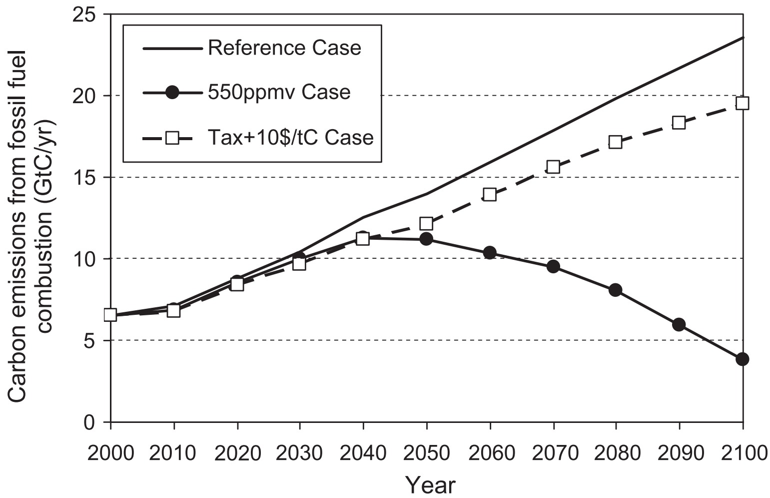

Fig. 7. World carbon emissions from fossil fuel combustion.

Table 6
Growth rate of net carbon emissions decomposed into growth rates of key indicators (unit: %/year)

	2000–2020	2020–2050	2050–2100
[1] Population growth			
#Reference Case, 550 ppmv Case, Tax + 10$/tC Case	1.22	0.48	0.33
[2] Growth of GDP per capita			
#Reference Case	1.52	1.90	1.18
550 ppmv Case	1.51	1.87	1.10
Tax + 10$/tC Case	1.50	1.89	1.18
[3] Growth of energy intensity (Primary energy consumption per GDP)			
Reference Case	– 1.12	– 0.79	– 0.57
550 ppmv Case	– 1.22	– 0.96	– 0.63
Tax + 10$/tC Case	– 1.26	– 0.80	– 0.60
[3-1] Growth of final energy consumption per GDP			
#Reference Case	– 0.98	– 0.89	– 0.72
550 ppmv Case	– 1.10	– 1.02	– 1.13
Tax + 10$/tC Case	– 1.14	– 0.90	– 0.76
[3-2] Growth of primary energy consumption per final energy consumption			
Reference Case	– 0.14	0.10	0.16
550 ppmv Case	– 0.12	0.07	0.51
Tax + 10$/tC Case	– 0.12	0.10	0.16
[4] Growth of carbon intensity (Net carbon emissions per primary energy consumption)			
Reference Case	0.00	– 0.05	0.08
550 ppmv Case	– 0.05	– 0.47	– 2.77
Tax + 10$/tC Case	– 0.08	– 0.33	0.03
[4-1] Growth of gross carbon emissions per primary energy			
Reference Case	0.00	0.02	0.04
550 ppmv Case	– 0.05	– 0.41	– 0.68
Tax + 10$/tC Case	– 0.08	– 0.25	– 0.01
[4-2] Growth of net carbon emissions per gross emissions			
Reference Case	0.00	– 0.07	0.04
550 ppmv Case	0.00	– 0.07	– 2.10
Tax + 10$/tC Case	0.00	– 0.07	0.04
Growth of net carbon emissions from fossil fuel combustion			
Reference Case	1.61	1.53	1.03
550 ppmv Case	1.44	0.90	– 1.99
Tax + 10$/tC Case	1.37	1.23	0.93

(1) # designates the model assumptions.
(2) The sum of [1], [2], [3] and [4] corresponds to the "Growth of net carbon emissions" by so-called Kaya identity (Kaya, 1989): $\partial/\partial t(\ln NE_t) = \partial/\partial t(\ln(NE_t/PE_t)) + \partial/\partial t(\ln(PE_t/Q_t)) + \partial/\partial t(\ln(Q_t/P_t)) + \partial/\partial t(\ln P_t)$ where NE is net carbon emissions, PE is primary energy consumption, Q is GDP, P is population.

To achieve stabilization at 550 ppmv, the energy intensity must be improved more than in Reference Case and this is achieved principally in the end-use sectors; the annual improvement rate in final energy consumption per GDP must be larger by 0.1 percentage point before 2050 and by 0.4 percentage point after 2050 than in the Reference Case, which indicates the importance of energy saving in end-use sectors for carbon emissions reduction. However, the end-use sectors are modeled in a top-down manner in DNE21 and therefore explicit technological options in end-use sectors can not be discussed here. Surprisingly, the growth rate of 0.51%/year of primary energy consumption per final energy consumption for 2050–2100 is substantially larger in the 550 ppmv Case than the 0.16%/year observed in the Reference Case. This increase in primary energy consumption is due to the implementation of CO_2 sequestration after 2050 when the growth rate of net carbon emissions per gross emissions in item [4-2] in Table 6 is a large negative number, − 2.1%/year, meaning the great importance of CO_2 sequestration technologies despite the increase in primary energy consumption which is required for CO_2 recovery, transportation, and injection of CO_2 into the ocean or underground. CO_2 sequestration will be studied further because of its importance in the next section. It is also observed that the growth rate of gross carbon emissions per unit of primary energy consumption is about 0.4 percentage point smaller for 2020–2050 and about 0.6 percentage point smaller for 2050–2100 in the 550 ppmv Case than in the Reference Case. These relations are attained by fuel switching, that is, switching from fossil fuels to non-fossil fuels such as renewables and nuclear energy, and also by switching among fossil fuels from carbon intensive fuels to less carbon intensive fuels.

Fig. 8 shows world primary energy production shares by fuel type in the three cases. The shares of biomass energy and wind power will increase in all the cases and contribute to decrease gross carbon emissions per unit of primary energy consumption. The share of primary biomass energy in 2100 are projected to be 10.3%, 18.3% and 13.6% in Reference Case, 550 ppmv Case and Tax + 10\$/tC Case, respectively, and the share of primary wind power in 2100 will be 2.4%, 4.1% and 2.9% in Reference Case, 550 ppmv Case and Tax + 10\$/tC Case, respectively. Photovoltaics will grow after the middle of this century in 550 ppmv Case; in 2100 PVs will account for about 4.9% of total primary energy.

Item [3-2] in Table 6 shows that the effects of energy saving or energy efficiency improvement in primary energy consumption is small although the energy supply side plays an important role in reducing carbon emissions. This is partly because fuel switching such as from coal to biomass accompanies the lowering in energy efficiency.

4.2.2. Contribution of technological options to carbon emission reduction in 550 ppmv case

Table 6 represented the contributions of various indicators to carbon emissions by annual change rates for the three cases. We now look at how large each technological option contributes to carbon emission reductions in the 550 ppmv Case relative to in Reference Case. Here, the net carbon emissions are expressed by Eq. (7). E_n/E_g reflects CO_2 sequestration, E_g/PE_F is the gross CO_2 emission per unit of primary fossil fuel, and PE_F/PE is the fossil fuel ratio in total primary energy consumption.

$$E_n = \frac{E_n}{E_g} \times \frac{E_g}{PE_F} \times \frac{PE_F}{PE} \times PE \tag{7}$$

where E_n is net carbon emission, E_g is gross carbon emission, PE_F is primary fossil fuel consumption, PE is total primary energy consumption

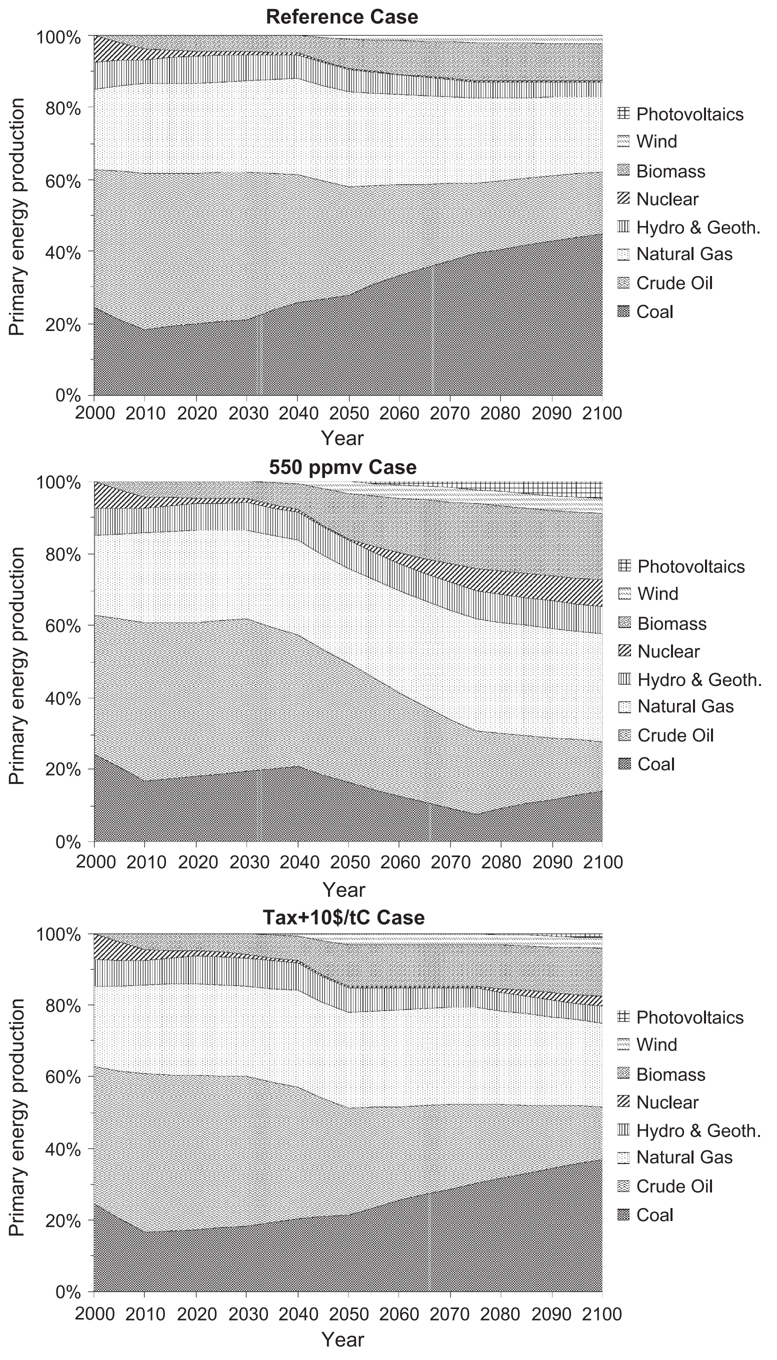

Fig. 8. World primary energy production shares by fuel type in the Reference Case, the 550 ppmv Case and the Tax + 10$/tC Case.

In this paper, we define the contributions of technological options to carbon emission reductions for the 550 ppmv stabilization using Eq. (8); the first term represents CO_2 sequestration contribution, the second term is the contribution of fuel switching among fossil fuels, the third term is the contribution of fuel switching to non-fossil fuels, and the fourth term is the contribution of energy savings in both the energy supply side and the end-use sectors. In addition, the contribution of the shift to non-fossil fuels is decomposed into that of each of the non-fossil fuels, i.e., nuclear power, wind power, etc., corresponding to the proportion of the total reduction from the Reference Case.

$$\begin{aligned} E_{\mathrm{n}}^{\mathrm{REF}} - E_{\mathrm{n}}^{\mathrm{CON}} &= (E_{\mathrm{g}}^{\mathrm{REF}} - D^{\mathrm{REF}}) - (E_{\mathrm{g}}^{\mathrm{CON}} - D^{\mathrm{CON}}) \\ &= (D^{\mathrm{CON}} - D^{\mathrm{REF}}) + \mathrm{PE}^{\mathrm{CON}} \left(\frac{E_{\mathrm{g}}^{\mathrm{REF}}}{\mathrm{PE}^{\mathrm{REF}}} - \frac{E_{\mathrm{g}}^{\mathrm{CON}}}{\mathrm{PE}^{\mathrm{CON}}} \right) \\ &\quad + \frac{E_{\mathrm{g}}^{\mathrm{REF}}}{\mathrm{PE}^{\mathrm{REF}}} (\mathrm{PE}^{\mathrm{REF}} - \mathrm{PE}^{\mathrm{CON}}) \\ &= (D^{\mathrm{CON}} - D^{\mathrm{REF}}) + \mathrm{PE}^{\mathrm{CON}} \frac{\mathrm{PE}_{\mathrm{F}}^{\mathrm{CON}}}{\mathrm{PE}^{\mathrm{CON}}} \left(\frac{E_{\mathrm{g}}^{\mathrm{REF}}}{\mathrm{PE}_{\mathrm{F}}^{\mathrm{REF}}} - \frac{E_{\mathrm{g}}^{\mathrm{CON}}}{\mathrm{PE}_{\mathrm{F}}^{\mathrm{CON}}} \right) \\ &\quad + \mathrm{PE}^{\mathrm{CON}} \frac{E_{\mathrm{g}}^{\mathrm{REF}}}{\mathrm{PE}_{\mathrm{F}}^{\mathrm{REF}}} \left(\frac{\mathrm{PE}_{\mathrm{F}}^{\mathrm{REF}}}{\mathrm{PE}^{\mathrm{REF}}} - \frac{\mathrm{PE}_{\mathrm{F}}^{\mathrm{CON}}}{\mathrm{PE}^{\mathrm{CON}}} \right) + \frac{E_{\mathrm{g}}^{\mathrm{REF}}}{\mathrm{PE}^{\mathrm{REF}}} (\mathrm{PE}^{\mathrm{REF}} - \mathrm{PE}^{\mathrm{CON}}) \end{aligned} \tag{8}$$

where D represents the amount of CO_2 sequestration, REF designates Reference Case and CON designates 550 ppmv Case

Fig. 9 shows the contributions of the technological options to the carbon emission reduction in the 550 ppmv Case based on the definition of Eq. (8). The carbon emission reduction in 2050 is 2.8 GtC relative to the emission in the Reference Case; the contribution of energy saving is about 39% of total carbon reductions, that of biomass is about 25%, that of fuel switching among fossil fuels is about 17%, and that of wind power is about 14%. The carbon emission reduction in 2100 is 19.8 GtC relative to the Reference Case; the contribution of CO_2 sequestration is about 42%, those of energy saving, fuel switching among fossil fuels, nuclear power and biomass are about 17%, about 10%, about 10% and about 9%, respectively. It is notable that the CO_2 sequestration requires additional energy consumption for CO_2 recovery, transportation and sequestration processes, which undermines the "Energy Saving" effect (or causes negative effects in "Energy Saving") as shown in the interpretation of Table 6. Another key point is that Fig. 9 represents the effects as the difference from the Reference Case and thus the effect of energy saving in end-use sectors, for example, is expressed as the additional effect to that of the Reference Case; the energy saving effect already included in the Reference Case, which is the largest among the emission reduction effects of the key indicators as shown in Table 6, is not explicitly expressed in the figure. The same is true of all the other options such as wind power, biomass energy, etc.

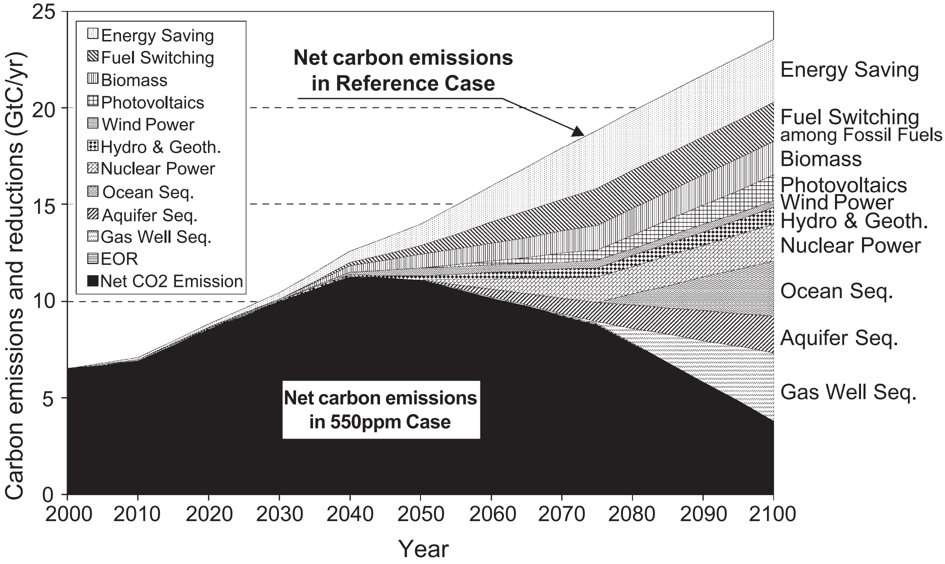

Fig. 9. Carbon emission reduction by technological options in the 550 ppmv Case.

4.2.3. Key technology for carbon mitigation-CO_2 sequestration

As seen in the previous section, CO_2 sequestration is considered to be one of the most important technologies for carbon emission reductions. However, the potential for subterranean CO_2 sequestrations is strongly dependent on regional geological conditions. The cumulative CO_2 sequestration levels for 100 years between 2000 and 2100 in the 550 ppmv Case are shown by region in Fig. 10. The cumulative amount of sequestration is 43.5 GtC in "Other Asia" where the main contributor is ocean injection while a

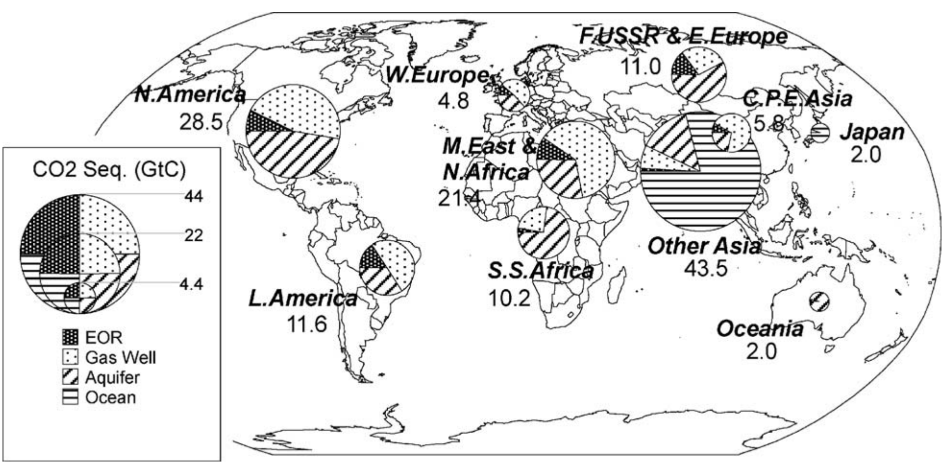

Fig. 10. Cumulative CO_2 sequestrations between 2000 and 2100 in the 550 ppmv Case.

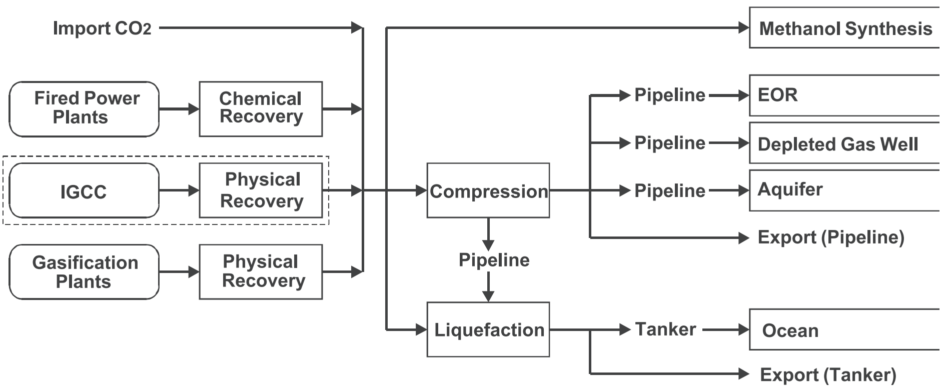

Fig. 11. Assumed CO_2 recovery and sequestration processes in DNE21.

considerable amount of sequestration is implemented in "N. America", where the main contributors are aquifer and gas-well injection. The large amount of ocean injection in "Other Asia" is principally due to the small amount of subterranean CO_2 sequestration capacity available as compared with rapidly growing energy consumption in this area.

In terms of CO_2 recovering technologies, 4.1, 3.1 and 1.5 GtC/year are captured by chemical recovery from flue gas, physical recovery in IGCCs, and physical recovery in gasification plants, respectively, in 2100. The CO_2-removed gas in gasification plants is used to make hydrogen fuel to be used in end-use applications (Fig. 11).

Sensitivity analyses on CO_2 sequestration technologies were made where the costs of component technologies of sequestration are varied by ± 50%, and the results are shown in Table 7. The table shows that the amount of CO_2 sequestration and CO_2 shadow price are relatively robust against the changes in technology costs. These results also support the importance of CO_2 sequestration technologies because the large amount of sequestration is relatively unchanged by the technology cost assumption within the range considered here.

Table 7
Sensitivity analyses on costs of component technologies of sequestration

Cost change	Cumulative CO_2 sequestration between 2000 and 2100 (in base assumption = 100)		CO_2 shadow price in 2100 (in base assumption = 100)	
	− 50%	+ 50%	− 50%	+ 50%
All types of recovery at the same times	114	82	85	114
Chemical recovery only	111	97	86	106
Physical recovery only	101	97	98	103
IGCC with CO_2 rec. only	111	91	100	101
CO_2 transportation[a]	112	87	96	104
All types of injection at the same time	104	94	97	103
Gas well injection only	102	97	99	102
Aquifer injection only	103	97	97	103
Ocean injection only	100	100	100	100

[a] Both of tanker and pipeline costs changed at the same time.

CO_2 injection costs are particularly uninfluential on both the cumulative amount of CO_2 sequestrations between 2000 and 2100 and the shadow price of carbon in 2100. As compared with CO_2 injection costs, the CO_2 recovery costs, especially the chemical recovery from flue gas in fossil fuel power plants, are relatively influential on the amount of cumulative sequestration.

The above results suggest the importance of R and D efforts for CO_2 recovery technologies and recovery technologies of lower costs and higher efficiencies would have great value.

Public acceptance of CO_2 sequestrations will be one of the most crucial issues for actual CO_2 sequestration operations and research activities on safety issues are also of great importance.

5. Concluding remarks

We developed an optimization type integrated assessment model, which is composed of an energy systems model, a macro economic model and a climate change model. These three sub-models are hard-linked to each other. The simulation results with this model indicate that both of the 550 ppmv Stabilization Case and Carbon Tax Case of +10$/tC per decade can be achieved without severe economic losses. The optimum carbon emissions strategy is a combination of acceptance of a slight lowering in GDP growth, energy saving in end-use sectors, fuel switching and CO_2 sequestration. Continuous developments of better technologies for energy saving are required all through the 21st century. CO_2 sequestration technologies are one of the most important technologies after the middle of this century for 550 ppmv stabilization.

The cumulative amount of CO_2 sequestration is 43.5 GtC in "Other Asia" by the end of the century and its main contributor is ocean sequestration. A considerable amount of sequestration is also projected in "N. America" where the main contributors are aquifer and gas-well sequestration of CO_2.

Sensitivity analyses on CO_2 sequestration costs show the effect of CO_2 sequestration technologies on carbon emissions reduction relatively robust over a broad range of assumed costs. CO_2 injection costs have little influence on the amount of cumulative CO_2 sequestration and on the shadow price of carbon. As compared with the CO_2 injection costs, CO_2 recovery costs, especially chemical recovery from flue gas in fossil fuel power plants, are relatively influential on the amount of sequestration and the shadow price of carbon. R&D efforts for CO_2 recovery technologies of low cost and high efficiency could be very important. In addition, research activities on the safety and reliability of sequestration technologies are welcomed since the public acceptance is becoming an issue of great importance in the consideration of large scale technologies.

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Response from a MARKAL technology model to the EMF scenario assumptions

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Abstract

This paper describes the modelling effort and analysis undertaken at ECN Policy Studies in the EMF-19 framework by using the Western European MARKAL model. The model structure and the advanced economic feed back formulation used is briefly described. Scenarios introducing carbon emissions reduction targets (by concentration level or by carbon taxes) lead to changes in energy mix, in technology deployment and in electricity production compared to a reference case. The impact and importance of carbon capture and storage as it appears as part of the solution to achieve the emission targets is analysed.

JEL classification: C610—Optimization Techniques; Programming Models; Dynamic Analysis

Keywords: MARKAL; Climate policy; Technology energy modeling; Energy system analysis

1. Introduction

Energy system models have acquired over time the capability to analyse environmental issues besides technological changes. Especially technology-rich models can provide interesting insights on future developments and deployments in the energy sector when the system is subjected to additional (external) constraints. Over time, especially after the Rio and Kyoto conferences, these constraints concern environmental aspects of the economic system, or the energy system in particular. Since then, several persons and teams at ECN Policy Studies have been working on the environmental impacts and consequences of climate policies on energy systems. To analyse these effects, long-term models are

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developed and used. Results of the recent studies can be found in Ybema and Kram (1997), Lako and Ybema (1997), Lako et al. (1998), Lako and Seebregts (1998), Seebregts et al. (2000, 2001), Gielen et al. (2000), Jansen et al. (2001) and Sijm et al. (2002).

2. Model version used

2.1. MARKAL

The model used is a MARKAL model, a bottom-up-technology-based linear optimisation model. MARKAL, in its standard form, is a linear programming optimisation model that identifies the least-cost combinations of technological processes and improvement options that satisfy a specified level of demand for goods and services under certain policy constraints, notably the achievement of certain specified GHG reduction objectives, in a way that the overall system costs are minimised over all time periods simultaneously. This is done for a part of the economy, whereby certain parameters have to be provided from outside the model.

The model comprises the whole energy chain, from supply resources (by import, domestic extraction, stock changes and export) through conversion and transformation (refineries, power plants, heat plants, ...), distribution to end use (by processes, end users, ...) (e.g., see Seebregts et al., 2001 for a concise recent overview). This classic energy system model has been enlarged with an agricultural activities' module. The latter contains not only the food cultivation and processing chain, but also energy crops and forestry activities. Because all of these activities require land, there is competition for land within the model structure, because the total amount of land is limited. The agricultural module is rather stylised in nature. The influence of future agricultural policies, especially within the EU, has not been elaborated and a status quo of current practices has been assumed.

The model is represented schematically in Fig. 1, with the right-hand side showing the driving demand levels and from left to right the energy system with its components. The introduction of the biomass options increases the number of potential interactions in the model, energy crops use energy during their growing and processing phase, but delivers an energy carrier to the end users directly or to a conversion process (fuel conversion or electricity or heat production). Biomass energy can also be delivered as export outside the model region.

The regional coverage of the model is Western Europe, namely the EU15, Norway, Switzerland and Iceland, and is treated as one single region. No country-specific distinction is made, however, for some technology applications, namely in the building sector, a distinction is made between the north, middle and south. The model version used for EMF-19 covers the 1990–2100 period in 10-year steps and contains over 70 energy and material demand categories and more than 850 technologies. CO_2 emissions from fuel combustion and industrial processes are included as well as CO_2 storage as a feedstock or in materials and CO_2 uptake by land use, land use change and forestry (LULUCF) are included. For the other greenhouse gases, CH_4 and N_2O from the energy system and agriculture are partially included, although not many specific CH_4 or N_2O reduction options are represented.

As the focus of EMF-19 lies on technology response to climate change targets, more attention will be given to the technologies in the model. The model contains both existing

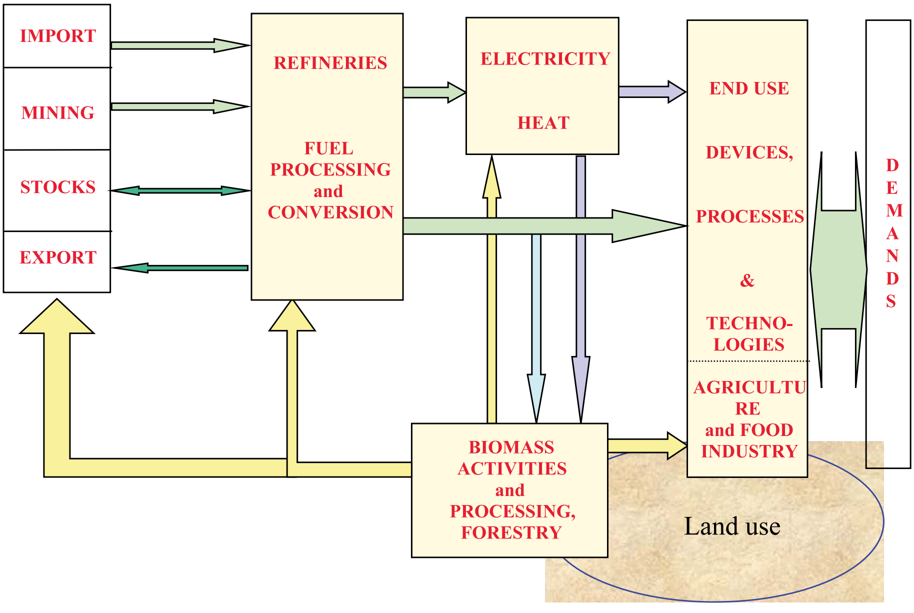


Fig. 1. The structure of the MARKAL model.

and future technologies, so even in a base case scenario, without additional constraints, a shift towards more cost-efficient technologies occurs. A number of conservation options in the end use sectors are included. These options become more attractive for the optimal solution in emission control scenarios where the existing or business as usual technologies incur a higher penalty. In addition, a number of CO_2 removal technologies have been included: 1 geological and 21 biological (sink) options. A specific geological storage option has not been identified, but an overall yearly potential for geological storage, expressed in megatons CO_2 per year and variable over time is used as upper limit for this CO_2 removal option. The biological options are limited by the competition for land use. CO_2 uptake by forests occurs at an average annual uptake rate and does not follow the typical non-linear saturation (S-curve) profile of real uptakes in forests.

Fourteen CO_2 capture technologies are specified for large point sources in the power sector, in industry (iron and steel, ammonia production, etc.) and in the fuel conversion sector (e.g., H_2 production). They provide the CO_2 that can be stored in the geological storage option. They are modelled as part of the fuel flow in which the CO_2 is capture and removed. The following technologies are included in the database:

- Sponge iron production for DRI with CO_2 capture
- Cokes for iron production with CO_2 capture
- Coal for iron production with CO_2 capture
- Wood to fuel for iron production with CO_2 capture
- Ammonia production conventional with CO_2 capture
- Ammonia production advanced with CO_2 capture

- Natural gas for combined cycle (CC) with CO_2 capture
- Wood for co-combustion in CC with CO_2 capture
- Wood for co-combustion in IGCC with CO_2 capture
- Coal for IGCC with CO_2 capture
- Natural gas for CC plant with CO_2 capture
- Natural gas to hydrogen with CO_2 capture
- Coal to hydrogen with CO_2 capture
- Coal for integrated gasification solid oxide fuel cell (SOFC) plant with CO_2 capture.

The biological storage options take CO_2 from the whole system and cannot be attributed to a single sector or technology like the geological storage.

The MARKAL type of models are well-known and documented, so only the additional feature of the model version used here, namely the price elastic demand functions will be discussed in more detail. In this study, the already available model option to include endogenous technology learning via learning curves (Seebregts et al., 2000) has not been used. The reason for that is that not for all relevant technologies, a robust set of parameters describing the learning curve was available at the time of performing the scenario runs.

2.2. Elastic demand

MARKAL is a demand driven model and the user has to provide the forecasts for the final demand for energy and material services for all time periods. The forecasts are obtained from other sources or models. These service demands are not equal to the final demand for certain energy carriers or materials, e.g., the demand for residential houses (in physical units) will result in a final demand for heating energy and building materials. Traditionally these demand levels are price insensitive, i.e., the demand level remains unchanged if the supply prices change. This demand level is represented by the dotted line in Fig. 2. The model generates a supply curve that satisfies the objective function and which is stepwise because it is built up by discrete technologies. The total cost derived from the solution can be interpreted as the integral under all assumed supply curves.

In an option recently added to the MARKAL model, price elastic demands are included (Loulou and Lavigne, 1996). The exogenous useful energy demands have been replaced with energy demand functions relating the demand to the market prices (equal to the marginal cost represented by the shadow price from the standard MARKAL solution). At this stage, a rather simple demand function is taken without substitution between demand categories, with price elasticities and with a time-dependent shifting parameter: In addition, the demand curve is linearised stepwise and the user can define the maximum allowed deviation upwards and downwards from the equilibrium point.

The model will generate the same equilibrium point in the absence of any additional constraint. If, for example, a CO_2 emission target is set, the model will adjust the demand levels and the supply curves to minimise the overall system cost. This could mean that instead of deploying emission reducing technologies, the models changes a demand level along a stepwise demand curve. A change in demand level also means a change to a different supply curve, so the equilibrium point will shift along the demand curve. The

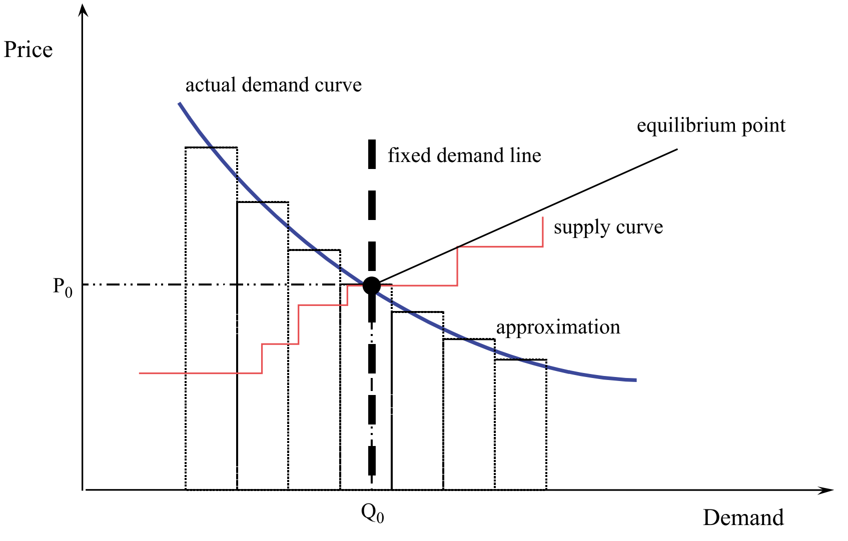


Fig. 2. Elastic demand curves in MARKAL.

objective function becomes the minimisation of the area under the supply curves, or the maximisation of the area between the demand curves and the supply curves. The area between the demand curve and the equilibrium price level is a measure of consumers' surplus, the area between the equilibrium price level and the supply curve is a measure the producers' surplus, as illustrated in Fig. 3.

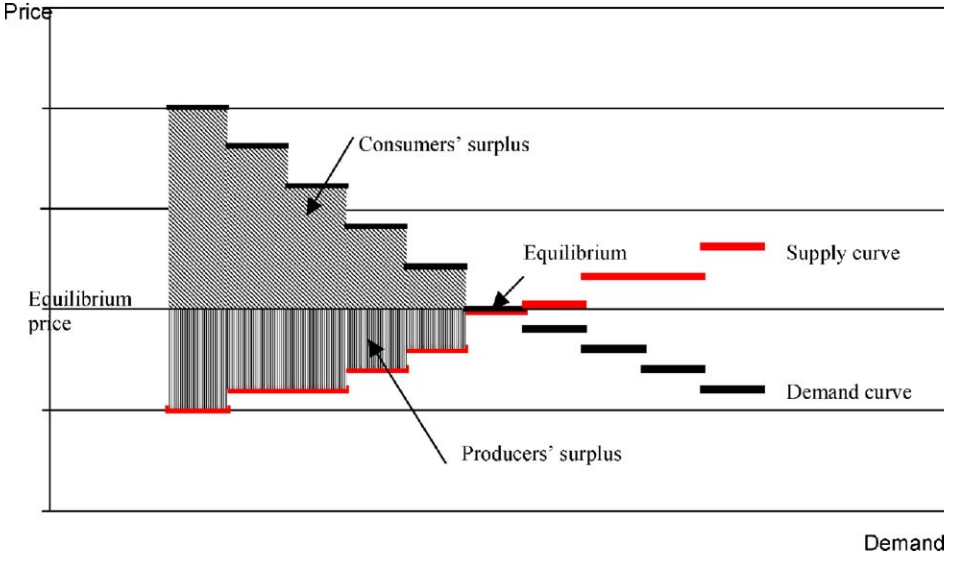


Fig. 3. Producers' and consumers' surplus using elastic demand curves.

The reason to choose this price elastic demand option is that under the scenarios which have been run for EMF-19, it is not plausible that the energy system will maintain its original demand levels when the system emissions have to be reduced so significantly, or if there is a high CO_2 tax. The model does not comprise the whole (macro) economy with all its interactions and substitutions. To maintain the technology richness of a bottom-up model, this partial equilibrium formulation is employed. The results from this model version reflect the price response behaviour of multiple actors in a complex energy system when confronted with constraints (e.g., emission targets).

3. The scenarios

A number of scenarios and sensitivity cases have been run for EMF-19 to explore the technology response to different CO_2 constraints:

- a modellers' reference;
- a standardised reference according to IPCC B2 scenario;
- a 550 ppmv stabilisation case;
- a 550 ppmv with an 50% increase and decrease in sequestration cost assumptions;
- a US$10 per decade carbon tax, starting from 2010 on;
- a US$10 per decade carbon tax from 2010 onwards with a 50% increase and decrease in sequestration cost assumptions;
- a US$25 per decade carbon tax from 2010 onwards with a hold at US$100;
- a US$100 carbon tax from 2010 onwards.

The Modellers' Reference or base case scenario is a market-driven scenario with the following characteristics (see also the original description of this 'Market Drive' scenario in Lako et al., 1998 and Seebregts et al., 2000):

- market mechanisms are the best way to produce wealth;
- market forces determine the penetration of new, more efficient technologies and the level of environmental protection;
- there is a stagnation of GDP growth after 2020 caused by too much privatisation [2.4% $\Rightarrow$ 1.8% (2050) $\Rightarrow$ 1.5% (2070)];
- energy demand becomes decoupled from economic growth;
- technology and sector specific hurdle rates are used on top of an overall discount rate (equalling ?.? percent).

The standardised reference scenario contains the same technological options and assumptions as the modeller's reference scenario, but with different deployment rates, e.g., advanced and renewable technologies and with lower overall demand levels and growth rates, reflecting the assumptions made in the IPCC B2 scenario.

The 550 ppmv case is a commonly accepted CO_2 stabilisation case for this century in order to prevent dangerous impacts from climate change. As the MARKAL model does not have a climate module to calculate concentrations from emissions or to estimate the

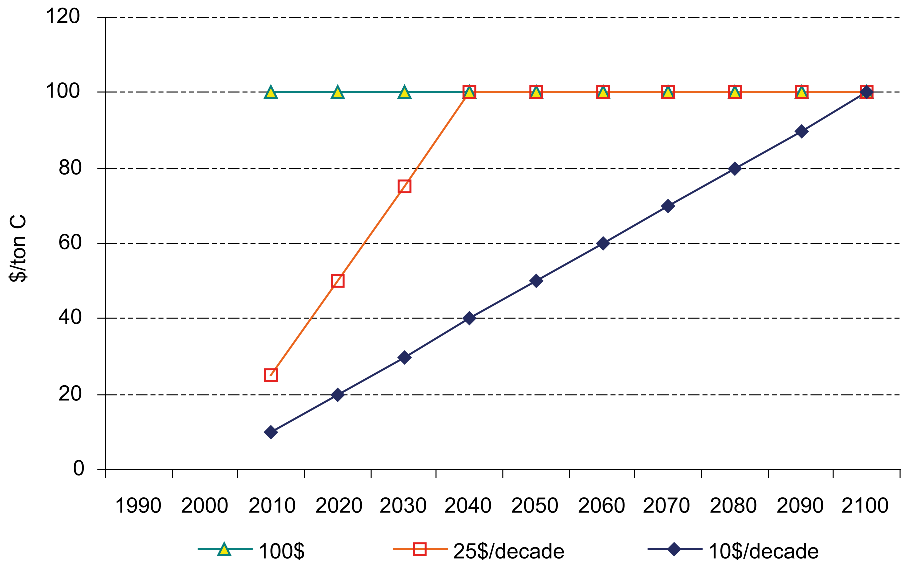


Fig. 4. Carbon tax assumptions (US$/ton C).

effects in the atmosphere, the following approach is taken in such cases: From integrated climate models, a permitted amount of emissions is obtained which corresponds to a given concentration level. The annual emissions and the emission trajectory over the next 100 years differs according to the assumptions in these models which are not necessarily the same as in the MARKAL model, especially on economic growth or technologies. Therefore, only the total over the 100 years is considered, resulting in an allowed cumulative amount of 352 Gton CO_2 over the 100-year period. A similar approach was adopted and described in Lako et al. (1998).

The scenarios with a carbon tax, which was converted to a CO_2 tax for the model, had to follow a prescribed level as illustrated in the Fig. 4. All tax scenarios have US$100/ton carbon as upper level, reached from 2010 onwards, in 2040 or in 2100. These different tax profiles will introduce different technology responses in the early years of the model (2010–2050) but will convert to more similar results at the end of the time horizon.

For the price-sensitive cases, the investment costs of all CO_2 capture, removal and storage options (geological and biological) have been increased or decreased by 50% compared to the original level used in the modeller's reference. Because some technologies have time-dependent investment cost profiles, they will also have them in the sensitivity cases.

4. Results

4.1. Primary and final energy

Fig. 5 shows for each of the scenarios the primary energy mix for the years 2020, 2050 and 2100. As can be noticed, the total level of primary energy demand does not change

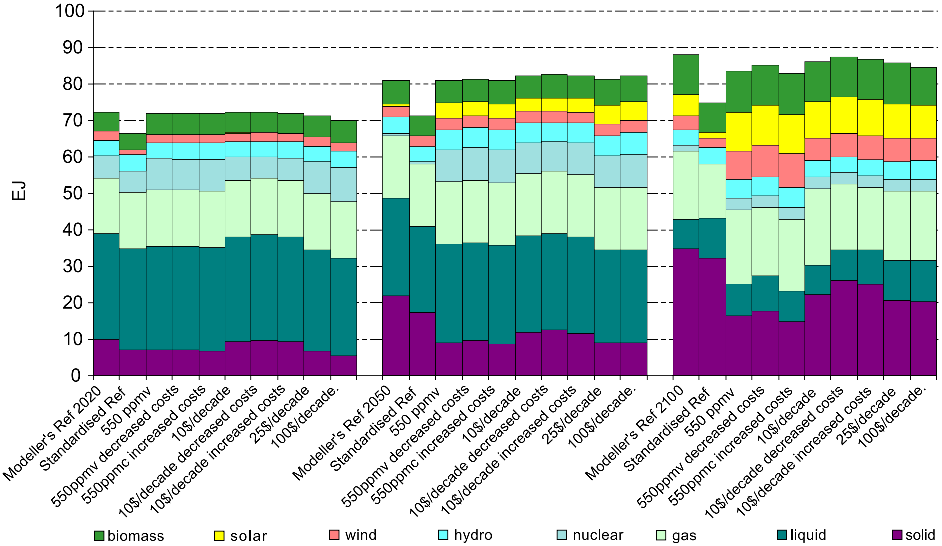


Fig. 5. Primary energy mix in 2020, 2050 and 2100 (EJ).

much (between −6% and +2%, with the exception of the standardised reference which uses lower demand levels). Even so, the energy mix changes considerably between the scenarios. In 2020, the solid and liquid fossil fuels decline already somewhat in the 550 ppmv and the high tax (US$25–100) cases compared to the modellers' reference case (called short base case), this in favour of nuclear energy. In 2050, solar appears and nuclear remains in all non-reference cases. By 2100, solar has established a firm share in the primary energy mix, and wind has also an increased share. The carbon heavy fossil fuels (solid and liquid), in contrast to gas, see their share decline further.

Two scenarios are investigated in more detail, namely the reference case and the 550 ppmv case. They represent the two most interesting cases, namely the business as usual and the most stringent emissions reduction case.

In Fig. 6, the evolution of the primary energy mix over the whole model period is given. As already mentioned above, there is a small difference in the total level, a somewhat higher level (2 EJ) in 2040 and 2060 and about 4 EJ lower from 2080 on. The major difference occurs in the mix of energy carriers. In the base case, coal becomes the preponderant fuel for the entire energy system, even more than liquid fuels which are mainly used in the transportation sector. Modest increases in fuel costs for coal and an abundant supply, combined with the availability of more efficient coal-fuelled technologies, explain this trend. In the 550 ppmv case, coal hardly increases above the present consumption. Liquid fuels see in both cases a slight increase till 2070 and a decrease from that year on, the switch towards alternative fuels for transportation (natural gas, biofuels, H_2) lies at the basis of this. The consumption of natural gas grows steadily and is almost equal in both cases, although it is slightly higher in the 550 ppmv case. While in the base case, nuclear energy, solely used in the electricity production, almost disappears after 2030, in the 550 ppmv case, there is a continuation at current levels. The largest difference is to be found in the renewables: Wind

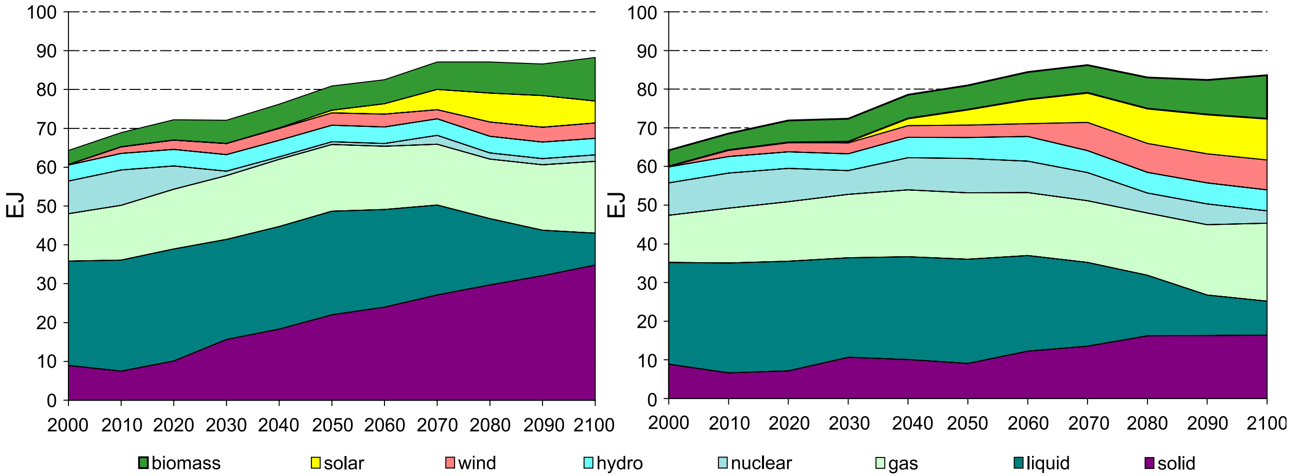


Fig. 6. Primary energy evolution for the reference case (left) and the 550 ppmv case (right) (EJ).

and solar see their use increase or even double, hydro does not change much because there is little potential for capacity expansion in Western Europe, and what is available is used. Biomass increase slightly but remains restricted by the competition with agricultural crops and food growing on available land and land use.

The share of nonfossil energy carriers is a good illustration of how the mix changes, as illustrated in Fig. 7. From an initial share of 25%, the share decreases in the base case to 20% (phase out of nuclear mainly) and reaches 30% by 2100 due to an increase in renewables. In the 550 ppmv case, the share increases constantly to reach 45% by the end of the modelling period, the increase in primary energy consumption is almost completely taken up by the nonfossil fuels.

The final energy consumption in the industry, transport, residential, commercial and services sectors is illustrated in Fig. 8. Liquid fuels remain the major energy carrier for end use and the transportation sector is the largest consumer. In the 550 ppmv case, there is not much behavioural change in that sector under the impulse of an overall emission constraint. In general, there is little change in the total level of final energy use and in the mix of energy carriers consumed. Only in the later periods is a reduction of about 4–7 EJ achieved in solid fuels and electricity. Because of the high carbon content, there is a switch from solid fuels towards gas that sees its consumption increase with 1–2 EJ. Electricity decreases because of the cost increases of electricity for the end users due to the large carbon reducing efforts in the power generating sector. The carbon constraint scenarios augment the marginal cost of electricity with about 1–2 eurocents/kW h, an increase from 20% to 40%, making it somewhat less competitive for the end users (Fig. 9).

4.2. Carbon emissions

Each of the scenarios results in an emission path for carbon. This is the carbon from fuel combustion including any occurring emissions which are later removed by biological and geological carbon sequestration, and they can be considered as the gross emissions of the entire system. Net emissions are the emissions actually released into the atmosphere, so the

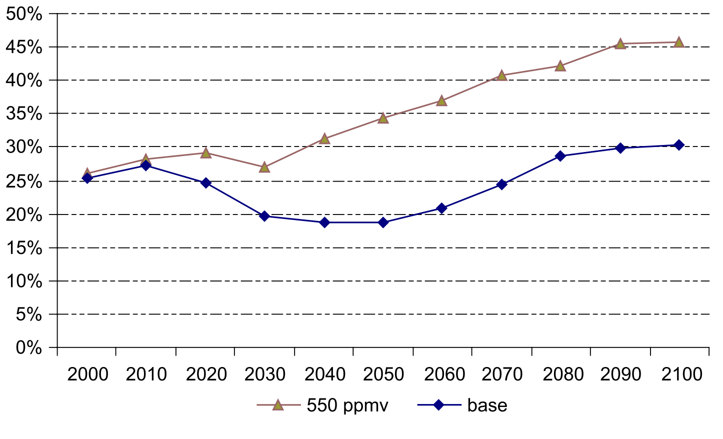


Fig. 7. Share of nonfossil fuels in the primary energy mix (%).

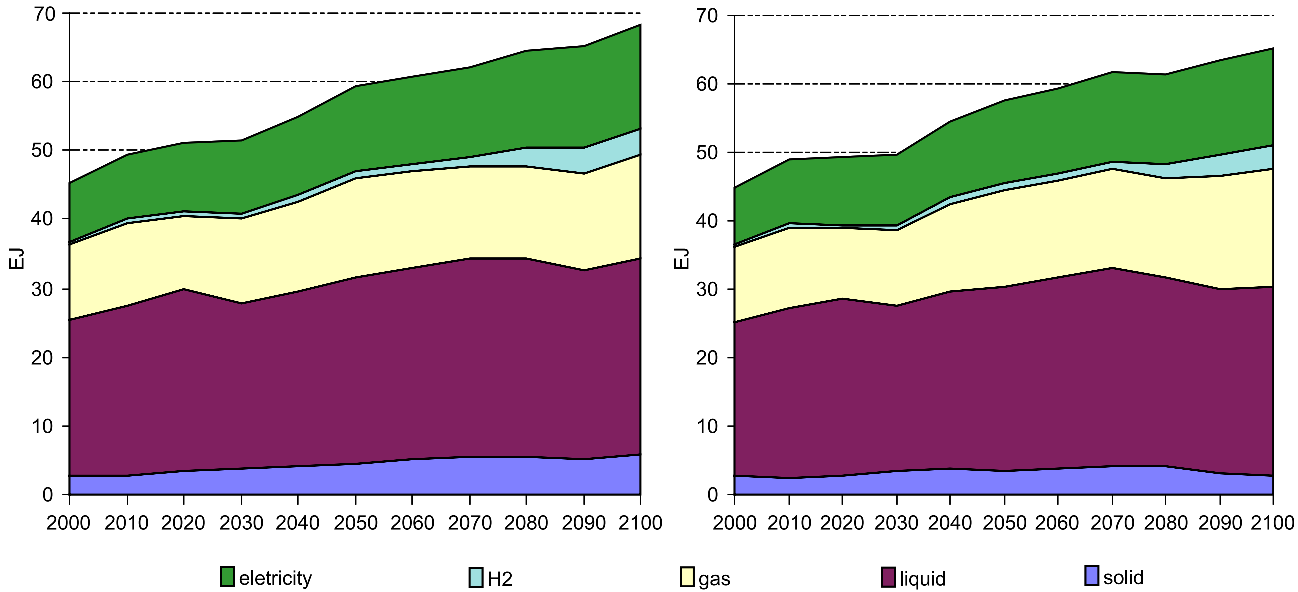


Fig. 8. Final energy mix: reference case (left) and 550 ppmv case (right) (EJ).

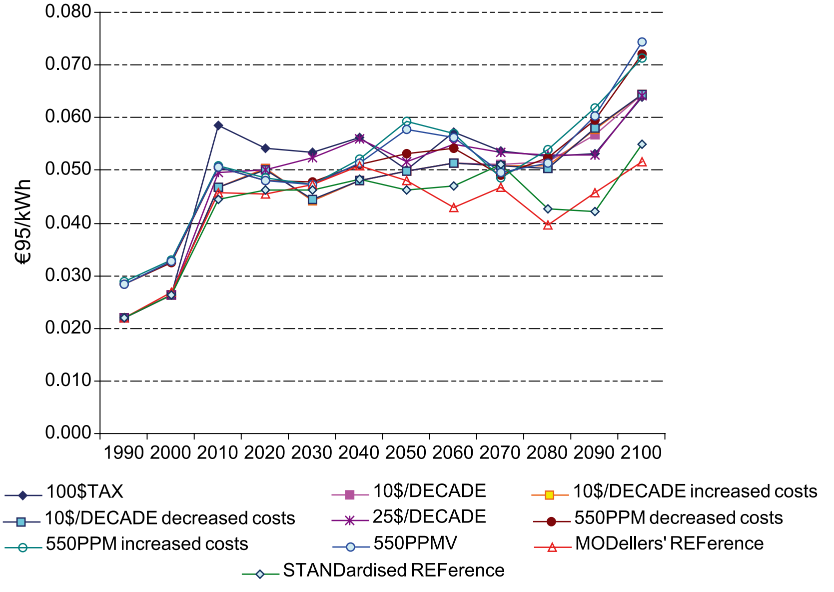


Fig. 9. Marginal electricity costs (95/kW h).

gross emissions diminished by the removals. Carbon emissions from industrial processes are reported separately and are not included in the emission results mentioned here.

In the base case, overall carbon emissions see a growing trend, primarily caused by the increase in coal consumption, and peaks at 1200 Mtons around 2050–2070 and is around 1100 Mtons by 2100, a reduction caused by a decrease in consumption of liquid fuels.

The emissions in the US$25 and US$100 tax cases differ in the early periods, but when the tax level is equal, the emissions are also more or less equal. The fact that they do not correspond 100% for the later model years lies in the fact that the model makes choices in energy use and technology investment and deployment in early years which have consequences for later periods.

The 550 ppmv case and the US$10/decade case and their sequestration cost variants result in a range in the emissions (Fig. 10), the maximum difference in each case is about 100 Mtons of carbon. As can be expected, the US$10/decade case shows a gradual reduction in emissions, while the 550 ppmv case sees the sharpest reduction after 2060, the model pushes backward the bulk of the effort to reach the target.

In the following, summarising Table 1, some cross scenario comparisons of gross carbon emissions are made: The emission level in 2100 is between 20% and 45% lower than the reference case while the total accumulated gross emissions over the whole model period vary between 76% and 87% of the reference case level.

Emission reductions are not only achieved by fuel switch, by the enhanced utilisation of renewable energy carriers or energy conservation; the price elastic demand version of MARKAL also introduces a demand reduction and hence a supply reduction as well. This price elasticity results in a reduction of total system costs, whereas one would expect an increase due to the anticipated reaction of the system to the implied reduction constraints.

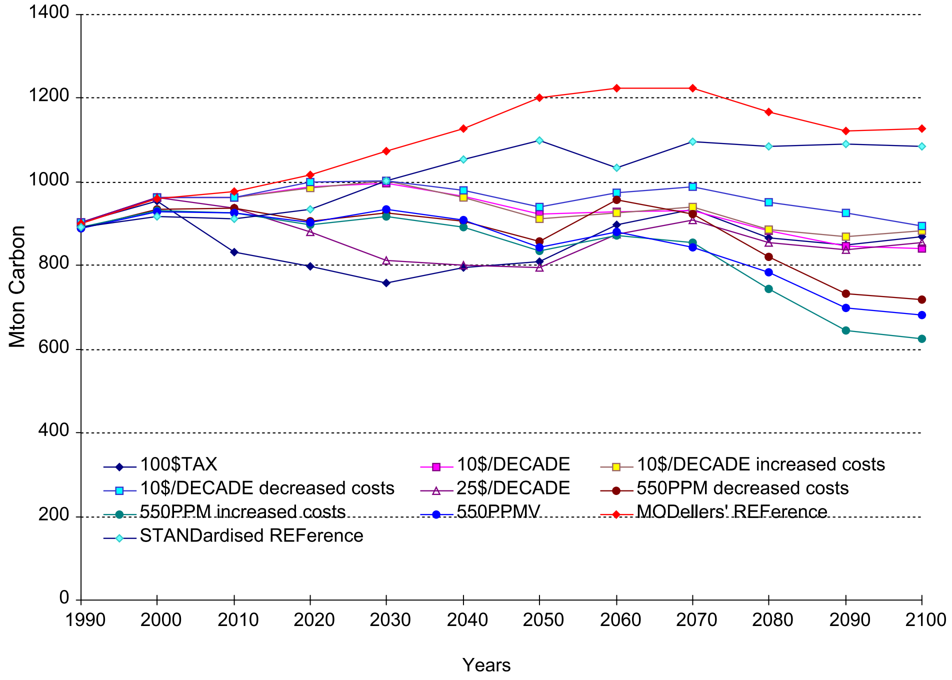


Fig. 10. Gross carbon emissions (Mtons C).

The decrease in system costs by demand reductions can not offset all of the cost increases caused by investments in and deployment of more expensive high efficiency or emission reducing options. At some points over the modelling horizon, the value of the objective function (total system costs) reaches the same level as the reference case. In general the total system costs are 1–2% lower than in the reference case (Fig. 11).

Another measure for this effect is the change in consumer and producer surplus, or welfare loss, related to the annual system cost of the reference case (Table 2). Over the

Table 1
Relative gross carbon emission levels (%)

Scenario	Gross carbon emission level in 2100 compared to the reference case (%)	Cumulative gross carbon emissions 1990–2100 compared to the reference case (%)
US$100 tax	77.1	78.2
US$10/decade	74.5	84.8
US$10/decade increased costs	78.2	85.3
US$10/decade decreased costs	79.4	87.5
US$25/decade	75.8	79.4
550 ppmv decreased costs	63.7	80.1
550 ppmv increased costs	55.4	76.4
550 ppmv	60.5	77.9
Modellers' reference	100.0	100.0
Standardised reference	96.3	93.0

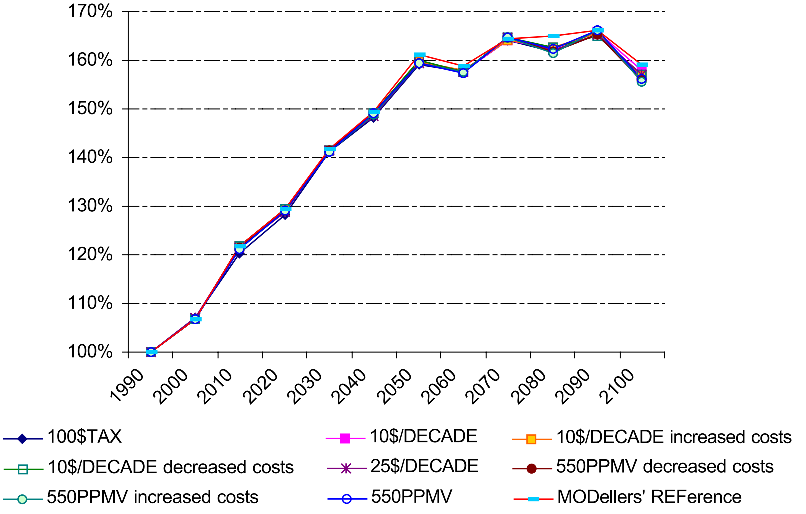


Fig. 11. Annual total system cost relative to the 1990 reference case level (%).

whole model period, this results in a decrease of − 0.19% (US$10/decade decreased costs scenario) up to − 0.80% (550 ppmv increased costs scenario). The range within one case (550 ppmv or the US$10/decade tax) is relatively large, several 10ths of a percent.

The model generates not only total carbon emissions (by accounting for fuel consumption and the associated emission levels) but also gives detailed emission levels. The focus of this study is the carbon uptake by biological (sinks) and geological (sequestration) model options, hence, more analysis is given in this area. Fig. 12 represents the total annual level of carbon, which is removed from the system, i.e., this is carbon that is produced by fuel consumption but not released into the atmosphere, or the difference between the gross and net emissions.

The base level of carbon uptake is around 20 Mtons/year from 2020 on. As soon as a carbon constraint is in place, be it an emission target or a carbon tax, carbon uptake above the reference level occurs. In some scenarios, especially the ones with the lower costs for carbon removal technologies, the maximum potential of uptake, estimated at about 150 Mtons carbon/year, is reached, sometimes even as early as 2070.

Table 2
Average annual change in consumer and producer surplus (relative to reference case)

US$100 tax	− 0.40%
US$10/decade	− 0.31%
US$10/decade increased costs	− 0.26%
US$10/decade decreased costs	− 0.19%
US$25/decade	− 0.38%
550 ppmv decreased costs	− 0.52%
550 ppmv increased costs	− 0.80%
550 ppmv	− 0.70%

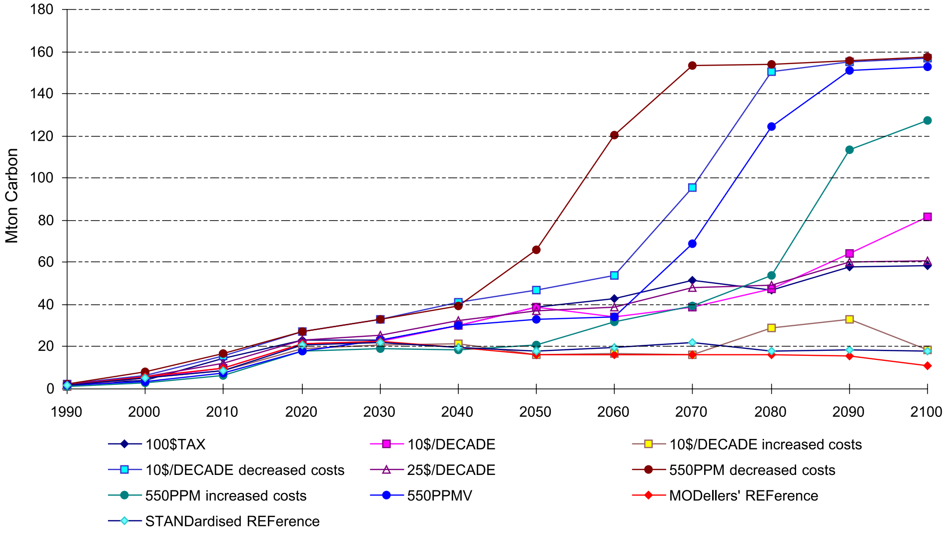


Fig. 12. Carbon removal (Mtons/year).

In more detail, the carbon removal and uptake in the reference case is mainly achieved through biological options, biomass, soils and coniferous and non-coniferous woods (Fig. 13). The uptake offsets the release of carbon from land use and land use change activities (the area below the 0 axis), hence the positive effect of biological uptake. The contribution from biomass and soils remains more or less constant, the one from coniferous woods, mostly in Middle and North Europe, increases constantly, non-coniferous wood is limited and sees its peak around 2040–2070.

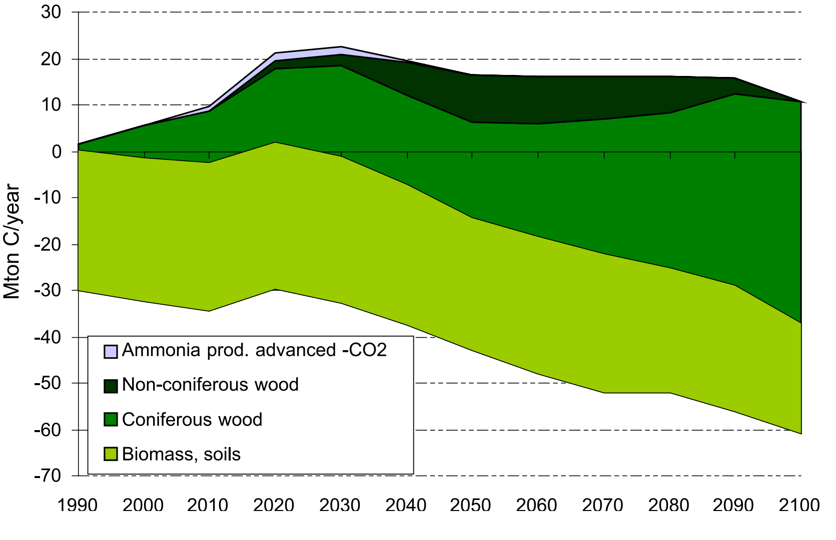


Fig. 13. Carbon removal by option (Mtons carbon/year), reference case.

There is some industrial based carbon removal in ammonia production where the advanced production technology includes a small amount of carbon removal into geological storage, 1–2 Mtons carbon/year in 2010–2040.

In the stabilisation 550 ppm case, carbon removal appears as a major contributor in achieving the emission constraint, the contribution from the different actors is quite different than in the reference case. The bulk of the carbon removal originates from the power sector, industry and fuel conversion and is stored in the geological uptake option. Fig. 14 shows the contribution of the different options in the total carbon uptake: For the biological uptake, no distinction is made regarding the origin of uptake; for the geological uptake, a distinction is made by origin of the removed and stored carbon. The biological uptake does not differ much compared to the reference case, apparently, there is little room for enhanced LULUCF uptake in Western Europe under the current (agricultural) policy assumptions.

The largest contribution to the geological removal comes from a coal based IGCC (Integrated Gasification Combined Cycle) with carbon removal and from H_2 production from natural gas with removal of the carbon released in this process. They each take about 60 Mtons/year by the end of the modelling horizon. H_2 production with carbon removal appears from 2030 on, limited at first but expanding slowly till 2080 where a considerable expansion takes place. Coal IGCC starts from 2060 on and levels off after 2080. The other activities, carbon removal from wood chips gasification and in industry, remain small and account for less than 20 Mtons.

Looking in more detail into the 550 ppmv cases (Fig. 15), the variation in costs for the sequestration technologies offers some interesting differences. In the two variations, only the investment costs of the technologies which can remove or take up carbon has been changed, the difference compared to the medium 550 ppmv case is plus or minus 50%.

In the decreased cost case, H_2 production from coal has taken virtually all H_2 production (with carbon removal), gas-based H_2 is limited. IGCC with removal starts much earlier, in 2040, but contributes less to the total annual removal. The industrial removal options are in this case less present than in the plain 550 ppmv case. The cost

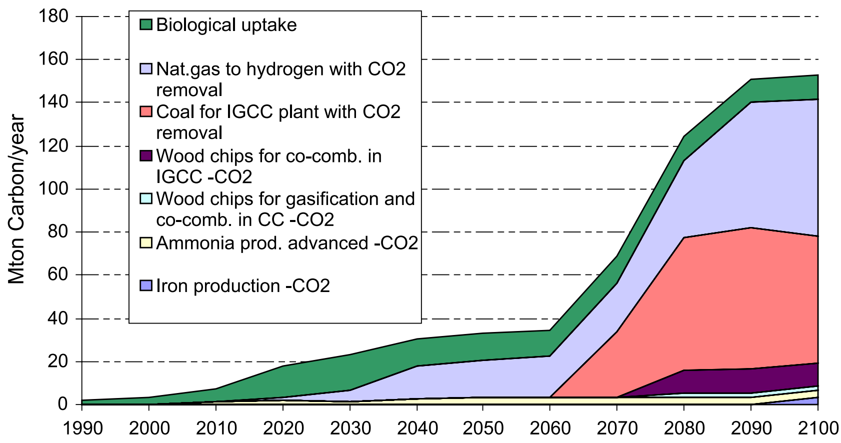


Fig. 14. Carbon uptake in the 550 ppmv stabilisation case (Mtons carbon/year).

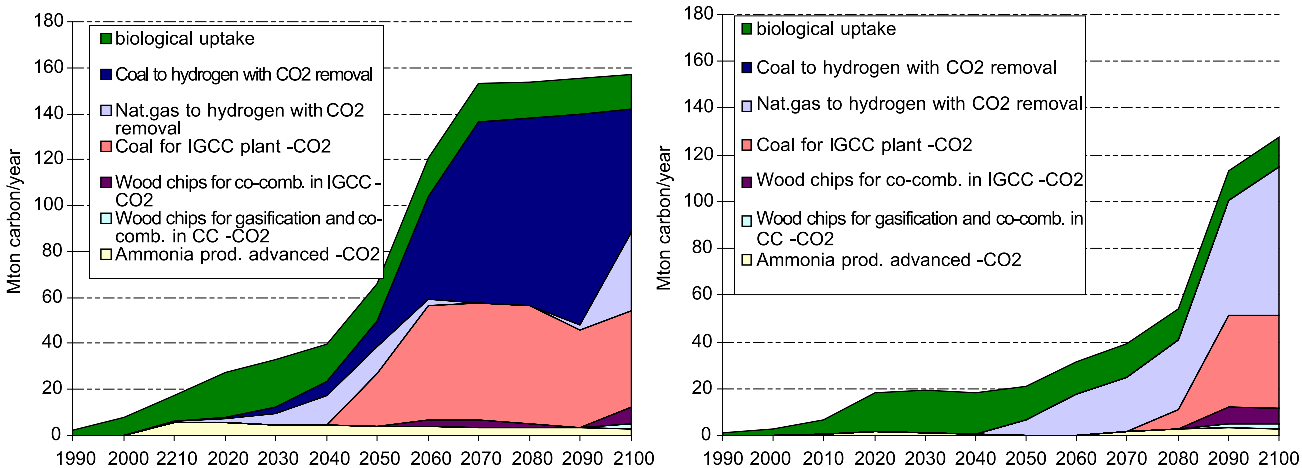


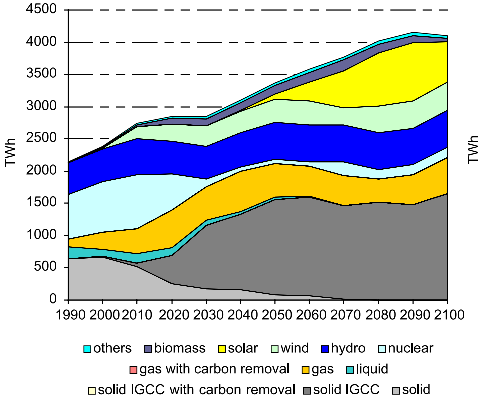
Fig. 15. Carbon uptake in the 550 ppmv variants, decreased costs (left) and increased costs (right) (Mtons/year), cf. Fig. 14.

increase case not only starts the bulk of the removal later (2080 compared to 2060 in the plain 550 ppmv case), but the total level is lower as well and reaches only 130 Mtons/year instead of 150 Mtons in 2100. H_2 production with carbon removal based on natural gas is the major source activity for the removed carbon, together with coal IGCC with removal.

A cost decrease assumption for removal technologies clearly favours solid fuel based options, whereas a cost increase eliminates most of them, only IGCC with carbon removal seems to play a part in the removal activities within the range of sequestration costs considered here.

4.3. Power generation

As carbon removal options appear in all solutions, it may be worth looking into more detail into the power sector, one of the major contributors to carbon removal (Fig. 16). More specifically, the power production mix will be described for the reference case and for the 550 ppmv case. In the reference case, electricity production is and stays mainly coal based, however, from 2010 onwards, there is a switch from classic coal towards IGCC. Liquid fuel disappears for electricity production and gas stabilises after 2020. The existing nuclear capacity is not renewed and is consequently phased out gradually. Among the renewable sources, hydro is important but has already reached almost its full potential, so there is little room for expansion in capacity and hence in production. Wind sees a modest growth, continuing at the current rate and stabilising later on. The source with the largest growth is solar PV based electricity production (solar thermal remains small). Its share reaches 15–20% of total production. Carbon restrictions and a favourable decreasing investment cost trend (exogenously determined) make solar PV competitive. Being a non-continuous source of electricity, together with wind and some hydro, this means that to ensure security of supply at all times, there is a considerable overcapacity of other power plant types, which can come into production whenever the demand requires it. The load factor of the other plants, related to the installed capacity is low, between 45% and 55% on an annual basis. So the system has to bear the extra expenses of those unused GW being



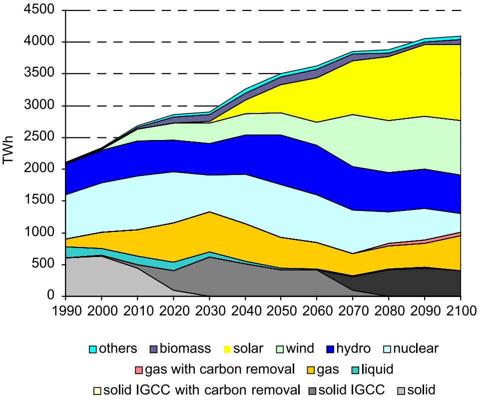


Fig. 16. Electricity production mix for the reference case (left) and the 550 ppmv case (right) (TW h).

installed in order to provide supply security at those times when the intermittent or seasonal production is not sufficient.

The production mix in the 550 ppmv case sees some major changes compared to the reference case although total electricity generation does not differ much (a few % only). Coal disappears as a major source and that which remains is used in IGCC, first without and later with carbon removal. Gas increases rapidly early on, but decreases slightly afterwards. In the later periods, some gas with carbon removal also appears. Hydro, biomass and others (waste, tidal and geothermal) hardly change, in contrast to wind and solar which see their share increase. Wind breaks through from 2060 on, while solar starts a significant penetration by 2040. The exogenous cost assumptions for solar PV foresee a much more decreasing trend than wind and could explain the favourable position of the latter.

5. Conclusions

Analysis with ECN's MARKAL Western European technology model shows that under carbon emission constraint scenarios, not only renewable energy but also carbon capture and removal are important actors in achieving carbon emission reduction objectives. Renewables, especially wind and solar, are important in the power sector, but nonrenewable technologies, especially nuclear and gas fuelled are also important. Biomass-based technologies remain limited because of the strong competition with agriculture for land to grow the necessary energy crops. The switch towards more renewable "green" electricity also results in higher electricity costs, about 20–40% higher. This cost increase also affects the final consumption of electricity that is reduced by 7% in 2100. Electricity production although changes less, there is more electricity used in fuel conversion processes and this balances the reduction in final demand.

Carbon capture occurs in industry and in the power sector, the largest point sources of carbon and hence the sector where carbon capture and removal are most likely to be introduced. Capture and storage contributes for another 50–160 Mtons of annual reduction in actual emissions, a quarter to half of that which is achieved by fuel switching, technological changes and demand reductions.

This analysis shows clearly that carbon emission reductions can hardly be achieved by just a single technology or technology group (e.g., renewables). The future technology mix required to achieve less carbon in the energy system is a combination of carbonless (renewable) technologies and carbon free technologies (fossil fuelled technologies with carbon capture and storage). That the impact of the latter can be important, as seen in this modelling exercise, can only invite to continue research and analysis in this field.

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Carbon concentration target and technological choice ☆

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Abstract

There is great uncertainty about the choice of technologies for carbon mitigation policy in the long run especially if carbon storage options are considered. A sensitivity analysis of the costs of carbon sequestration is conducted here and relative importance of sequestration technology is assessed in a long-term carbon management framework. Carbon recovery with geological and ocean sequestration could be included among the available carbon abatement technologies and its abatement potential is sensitive to the carbon transport and storage cost assumption.

JEL classification: O33; Q21; Q31; Q40

Keywords: Integrated assessment; Carbon sequestration; Uncertainty

1. Introduction

Global environmental issues including climate change are gaining attention as the 21st century begins and will be an important determinant of the 21st century's energy mix. The positions of parties to the United Nations Framework Conventions on Climate Change (UNFCCC) are not identical regarding Kyoto Protocol (UNFCCC, 1997) ratification. The protocol requires greenhouse gases (GHGs) emission reduction from

☆ The views represented in this paper are solely those of the individual author and do not represent organizational view of the Institute of Applied Energy.

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2008 and 2012. In spite of the possible withdrawal of the United States and other parties from the protocol, the protocol will be effective by ratification by 55 UNFCCC parties and 55% coverage of the total 1990 carbon dioxide (CO_2) emissions of ANNEX I parties.

The Kyoto Protocol GHG emission target is an initial step for the developed regions and economies in transition to mitigate negative effects resulting from global climate change. In addition, global scale mitigation and/or adaptation strategies will be required in the long run.

The chapter two of the third assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2001) included a wide range of CO_2 mitigation measures that could stabilize atmospheric CO_2 concentrations. These measures are categorized into seven types: demand reductions and/or efficiency improvements, substitution among fossil fuels, switch to nuclear energy, switch to biomass, switch to other renewables, CO_2 scrubbing and removal, and afforestation. Among these options, CO_2 scrubbing and removal technology is under development so that CO_2 transport and storage into geological formation and/or ocean can be conducted. At this point, the storage technology is not established except for enhanced oil recovery and new IPCC assessment activities on carbon capture and storage (IPCC, 2002) were initiated in response to a UNFCCC request to evaluate the current technological status of capture and storage possibilities. Therefore, I analyzed the carbon transport and storage cost sensitivity of carbon mitigation strategies for achieving a CO_2 concentration target, and tried to assess the relative importance of CO_2 storage options.

2. Approach

The design of the Global Relationship Assessment to Protect the Environment (GRAPE) model is described in the recent assessments (Kurosawa et al., 1999; Kurosawa, 2000). The model consists of five modules dealing with issues on energy, climate, land use, macroeconomics and environmental impacts. The model includes 10 world regions: North America (NAMR), Western Europe (WEUR), Japan (JAPN), Oceania (OCEA), China (CPAS), Southeastern Asia and other Asia (SEAS), Middle East and North Africa (MENA), Sub-Sahara Africa (SSAF), Latin America (LAMR), and Former Soviet Union and Eastern Europe (FSEE). NAMR, WEUR, JAPN, OCEA and FSEE regions are ANNEX I regions with net GHG emission ceilings in the Kyoto Protocol. To include long-term climate change dynamics, the base year and time horizon of the model are 2000 and 2100, respectively. The model uses a nonlinear dynamic intertemporal optimization methodology maximizing regional utilities, which are functions of macroeconomic consumption and population.

2.1. Major changes in the energy module

The energy module structure is basically a simplified version of the New Earth 21 model (Fujii, 1992) as used in previous assessments. Resources included in the analysis are natural gas, oil, coal, nuclear, biomass, hydropower and geothermal, solar (photovoltaics) and wind. Supply curves of exhaustible resources are formulated with costs represented as increasing functions of cumulative resource extraction. The cumulative resource extraction and production cost relationships follow Rogner (1997), which was used in the IPCC special report on emissions scenarios (SRES) (IPCC, 2000a). The most speculative grade of oil and gas is excluded from the available resource since it includes uncertain resources such as methane hydrates. The potential of residual biomass energy is taken from an assessment by Yamaji et al. (2001) and the approximate supply cost range is from 50 to 250 US$/TOE for direct use for generation. Biomass can also be used to satisfy nonelectric demands after ethanol conversion.

Nuclear power supply consists of uranium-fueled light water reactors (LWRs) with a once-through fuel cycle and fast breeder reactors (FBRs) with a closed fuel cycle. The latter is assumed to be available after 2050. According to the Nuclear Energy Agency and International Atomic Energy Agency (OECD/NEA and IAEA, 2000), the upper limit of the uranium resource is set to 15 million metric tons. FBRs have initial fuel loading requirements; that is, LWRs are required to produce the initial fuel for the FBRs. Therefore, the model includes an initial penetration constraint on FBRs related to the number of LWR required for fuel reprocessing. A breeding related constraint is set in the form of FBR capacity expansion rate, and FBR capital costs are 1.5 times that of LWRs. The capital costs of fossil fuel and LWR generation are taken from the International Energy Agency (IEA, 1998). Wind and solar generation costs are assumed to shift down because of technological progress and learning. The annual supply cost reduction rate is 2% and 1% per year, respectively.

2.2. Land use module

Land use is classified into five categories. These are cropland, grassland, forest, urban area and other areas. Urban area is exogenously assessed and other area categories are endogenously allocated considering their food supply potential and other factors. Since the purpose of this paper is not land use assessment, except for forestry, a detailed explanation is omitted. The basic framework assumptions are from a previous assessment (Yagita, 1997) and an input data update was made based on FAOSTAT (FAO, 2002).

It should be mentioned that a CO_2 balance from forestry area change is included in the analysis. This carbon stock change is regarded as carbon emission or credit from deforestation, afforestation and reforestation activities as defined in the Kyoto Protocol, and is not related to sink enhancements such as forest management. Experts have reported that carbon stock growth rate and CO_2 uptake duration period to the saturation level by afforestation and reforestation activities depend on climate zone. In this analysis, the uptake duration period is set to 30 years for tropical, subtropical and temperate zones, and 50 years for subarctic and arctic zones. It is assumed that forest area decrease resulting from deforestation leads to immediate release of CO_2. Regional forestry CO_2 stock saturation level estimates are shown in Table 1 based on the judgements from the IPCC special report on land use, land-use change and

Table 1
Regional CO_2 stock saturation level estimate per forestry area

Unit: ton C/ha	
Region	
MENA	3.0
FSEE	3.5
NAMR, WEUR, JAPN	5.0
OCEA, CPAS	6.0
SEAS	8.0
SSAF, LAMR	10

forestry (IPCC, 2000b). These provisional numbers will be updated based on future assessments.

2.3. Other modules

GRAPE has other modules related to the macroeconomy, climate and environmental impacts. The basic design of these modules is the same as previous assessments (Kurosawa et al., 1999; Kurosawa, 2000), except for the non-CO_2 GHG emission abatement-related assessment. Recent model revisions include endogenous assessment of methane and nitrous oxide mitigation measures for energy and agriculture activities and can be found in Kurosawa (2001).

3. Long-term energy scenarios and technology choice

Simulation results from the reference case and CO_2 concentration stabilization cases are compared. There is no GHG emission control policy in the reference case (REF), while the atmospheric CO_2 concentration is stabilized to 550 ppmv, double the preindustrial period, in the other cases. The utility discount rate adopted is 2% per year. Three cases are used to evaluate CO_2 sequestration (i.e., separation, transport and storage) cost uncertainty in the stabilization cases; standard cost (550), cost doubling (550 + s), half cost (550 − s).

3.1. Primary energy supply and power generation

The fossil fuel share in total primary energy drastically increases, caused by increasing coal generation and nonelectric natural gas use in the REF case (Fig. 1). Energy conservation in the whole period and growth in noncarbon energy options (especially nuclear, biomass and solar) are observed in the latter half of the century in the 550 case (Fig. 2). Current global electric power supply is mainly composed of fossil fuels, nuclear and hydropower, and significant future demand growth is expected in the developing regions. Regular fossil fuel generation facilities are utilized for several decades, and their CO_2 emissions vary by fuel and are inversely proportional to generation efficiencies. Therefore, the choice of electric generation

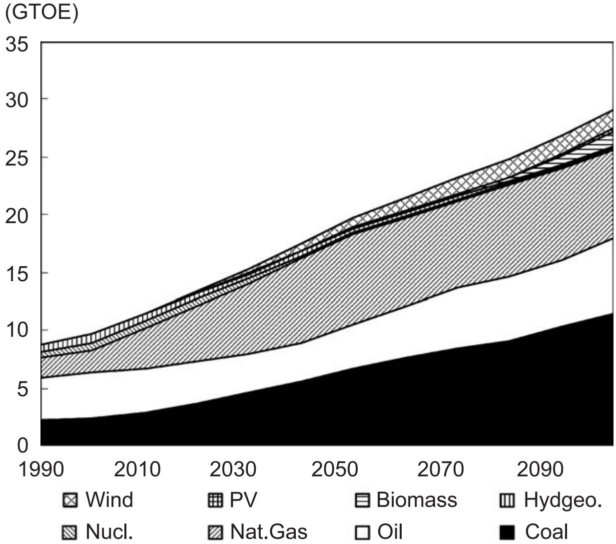

Fig. 1. Global primary energy supply in REF case.

technology has a large impact on CO_2 emissions. Marked share increases in solar, nuclear, biomass, and IGCC with carbon recovery are observed in the 550 case electric power supply in the latter half of the century (Fig. 3) while the coal share expands in the REF case. There exist regional differences in the energy supply mix

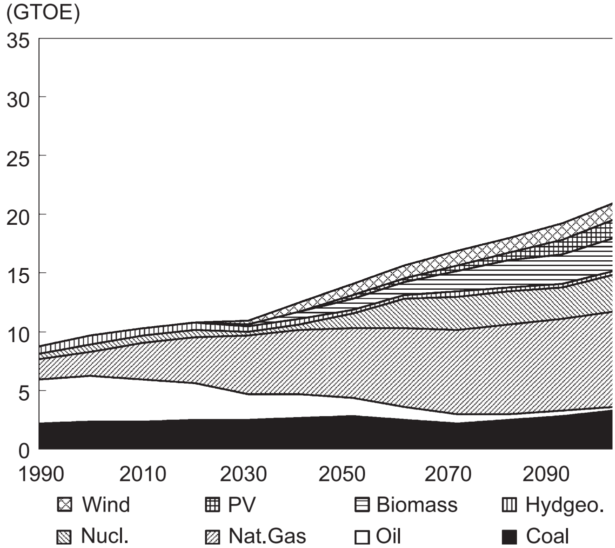

Fig. 2. Global primary energy supply in 550 case.

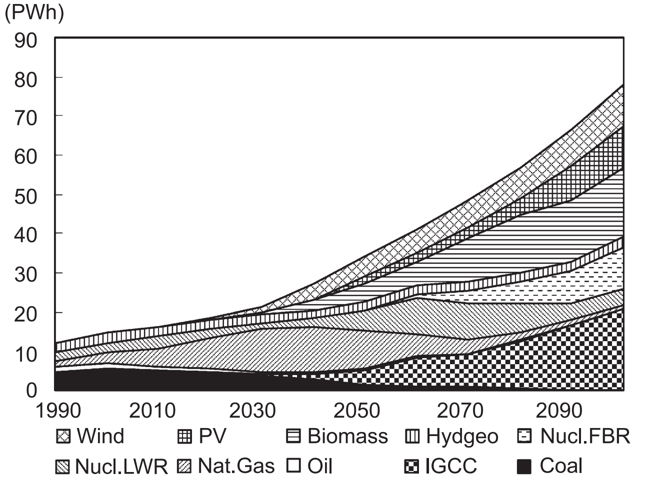

Fig. 3. Global electric power generation in 550 ppmv concentration stabilization case.

because of difference in energy resources available and other reasons. These differences are apparently recognized in the biomass energy penetration patterns in the CO_2 concentration constraint cases since no biomass trade among modeling regions is assumed.

3.2. Electric power supply under CO_2 concentration stabilization and sequestration cost uncertainty

A sensitivity analysis on CO_2 transport and storage costs was conducted because storage cost uncertainties are large. Transportation and storage cost are changed to 200% (550 + s) and 50% (550 − s) of the standard value. The captured carbon from integrated gasification combined-cycle (IGCC) generation is transported and injected into geological formations for enhanced oil recovery, into depleted gas wells and aquifers, or into the ocean. The initial cost estimates of these options, following the assessment of Fujii (1992),

Table 2
CO_2 transport and storage cost of geological and ocean sequestration

Unit: 2000 US$/ton C

Sequestration type	Storage cost (initial)	Transport cost	Storage and transportation cost		
			(550)	(550 + s)	(550 − s)
EOR	43	35–85	78–127	156–255	39–64
Aquifer	104	35–85	139–189	278–377	70–94
Gas well	60	35–85	95–144	190–289	47–72
Ocean			84–175	168–350	42–88
Whole range			78–189	156–377	39–94

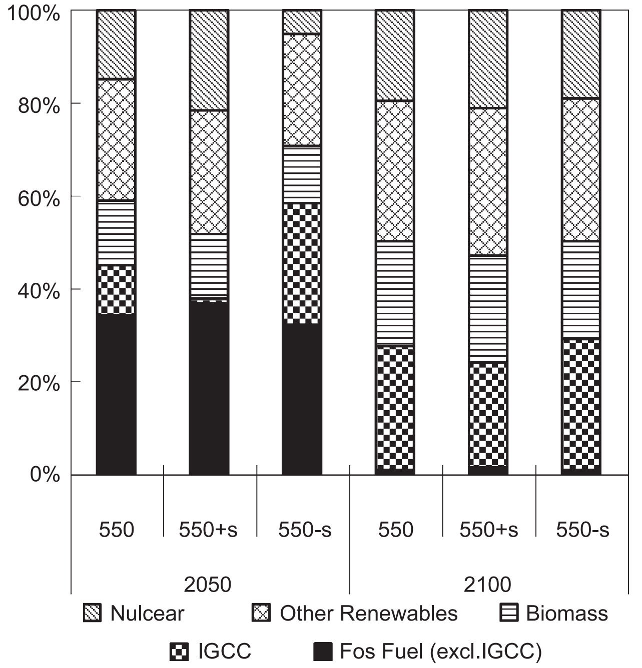

Fig. 4. Global electric power generation share in 2050 and 2100.

when the storage is initiated is summarized in Table 2. The initial storage cost is set to the same value around the world, but the cost increase rate per unit of carbon injected depends on regional storage potential.

Fig. 4 shows power generation shares for 2050 and 2100 in 550 ppmv CO_2 concentration stabilization cases. The sequestration cost differences affect the share of IGCC and nuclear share in 2050. The fossil fuel generation share in 2100 is quite small because the marginal cost of carbon mitigation rises significantly by then. These results lead to the conclusion that various kinds of energy technology options such as renewables, nuclear, and carbon sequestration should be included in a long-term carbon management policy.

4. The global carbon balance and marginal abatement costs

Anthropogenic CO_2 emissions from energy and land-use change in the REF case increase linearly and reach approximately 21 Gton C in 2100. On the other hand, net CO_2 emissions in the 550 case are approximate 4.3 Gton C at the end of this century, requiring a 79% reduction from the REF case. The breakdown of the reductions consists of 61% by fossil fuel emission reductions, 13% by carbon storage and 5% by afforestation. The global carbon balance in the concentration 550 ppmv stabilization case is summarized in Fig. 5. The use of geological and ocean sequestration of carbon is sensitive to its cost in

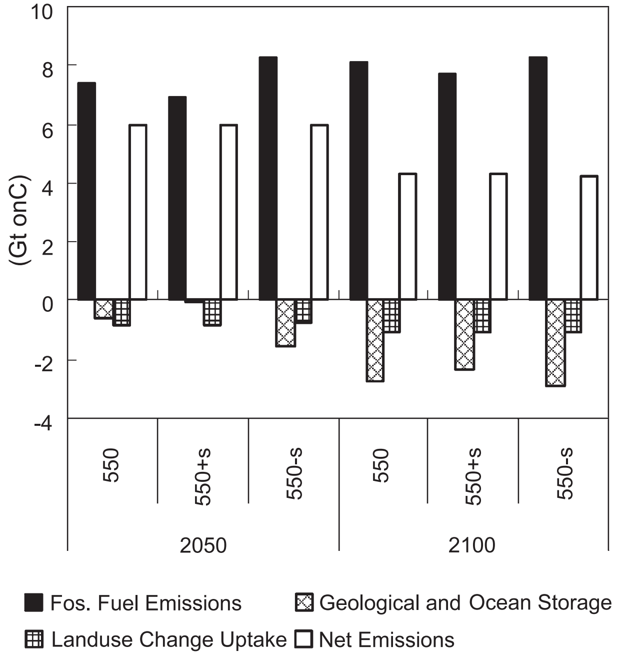

Fig. 5. Global carbon balance in 550 ppmv concentration stabilization cases.

2050 but not in 2100. Fig. 6 shows the marginal carbon abatement cost in the carbon concentration stabilization cases. The marginal cost is initially approximately 50 US*/tonCandincreasesexponentiallytomorethan3000US∗/ton C at the end of the century. The differences among cases expand gradually.

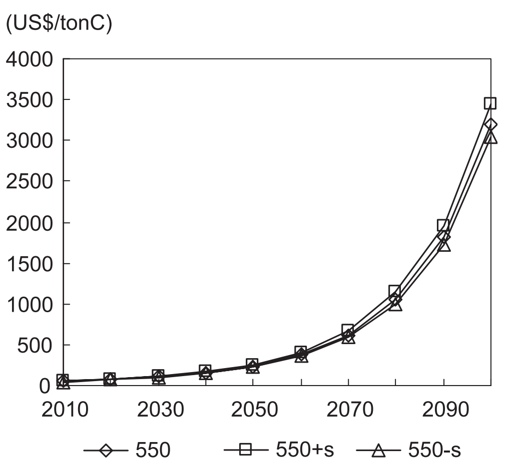

Fig. 6. Marginal carbon abatement cost in 550 ppmv concentration stabilization cases.

5. Discussion

This analysis is not intended to assess the impacts of the Kyoto Protocol. The parties that ratified the protocol will have strong incentive to reduce their net GHG emissions to the assigned amount and their short term CO_2 mitigation policy would be changed drastically, if the protocol goes into force. It should be added that carbon mitigation policy at the global scale requires developing region participation that necessitates regional equity balancing.

Enhanced coal-bed methane (ECBM) recovery by CO_2 injection to deep unminable coal seams has been proposed as a geological storage option recently and there is room for further investigation.

The uncertainty about carbon storage has several aspects such as economic efficiency, the environmental impacts of injected CO_2, and possible rediffusion into the atmosphere, etc. The sensitivity analysis above is limited to economic uncertainty except for monitoring and verification. Other uncertainty aspects need to be evaluated from both natural and social science points of view.

6. Conclusions

The following conclusions are obtained from the analysis:

(1) A sensitivity analysis on carbon concentration cases (550, 550 + s and 550 − s) provides different penetration patterns for the geological and ocean sequestration options. Their long-term potential scale could be the same as forest sink scale.
(2) Carbon recovery with geological and ocean sequestration should be included among the carbon abatement technological options and its abatement potential is sensitive to the carbon transport and storage cost assumption employed.

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Representing energy technologies in top-down economic models using bottom-up information

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Abstract

The rate and magnitude of technological change is a critical component in estimating future anthropogenic carbon emissions. We present a methodology for modeling low-carbon emitting technologies within the MIT Emissions Prediction and Policy Analysis (EPPA) model, a computable general equilibrium (CGE) model of the world economy. The methodology translates bottom-up engineering information for two carbon capture and sequestration (CCS) technologies in the electric power sector into the EPPA model and discusses issues that arise in assuring an accurate representation and realistic market penetration. We find that coal-based technologies with sequestration penetrate, despite their higher cost today, because of projected rising natural gas prices.

JEL classification: D58; O33; Q2; Q4

Keywords: Energy technology; Climate change; General equilibrium modeling

1. Introduction

The threat of climate change due to the atmospheric accumulation of greenhouse gases has led to the development of numerous models of complex socio-economic systems that drive anthropogenic emissions. Such models form a key component of integrated climate policy analysis. A critical factor governing future anthropogenic emissions is the rate and

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magnitude of technological change toward low- or no-carbon emitting technologies (IPCC, 2001). Two broad approaches exist for modeling the interaction between energy, economic, and environmental systems and technology (van der Zwaan et al., 2002). The bottom-up approach depicts a rich set of representative energy-using technologies at a level of detail such that engineering studies can be used to cost out a representative example (e.g., a 500 megawatt coal fired power plant, or a 1-MW wind turbine). The technologies are typically described as a set of linear activity models based on engineering data of life cycle costs and thermodynamic efficiencies. These models can be used to identify, for example, the least-cost mix of technologies for meeting a given final energy demand under greenhouse gas emissions constraints. They often take energy and other prices as exogenous and, therefore, may overestimate the potential penetration of a technology such as natural gas combined cycle power generation if, for example, its widespread use causes gas prices to rise.

Top-down models, the second modeling approach, typically represent technology using relatively aggregated production functions for each sector of the economy. For example, electricity production may be treated as a single sector with capital, labor, material, and fuel inputs. Continuous substitution among inputs (e.g., between gas and coal or between fuels and capital) represents what is in the bottom-up approach a discrete shift from one technology to another. The particular focus of the top-down approach is market and economy-wide feedbacks and interactions, often sacrificing the technological richness of the bottom-up approach.

The simple characterization of these two modeling approaches is used here only to provide a basic distinction for the reader who is not familiar with the decades-long debate about the pros and cons of these approaches. We make no attempt to describe the great diversity of models that include features of both the top-down and bottom-up approaches. This paper reviews our efforts to enhance the technological richness of a top-down economic model using bottom-up engineering information.[1] In this regard, we have chosen to use a computable general equilibrium (CGE) model of the world economy—the MIT Emissions Prediction and Policy Analysis (EPPA) model. Among the various top-down approaches, CGE models are the most complete in representing economy-wide interactions, including international trade, energy supply and demand, inter-industry demand and supply for goods and services, factor markets, and consumer demands. On the other hand, they are often the least rich in their representation of technological details.

In the work discussed here, we introduce three new electricity generation options that compete with the existing electricity generation technologies in the EPPA model. The three new power generation technologies are: (1) a natural gas combined cycle technology (NGCC or advanced gas) without carbon capture and sequestration, (2) a natural gas combined cycle technology with carbon capture and sequestration (gas CCS), and (3) an

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integrated coal gasification technology with carbon capture and sequestration (coal CCS). These compete in the EPPA model's electricity sector with conventional fossil generation, nuclear, hydro, wind, and biomass power generation. We focus on these particular sequestration technologies because David and Herzog (2000) identify these technologies—natural gas combined cycle generation with capture via amine scrubbing of the flue gas, and integrated coal gasification combined cycle generation with pre-combustion capture of the carbon dioxide (CO_2)—as two of the most promising technological options for producing electricity from fossil fuels with low CO_2 emissions.

The term carbon capture and sequestration as used herein refers only to these two fossil energy technologies and the subsequent capture (the separation of the CO_2 from the flue or pre-combustion gases) and sequestration (the deposition of the CO_2 into a reservoir). Other energy sources and capture processes are often considered under the umbrella of carbon capture and sequestration technologies, but they are not evaluated here. Previous work with the EPPA model (Biggs, 2000) has demonstrated the need to introduce NGCC technology without carbon capture to accurately assess the marginal additional cost of the carbon capture and sequestration technology. This advanced gas technology without carbon capture and sequestration represents a technology that was not widespread for the 1995 base year of the EPPA model, but is widely seen as the most likely technology to be installed where new capacity is needed, assuming natural gas prices do not rise greatly relative to other fuels. This paper describes the method of analysis and the results obtained from introducing these technologies into multiple regions of a general equilibrium, global economic model. This analysis expands upon previous work (Biggs, 2000; Kim and Edmonds, 2000; Biggs et al., 2000; Dooley et al., 1999; Eckaus et al., 1996) by introducing CCS technologies into multiple regions of a CGE model.

We begin with an overview of the MIT EPPA model in Section 2. Section 3 presents the bottom-up engineering cost model information and considers the translation of bottom-up information into the data required for a top-down representation. The next three sections then discuss specific issues that arise in assuring that the CGE representation of the technology accurately represents key engineering information and that market penetration of the technology is realistically represented. In particular, Section 4 examines the treatment of thermodynamic energy efficiency within production functions. Section 5 describes our approach for modeling technology penetration. Section 6 describes our methods of capital stock vintaging and malleability. Finally, Section 7 describes results of policy simulations.

2. The MIT EPPA model

The EPPA model is a recursive dynamic multi-regional general equilibrium model of the world economy developed for the analysis of climate change policy as explained in Babiker et al. (2001). The current version of the model is built on a comprehensive energy-economy data set, GTAP-E as described by Hertel (1997), that accommodates a consistent representation of energy markets in physical units as well as detailed accounts of regional production and bilateral trade flows. The base year for the model is 1995, and it is solved recursively at 5-year intervals through 2100 to capture the long-term dynamics of resource scarcity and capital stock turnover. EPPA consists of 12 regions, which are linked by international trade, nine production sectors, and a representative consumer for each region as shown in Table 1. Capital, labor, and a fixed factor resource for each fossil fuel and for agriculture comprise the primary factors of production.

Constant elasticity of substitution (CES) functions are used to describe production and consumption within each region and sector. CES functions take the form of Eq. (1) and have an elasticity of substitution σ, related to ρ (ρ=$(1-\sigma)/\sigma$), that is constant as relative input prices change.

$$Y = \left[A_1 X_1^{\rho} + \cdots + A_m X_m^{\rho}\right]^{1/\rho} \tag{1}$$

In Eq. (1), Y is output, X_m, $m=1,..,n$, are inputs, and the A_m are share parameters. Under base year conditions, normalizing prices to 1.0, the A_m are the actual input shares in production, S_m. The factor shares, S_m, are the percentage of each input required to produce the output, Y. The sum of S_m over all n equals unity. A limiting feature of the CES function is that with more than two inputs, the elasticity of substitution is identical between all pairs of inputs. This limit is overcome by 'nesting' inputs, that is, by representing sub-groups of inputs as separate CES functions, and aggregating these nests using CES functions. It is then possible to specify a separate elasticity for each of these nests. As we discuss in the next section, the main purpose of using engineering cost data is to use it to parameterize a CES production function like that in Eq. (1).

As previously identified, the EPPA model includes a conventional fossil electricity sector and separate nuclear, hydro, biomass, and combined wind and solar generation technologies. While the representation of individual technologies allows one form of technical change in the solution, three other characterizations of technical change exist within the EPPA model. First, exogenous improvements in labor and land productivity create higher levels of output for a given labor and land input. A second source of technology improvement is an autonomous energy efficiency improvement factor or AEEI. Similar to the labor productivity improvement, it represents non-price induced technological change that lowers the amount of energy input required in intermediate production sectors and in final consumption. The AEEI means that less energy is used with no additional inputs so that there are economic savings as a result. Bottom-up analysis of specific technological options often find technologies that are not yet fully adopted that would save producers and consumers money: the AEEI does the same thing in the EPPA model and a similar factor is used in most other top-down models. A third way in which technological change is represented in the EPPA model is through price induced input

Table 1
EPPA regions, sectors, and factors of production

Regions	*Annex B* (United States, Japan, European Union, Other OECD, Eastern European Associates, Former Soviet Union) and *Non-Annex B* (Brazil, China, India, Energy Exporting Countries, Dynamic Asian Economies, and rest of world)
Production sectors	Coal, oil, refined oil, gas, electricity, energy intensive industries, agriculture, investment, and other industries
Primary factors	Labor, capital, and fixed factor resources for coal, oil, gas, shale oil, and agriculture

substitution. Substitution of one fuel for another or between fuels and capital and labor represents what in a bottom-up model would be discrete changes from one technology to another.

3. Translating bottom-up information into a top-down specification

3.1. Bottom-up costs

We extract from the bottom-up engineering models the relative cost of electricity from CCS technologies compared to conventional technologies, the thermodynamic efficiency, and the shares of capital, labor, and energy inputs to represent the CCS technologies in EPPA. We base the generation cost and efficiency of CCS technologies on the bottom-up engineering costs as estimated by David and Herzog (2000). Their analysis averages several generation cost studies from the US and Europe of advanced gas and coal generation technologies both with and without carbon capture. Given the cost structure of the CGE model, it proves useful to consider the total unit cost of electricity as the sum of generation (including CO_2 capture), transmission and distribution (T&D), sequestration, and the cost of carbon permits to cover the portion of carbon that is not captured:

$$C_{\text{Electricity}} = C_{\text{Generation}} + C_{\text{TD}} + C_{\text{Sequestration}} + \kappa P_{\text{Carbon}} \quad (2)$$

where the constant κ is the technology-specific rate of carbon emitted per unit of electricity produced. Formulated as such, Eq. (2) makes explicit the dependence of the cost of electricity on the price that must be paid for any carbon that is emitted to the atmosphere by the technology as even capture technologies cannot capture 100% of the carbon in the fuel.

The generation costs, as described by David and Herzog (2000), are based on known, but more efficient, state-of-the-art, technologies that are limited in use today. We use David and Herzog's (2000) set of cost estimates that assume that small technical improvements are made prior to commercial availability in 2020. These technology-based studies do not include estimates of transmission and distribution (T&D) costs but these costs must be incorporated as they are included in other electric technologies within EPPA. T&D costs were derived from US data (U.S. DOE, 1999). Sequestration costs include pipeline transport of the captured CO_2 of up to 500 km, its injection into a reservoir, and other costs related to the disposal site such as monitoring. We use a constant cost of $37 per metric ton of carbon for the sequestration component of the costs where the carbon is transported and injected into the reservoir as liquid CO_2. This cost estimate is from Herzog (2000). Based on the analysis of David and Herzog (2000), we assume the technologies capture 90% of the carbon content of the fuel input.

Table 2 below presents the total cost of electricity, including T&D costs, but net of emission penalties from the bottom-up data for the three technologies. At natural gas prices of nearly $3.00 per million Btu, the NGCC technology, estimated to be the lowest cost electricity producing technology currently available, produces electricity at 55 mills/kWh (Table 2, column 2), 16% less than the average cost of delivered power in the US at

Table 2
Electricity costs by technology, including transmission and distribution costs

Technology	Total electricity cost net of emissions cost (mills/kWh)	Cost ratio of CCS to conventional technology (Mark-up)	Thermodynamic efficiency (%)	Emissions constant κ (kg C/kWh)	Carbon entry price for CCS vs. NGCC, pulverized coal ($/mtC)
Advanced gas (NGCC)	55.3	0.84	60	0.092	NA
Gas CCS	71.0	1.08	54	0.010	$190/$35
Coal CCS	82.3	1.25	44	0.020	$380/$100

66 mills/kWh (DOE, 2000). The gas CCS technology is 8% more expensive than the average cost of delivered power and 28% more expensive than the NGCC technology at 71 mills/kWh. The coal CCS technology, at 82.3 mills/kWh, is 25% more expensive than the average cost of delivered power and carries a 49% premium over the NGCC technology. Column 3 shows the ratio of the cost of each of these technologies to the average cost of conventional generation, which we refer to as the cost 'mark-up'. The difference between the best available fossil fuel electricity generation option and the current cost of electricity production as represented in the input–output data in National Income and Product Accounts (NIPAs) data, the basis for CGE modeling, is why Biggs (2000) concluded that to accurately represent carbon capture and sequestration, one also needs to add the advanced gas technology. The CGE modeling approach assumes that the base year data represents an equilibrium condition, but the incomplete penetration of the advanced gas technology means that the electricity sector was in fact in disequilibrium in the base year. Adding the technology explicitly thus allows us to represent this disequilibrium and simulate the gradual move, over time, toward an equilibrium that includes this technology—depending, of course, on how fuel prices and other factor prices change.

Another important feature of the CCS technologies are thermodynamic efficiencies (Table 2, column 4), which are approximately 10% less than generation technologies without capture and sequestration. Finally, carbon emissions are much lower for the CCS technologies than for advanced gas generation but because only 90% of the carbon is removed, some emissions remain (Table 2, column 5). Given these data, Eq. (2) can be used to see how, from a partial equilibrium perspective, different generation technologies compare as the price of carbon changes, holding all other input prices constant. In particular, we can compute the carbon price that would be necessary to make the lower emitting technologies just competitive with conventional coal technologies or the advanced gas technology. These estimated break-even carbon prices, as compared with the advanced gas technology, the lowest cost alternative, and pulverized coal, the most ubiquitous conventional technology, are shown in the last column of Table 2. When compared with the advanced gas technology, and at the natural gas prices assumed above, the gas CCS technology becomes competitive at $190/mtC (metric tons of carbon), half that of the coal capture technology's carbon-equivalent price of $380/mtC. These carbon-equivalent prices drop substantially when the capture technologies are compared to

Table 3
Share of total electricity cost by category and technology

Technology	Cost category		
	Capital	O&M, G&A	Fuel
Advanced gas (NGCC)	0.49	0.21	0.30
Gas CCS	0.54	0.20	0.26
Coal CCS	0.66	0.22	0.12

pulverized coal technology, which at 0.21 kg C/kWh emits over twice as much carbon as the advanced gas technology. Evaluated against this technology, the gas CCS technology becomes competitive at $35/mtC while the coal CCS technology is competitive at prices above $100/mtC. These differences further emphasize the importance of representing the best-available non-capture fossil technology if one hopes to correctly estimate the potential penetration of CCS technologies.

These three technologies differ not only in total costs, but also in the levels of capital, labor, and fuel required to produce a unit of output. The bottom-up engineering cost data for the cost components listed in Eq. (2) are categorized as capital, fuel, operations and maintenance, and administrative and general. From these data, we can estimate input shares of capital, labor, and fuel, and these can be used directly as the CES share parameters (Table 3). These shares of capital and fuel inputs offer insight into how changes in various factor prices affect each technology. The advanced gas technology without capture and sequestration requires the lowest share of capital at 0.49, but the highest share of fuel at 0.30. The addition of the capital intensive CCS technology to an NGCC plant raises the capital share to 0.54 while reducing the fuel share to 0.26 even though capturing and sequestering the CO_2 requires more absolute energy per kWh of electricity produced. Capital represents an even greater input share for the coal capture technology at 0.66. A fuel share of 0.12 reflects both low coal prices and the capital-intensive nature of the technology. The shares of operations, maintenance, general and administrative costs range from 0.20 to 0.22 across the three technologies.

3.2. Top-down representation

Having determined the total costs of delivered electricity, the sources of those costs, thermodynamic efficiencies, and carbon emissions for the new technologies, we translate this bottom-up information into a top-down representation consistent with EPPA's modeling framework outlined in Section 2. We adopt the following conventions in translating the cost categories (capital, operations and maintenance, administrative and general, and fuel) into the factors of production found in EPPA (capital, labor, and energy). Bottom-up capital and fuel costs are respectively treated as inputs of capital and energy. Operations, maintenance, administrative, and general are grouped into labor costs. The shares of each input S_m are used as the A_m in the CES production functions, as depicted in Eq. (1), and are based upon the percentage that component contributes to the overall cost of the technology. Having separated out the various cost components, we develop the nesting structure of the CES production functions and subsequently specify substitution elasticities.

As shown in Fig. 1 below, the top-level substitution of the production function occurs between the capital–labor–energy bundle and a fixed factor resource. The fixed factor resource represents an endogenously specified production input that serves to limit the rate of penetration of a technology. In the context of large-scale electricity generating technologies, this may be thought of as an initially limited amount of engineering capacity to build and install new plants or a regulatory process that slows installation. The representation of the fixed factor will be discussed at length in Section 5. The capital and labor inputs for generation (X_{Kgen}, X_{Lgen}) and transmission and distribution (X_{Ktd}, X_{Ltd}) are grouped in the value-added bundle. This allows substitution between capital and labor and recognizes that transmission and distribution as well as generation are required to deliver a unit of electricity. The fuel and sequestration bundle consists of three inputs consumed in fixed proportions (substitution elasticity is zero): fuel with sequestered carbon ($X_{\mathrm{Fuel\ ex\ CO_2}}$), fuel excluding sequestered carbon ($X_{\mathrm{Fuel\ and\ CO_2}}$), and a capital–labor bundle specific to sequestration (X_{Kseq}, X_{Lseq}). Ninety percent of the fuel consumed by a generating plant with CCS, $X_{\mathrm{Fuel\ ex\ CO_2}}$, yields CO_2 that is subsequently sequestered. Consumption of this portion of the fuel is not subject to any carbon penalties. However, the remaining 10% of the fuel input, $X_{\mathrm{Fuel\ and\ CO_2}}$, emits CO_2 into the atmosphere that entails carbon penalties if there is a carbon policy in place. The nested structure leads to eight separate inputs for capital, fuel, and labor (Kgen, Lgen, Ktd, Fuel and CO_2, Fuel excluding CO_2, Kseq, Lseq).

The values for the various elasticities of substitution are shown in Fig. 1. Critical elasticities are those that represent the ability to substitute between fuels and other factors. These elasticities were chosen to ensure that the implied thermodynamic efficiency remained within a range that was technologically feasible, even under very high fuel and carbon prices. This consideration is discussed at greater length in Section 4. Consistent with the bottom-up technology information, the input proportions are fixed by the percentage of carbon captured from the fuel, which was established at 90% as described in Section 3. This portion of the fuel input requires capital and labor inputs for pipeline transport and injection of the CO_2. While the non-sequestered fraction of the fuel does not incur sequestration costs, it includes the costs of carbon taxes or shadow prices for

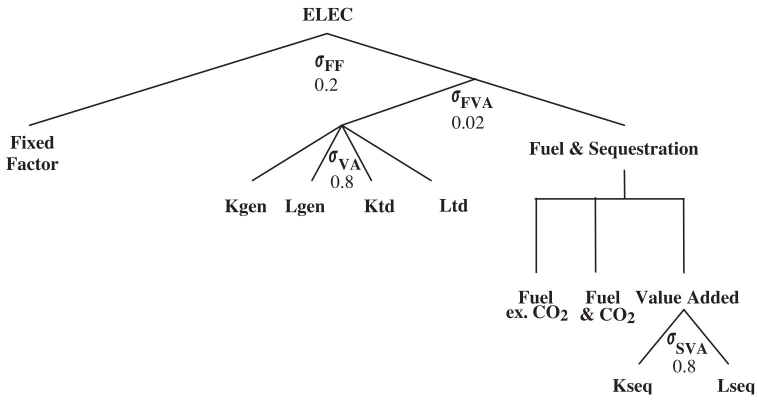

Fig. 1. CES nesting structure for CCS technologies.

releasing CO_2 into the atmosphere. The production structure and elasticities are the same for the advanced gas (NGCC) technology with two exceptions. The capital and labor inputs for sequestration, X_{Kseq} and X_{Lseq}, are both zero and the fuel input consists of only $X_{\mathrm{Fuel\ and\ CO_2}}$, which includes any carbon penalties since all of the CO_2 is emitted to the atmosphere.

Having defined a production function with cost share information based on a bottom-up cost model and introduced nesting to allow for input substitution where appropriate, we next specify the total cost of each new technology relative to existing production technologies. To obtain the correct entry condition for the technologies, we multiply each of the input share parameters $A_{m,b}$ in the production function by the 'mark-up' factor M_b found in Table 2, column 3 where the subscript b denotes the technologies identified in Table 2. We use the same M_b, the ratio of new technology cost to fossil fuel-based conventional generation, for all regions.[2]

The input shares $S_{m,b}$ now sum to M_b instead of unity. As indicated in the partial equilibrium analysis, the CCS technologies will not be competitive with conventional or advanced gas technologies until changes in input prices increase the costs of the conventional and advanced gas technologies. With an M_b of less than unity, the advanced gas technology is cheaper than the conventional technologies and is competitive immediately, given relative fuel prices in the base year.

4. Treatment of thermodynamic efficiency in CES production functions

The concept of thermodynamic efficiency for a power plant is well understood in engineering terms as the ratio of the energy content of the electricity produced to the energy content of the fuel input. One of the key sets of information we can use from engineering studies about the possible future evolution of generation technologies is the prospect (and limits) regarding improvements in this efficiency. EPPA retains physical accounts of fuel use and electricity output and so we are able to compute this ratio as it changes over time and under different policy scenarios. Preliminary analysis demonstrated that it is quite possible, with an exogenous AEEI efficiency trend combined with substitution elasticities typical of the econometric literature, to have a ratio of energy used to electricity produced in physical units (e.g., exajoules) that eventually exceeds 1.0 when fuel prices are high, violating the basic laws of thermodynamics. In addition to constraining future simulations, it also turns out that the thermodynamic efficiencies help us to adjust the production function parameters for different regions. To describe how this was done requires that we discuss in greater detail the relationship between the physical energy accounts and the economic accounts in EPPA.

The physical energy accounts as represented in EPPA are supplementary to the economic data that determine the model solution. The economic data uses aggregate

[2] This assumption works well in most regions with a substantial amount of conventional generation, but may understate the relative costs of the new technologies in regions with low levels of conventional fossil generation such as Brazil and Other OECD Countries (Canada, Australia, New Zealand, Turkey, Norway, Iceland, Switzerland) where hydroelectric power is the main electric generating technology.

sectors, based on National Income and Product Account (NIPA) data, where the aggregate is based on the economic principle that prices are used to weight heterogeneous goods that make up the aggregate. For example, our sector of refined oil products is an aggregation of a variety of products from petroleum refining including, for example, jet fuel, gasoline, diesel, and residual oil. Similarly, coal consumption is an aggregate of different grades of coal, with each grade or type of coal having a potentially different energy and carbon content and a different price. Higher valued products have larger weights in the aggregation so that the quantity index so calculated does not have a direct interpretation in physical energy units such as BTUs or exajoules, unless one can go back to the underlying price and quantity data. Often these data are based on expenditures or sales and so there is no separate price and quantity data at the level that is typically used in engineering cost studies. The supplementary physical data on fuel use, developed in GTAP to be consistent with the aggregate economic accounts in the base year, allows us, however, to calculate physical use of energy in simulations based on the economic indices of quantity that are simulated in the model.[3]

The relationship of EPPA-based data, the base year price of fuels in physical energy values ($/EJ), and thermodynamic efficiency is described in Eq. (3).

$$\frac{E_{\mathrm{elec},b,r}}{E_{\mathrm{fuel},b,r}} = \frac{Y_{\mathrm{elec},b,r}\frac{1}{p^{*}_{\mathrm{elec},r}}}{X_{\mathrm{fuel},b,r}\frac{1}{p^{*}_{\mathrm{fuel},r}}S_{\mathrm{fuel},b,r}M_b} \tag{3}$$

The left side of the equation is the thermodynamic efficiency for technology b in region r, the energy content of electricity output $E_{\mathrm{elec},b,r}$ divided by the energy content of the fuel input $E_{\mathrm{Fuel},b,r}$. The right hand side is the corresponding calculation that is needed to get this ratio from the economic data used in EPPA, where: $Y_{\mathrm{elec},b,r}$ is quantity of output of electricity (a dollar-weighted index); $p^{*}_{\mathrm{elec},r}$ is an average price of electricity constructed so that the supplementary physical data are consistent with the economic data base; $X_{\mathrm{Fuel},b,r}$ is the fuel input in a dollar-weighted index; $p^{*}_{\mathrm{fuel},r}$ is the corresponding price of the fuel in the base year; $S_{\mathrm{Fuel},b,r}$ is the production share of fuel, and M_b is the mark-up ratio from Table 2.

For technologies in use in the base year, and given the assumptions that the base year data reflects an equilibrium and that output of electricity from different technologies are perfect substitutes, $M_b = 1.0$.

For simulations of future conditions under reference or policy situations, the model simulates new values for Y, X, and price indices for each input reflecting real changes in factor prices over time and across policy cases. Thus, thermodynamic efficiency can be estimated from the economic data over time for existing technologies and for new, and currently unused, technologies such as the CCS technology.

[3] The aggregation is defined for the base year, and the weights remain unchanged in future simulations as, having once aggregated to this level, the model solution provides no information on how these weights change in the future. This physical quantity index is the value of fuel use in the base year under the normalization that prices are equal to 1.0. Prices diverge from 1.0 in simulations but the underlying prices used in the aggregation do not change and so the correspondence to the physical index of energy use remains.

The ability to check on the implied thermodynamic efficiency proved useful in evaluating the reasonableness of future projections of the model, in comparison with technological potential as previously discussed. It also proved useful in our initial calibration of regional costs, as we used cost data primarily from US- and EU-based studies of these technologies. Such a simplifying assumption, that 'best available technology' would be available worldwide, is common in either top-down or bottom-up modeling approaches. Given that large firms with a multinational presence are developing the technologies this assumption seems reasonable. The cost share data depend, however, not only on the technology characteristics but also on the prevailing prices for the various inputs. Here we faced the difficulty that, for most of the inputs, we did not have separate price and quantity data for each region for the detailed engineering estimates that was consistent with the NIPA-type data in the GTAP base year data. To correct for these differences at the engineering cost level would literally require a re-estimate of the engineering costs in terms of the price of all the items that would go into building the facility (concrete, steel, labor, siting) and running it (fuel and other operating expenses), item by item.

To use Eq. (3) to make a correction for regional differences in costs, we set the cost share of fuel, $S_{\mathrm{Fuel},b,r}$, given the regions price for the fuel, $p^{*}_{\mathrm{fuel},r}$, and electricity, $p^{*}_{\mathrm{elec},r}$, such that thermodynamic efficiency of the technology based on our engineering data and assumption of a globally available technology was met, proportionally adjusting the cost share of other inputs as necessary so that the share total summed to unity. Incorporating the above methodologies into a CES production function yields the generalized form in Eq. (4).

$$Y_{\mathrm{elec},b,r} = \left[M_b A_{1,b,r} X^{\rho}_{1,b,r} + \cdots + M_b A_{n,b,r} X^{\rho}_{n,b,r}\right]^{1/\rho} \tag{4}$$

These regional adjustments turned out to be quite important in some cases. Opposite extremes were witnessed in Japan and the Former Soviet Union. The ratio of Japan's electricity to fuel price in the GTAP data is much higher than in other regions, implying much higher non-fuel input costs for current generation, even with relatively high fuel prices in Japan.[4] Therefore, for the new technologies introduced for this analysis, using the fuel cost share based on our engineering data implied a thermodynamic efficiency approaching 15%. The situation was the opposite in the FSU, for which the GTAP data shows a very low electricity price implying that the cost share of other inputs was much lower than in other regions. Using the fuel cost share based on the engineering data implied a thermodynamic efficiency approaching 70%. We interpret these regional differences in the cost share of other inputs in current generation to represent regional differences in, for example, regulation (and the requirements it places in the technology) and in prices of other inputs. By adjusting the fuel shares for each region so that the

[4] Under the assumption of a constant returns to scale technology, and initial equilibrium, CGE models like EPPA require that marginal cost equals average cost equals output price in the base data, except as we have altered this for the new technologies with the factor Mb. A region with relatively high electricity price compared with the fuel price, given similar technological efficiency, implies that the cost share for other inputs is much higher for that region than for most regions.

thermodynamic efficiencies, as calculated using Eq. (3), are consistent with the engineering data presented in Table 2 (i.e. 44% to 60% depending on the technology), and with a constant mark-up across regions, we implicitly assume that regional cost factors causing differences in existing electricity generation technologies will also affect the cost structure of these new technologies.

5. Control of technology penetration rates

Evidence that a new technology takes over a market gradually, where the share of the market controlled by the technology plotted against time follows some type of S-shaped function, is widely observed (Geroski, 2000). There are many reasons cited for such gradual penetration. For example, long-lived capital in the old technology may only be replaced with the new technology as the old physically depreciates. In EPPA, the vintaging of capital, discussed in the next section, captures this process explicitly. But other processes also slow penetration. In the investment literature, many of these are often grouped under the concept of adjustment costs that occur with rapid expansion (e.g., Hayashi, 1982). At the engineering cost level, such adjustment costs may reflect the need to gradually develop an industry with sufficient specialized engineering resources and the necessary equipment to install new capacity. Penetration may also be slowed by regulatory approval processes.[5] Such limits increase the cost, and slow the penetration. In the absence of a specific representation of these processes, the rate of penetration of a constant returns to scale technology modeled in a CGE model like EPPA can be unrealistically rapid.

An approach for representing the penetration process, that is theoretically consistent with CGE modeling, is to explicitly introduce an additional quasi-fixed factor in the production function, specific to the new technology, whose endowment in the economy is initially quite limited.[6] This was represented in Fig. 1 by the top nested fixed factor, where the factor share is set at 1%. The prices of the fixed factor and annual rents are determined endogenously, depending on its quantity relative to demand for the technology, and the rents accrue to the representative consumer. As modeled, the fixed factor resource

[5] Another set of factors that contributes to slow penetration is grouped under the concept of 'learning'. Learning—that may occur in the regulatory process, in engineering firms constructing the plants, and in the companies purchasing and running plants—improves cost and performance, and therefore increases competitiveness and the rate market penetration. Often the concept of learning and adjustment cost are seen as opposing, adjustment costs raise the cost of the technology and learning leads to lower costs. Some of the main differences may be due largely to the perspective from which the process is observed. In the adjustment cost case, a long-run low cost is identified but adjustment costs explain why that low cost may not be achieved if rapid deployment is required (e.g., lack of experience of engineering companies). Learning instead focuses on a current high cost of the first few installations, and based on this information, identifies reasons that costs may fall (e.g., learning by engineering companies of how to construct the plants more efficiently).

[6] This general approach is applied to other backstop technologies in EPPA. Much of the adjustment cost literature and evidence on slow penetration is based on partial equilibrium concepts, or describes statistical or econometric estimates where the processes are suggested rather than explicitly addressed. This empirical evidence can be quite useful in parameterizing our penetration structure but this does not provide a theoretically consistent approach for CGE modeling.

endowment is initially limited but grows as a function of the technology's output. In the context of large-scale electricity generating technologies, this fixed factor may be thought of as engineering capacity to build and install new plants that is initially limited but that increases in availability as the technology moves from the pilot plant stage to viable market competition. We posit a functional form that produces exponential growth of the fixed factor for each technology and region as a function of output, Y, as shown in Eq. (5), where the region and technology subscripts have been dropped for simplicity.

$$FF = \alpha Y^{\gamma} + \lambda Y^{\zeta} \tag{5}$$

We consider the penetration rate of an analogous large-scale electric generating technology—nuclear power—to parameterize growth of the fixed factor. During the rapid growth of nuclear power in the US, the share of nuclear power expanded by up to 45% per year in the early 1970s dropping to 9% per year in the 1980s. We parameterize Eq. (5) to limit the share growth of the new technologies to roughly mimic that of nuclear power under a carbon tax of \$200/mtC. As long as output is growing, the endowment of fixed factor grows more than proportionally, and so the fixed factor becomes less scarce, rents fall, and in the long run it does not restrict the ultimate penetration of the technology. The partial equilibrium costs we specified in Table 1 are achieved when the demand for a technology's output balances the simulated price of the fixed factor. The first term in Eq. (5) is approximately linear with $\gamma = 0.8$ to 0.9 and $\alpha = 0.01$. This term governs the growth of the fixed factor at low levels of output Y_r as $\alpha \gg \lambda$. The second term accelerates fixed factor growth at high levels of output as $\lambda = 0.00001$ and $\zeta = 2.0$ to 2.2.

6. Capital stock vintaging

As examined in the work of Jacoby and Sue-Wing (1999) and as described in detail by Babiker et al. (2001), the EPPA model includes explicit vintaging of capital stock to capture the irreversible nature of physical capital investments. As used in the standard EPPA, substitution as described by the production function parameters, such as those in Fig. 1, applies only to a malleable portion of the capital stock. Malleable capital in any period includes new investment and a portion $(1-\theta)$ of the previous periods investments, remaining after depreciation, that is assumed to remain flexible. This representation allows for partial retrofit or redeployment of existing capital, while retaining the idea that there is not complete flexibility to reconfigure older vintages of physical capital. The vintaged portion of investment (θ) takes on a Leontief production structure for all inputs (Fig. 2), frozen at the factor shares that actually were simulated in the period in which it was put in place. For period t, and suppressing the technology subscript, the factor share parameters $A_{m,t}$, $m = 1, \ldots, n$ are updated to equal the $S_{m,t-1}$ simulated in period $t-1$ and the production structure is redefined as fixed coefficient, i.e., with elasticities of substitution all equal to zero.

As evidenced in Section 3, fossil fuel electric generating technologies are highly capital intensive. Thus, the vintaging approach used in other sectors of EPPA was adapted and applied to the new technologies we introduced. As will be shown in the

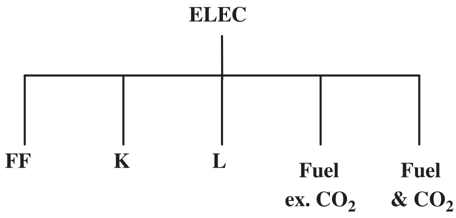

Fig. 2. Production function for rigid, vintaged capital.

results section, depending on the reference and policy case conditions, it becomes economically desirable to switch from one new technology to another as relative prices for carbon and fuels, and other conditions, change. Representing the irreversibility of investment (its long capital life) as an explicitly vintaged capital stock means that a large investment in advanced gas technology in period t cannot be redeployed or reconfigured as a coal plant with CCS in period $t+1$. Once vintaged capacity is put in place, it remains until it fully depreciates.

The vintaged portion of the capital follows the standard EPPA formulation, where four vintages are defined. A difference as applied for these technologies from the approach elsewhere in EPPA is that the $(1-\theta)$ malleable portion of the stock from previous periods remains specific to the technology. In the standard EPPA, the malleable portion can, in principle, be redeployed anywhere in the economy. This revised specification as applied to the three new technologies creates, in addition to the four new vintages of capital in each technology, three new distinct malleable capital stocks that are specific to these new technologies. Given EPPA's 5-year time step, this vintaging structure means that capital has a lifetime of 25 years, 5 years as malleable capital when it is new investment and the following 20 years as either vintaged capital or sector-specific malleable capital.

The evolution of capital over time is implemented in a set of dynamic equations. Malleable capital, $K^{M}_{b,r,t+1}$, for technology b in region r for period $t+1$ is comprised of new investment in the technology, $I_{b,r,t+1}$, plus the stock of capital invested in period t remaining after depreciation that also remains malleable where $(1-\delta)$ is the fraction of capital that remains after depreciation.

$$K^{M}_{b,r,t+1} = I_{b,r,t+1} + (1-\delta)K^{M}_{b,r,t} \tag{6}$$

Rigid capital, $K^{R}_{b,r,t+1}$ in period $t+1$ is comprised of the stock of capital invested in period t remaining after depreciation with fixed input share parameters.

$$K^{R}_{b,r,t+1,v} = \theta(1-\delta)I_{b,r,t} \qquad \text{for } v=1 \tag{7}$$

The quantity of rigid capital in subsequent periods undergoes depreciation.

$$K^{R}_{b,r,t+1,v} = (1-\delta)K^{R}_{b,r,t,v-1} \qquad \text{for } v=2,3,4 \tag{8}$$

We made the malleable capital technology-specific for these new technologies because, in reality, it is difficult to imagine that very much of the capital stock (e.g., turbines and pipelines) could be feasibly redeployed elsewhere in the economy. For the other sectors in EPPA, the assumption is that the malleable capital stock consists of structures, vehicles, and other such equipment that could be redeployed. These representations are simplifications of the complex process of capital stock turnover, but become necessary to limit the number of distinct capital stocks and maintain the computational feasibility of the model.

7. Scenarios and results

Using the methodology described above, we analyze the global adoption of CCS technologies under three policy scenarios as outlined in Table 4. They were designed to illustrate the potential of carbon sequestration under widely different future conditions, and our use of them in no way indicates an endorsement of any of them. The first scenario is a reference scenario where it is assumed that there are no constraints on greenhouse gas emissions. In the second scenario, an initial tax of \$50 per metric ton (\$/mtC) is placed on all regions beginning in 2010. The tax increases by \$25/mtC in every 5-year period and reaches a maximum of \$200/mtC by 2040. The tax applies only to carbon dioxide, excluding other greenhouse gases's from the tax. The third scenario is consistent with stabilization of CO_2 concentrations at approximately 550 parts per million sometime after the year 2100, when simulated through the MIT Integrated Global System Model (IGSM) under reference assumptions regarding the parameters of the IGSM (Reilly et al., 1999). The time profile of emissions reduction was defined by an emissions intensity target, in terms of all greenhouse gases, similar to the target proposed by the Bush Administration but applied to all regions and gradually tightened over time. The concept of a tightening intensity target, compared with a constant target, was conceptually described by the Bush Administration (Bush, 2002) but the specific emissions intensity targets beyond 2010 were not defined in that document. The concentration stabilization scenario places restrictions on both CO_2 and other greenhouse gases by reducing the emissions intensity, or ratio of CO_2 equivalent emissions to gross domestic product, in each region.[7]

This scenario is implemented in the model through a greenhouse gas quota. Emission quotas are established in each region that corresponds to an 18% emissions intensity reduction from 2000 to 2010 as suggested by the Bush Administration. Quotas in subsequent periods, E_{t+1}, are calculated from the product of an emissions intensity reduction factor $\Re_t$, the previous period's emissions intensity ε_t/G_t, and the expected gross national product (GNP) G_{t+1} as shown in Eq. (9). Expected GNP is approximated as the product of G_t, the current GNP and G_t/G_{t-1}, the ratio of current GNP over the previous period's GNP. The emissions intensity reduction factor $\Re_t$ begins at 18% in

[7] The stabilization at approximately 550 ppm is in terms of CO_2 alone. Because there are controls on other gases, their concentrations are also lower than in the reference. We do not try to state this as a target in CO_2 equivalent ppm as that does not make much sense, because GWP's, the basis for CO_2 equivalent, integrate radiative forcing over time whereas a concentration exists at a given point in time. CH_4 concentrations, the second most important anthropogenic contributor to warming after CO_2, are lower in 2100 than they are currently under these control scenarios.

Table 4
Description of policy scenarios

Scenario	Description
Reference	No greenhouse gas constraints in any regions.
Carbon tax	In 2010, a $50 per ton tax is placed on carbon. The tax increases by $25 every five years reaching a maximum of $200 per ton carbon emitted by 2040. Other greenhouse gases are not taxed.
Greenhouse gas concentration stabilization	Greenhouse gas concentrations are stabilized at 550 ppm shortly after 2100. Greenhouse gas emissions intensity is reduced by 18% from 2000 to 2010. Thereafter, emissions intensity is reduced by 12%, on average, every period. Trading is allowed between countries and across gases.

2015 and reaches a maximum of 26% by 2030. Trading is allowed among gases and regions.

$$E_{t+1} = \Re_t \left(\frac{\varepsilon_t}{G_t} \right) G_{t+1} \cong \Re_t \varepsilon_t \frac{G_t}{G_{t-1}} \tag{9}$$

The resulting emissions paths and carbon prices are presented below followed by an analysis of global CCS technology adoption for the three scenarios. Additionally, we evaluate the effects of alternative assumptions on the treatment of capital vintaging and malleability.

7.1. Aggregate economic and emissions results

While both policy scenarios significantly decrease emissions versus the reference case, emissions diverge greatly after 2030. Under the tax scenario, global greenhouse gas emissions remain relatively flat from 2010 through 2025 when the percentage increase in the carbon tax is the highest as shown in Fig. 4. Emissions growth increases in 2030 and accelerates after 2040 when the carbon tax has reached its maximum level. By 2100, the tax scenario reduces emissions by 37% from reference. The CO_2 concentration stabiliza-

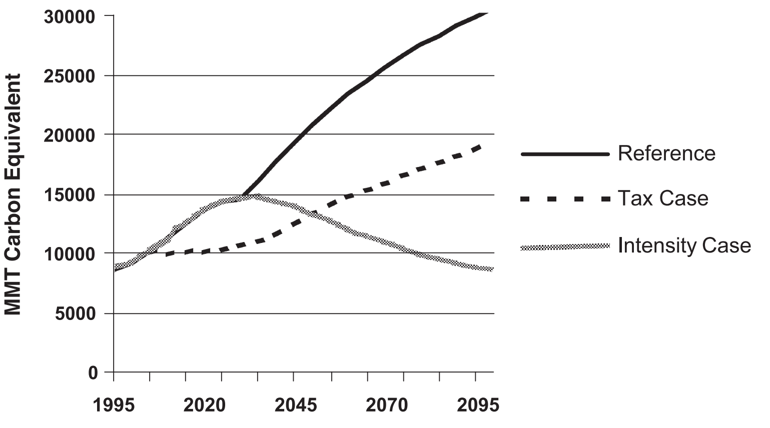

Fig. 3. Annual global greenhouse gas emissions for three scenarios.

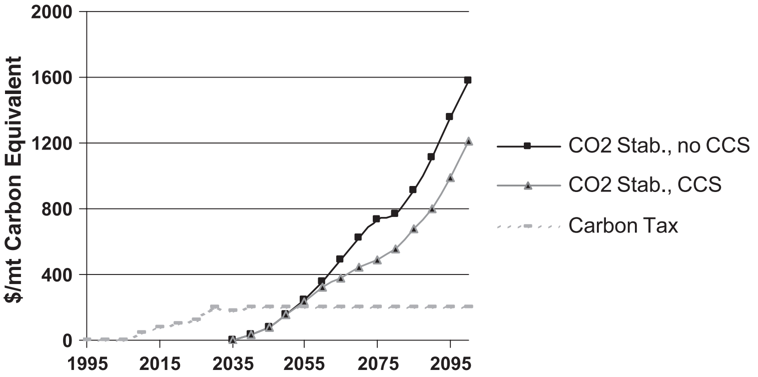

Fig. 4. Carbon-equivalent prices under three policy scenarios.

tion scenario, based on reductions in emissions intensity, experiences climbing aggregate emission through 2025 as economic growth outpaces emissions growth to meet the emissions intensity targets. After 2025, annual global emissions decline by 3–4% per period and reach 1995 levels by 2085. This emissions path generates a CO_2 concentration of approximately 530 ppm of CO_2 by 2100 on a path that is consistent with stabilizing concentration around 550 ppm sometime thereafter (Fig. 3).

The low emissions in the stabilization scenario bring about implicit carbon-equivalent prices ($/mt$C_{eq}$) that rise exponentially from a few dollars in 2030 to $1600/mt$C_{eq}$ by 2100 with the use of CCS technologies. The importance of CCS technologies in cost effectively meeting the intensity targets becomes evident when compared to a stabilization scenario with no CCS technologies. Carbon-equivalent prices under the latter scenario increase by 33% to nearly $1900/mt$C_{eq}$ in 2100 as depicted in Fig. 4. The rapid rise of carbon prices, in excess of $400/mt$C_{eq}$ after 2050, results from rising fossil fuel demand in industry and transportation that lack explicit low-carbon emitting technology options such as CCS.

7.2. Electricity sector results

The additions to the EPPA model on which we focused in this paper involved electricity generation technologies. We, therefore, provide detail on how these technologies enter into the electric sector under the reference and policy cases. In the reference scenario, total electricity production expands nearly five-fold to 64 trillion kWh by 2100. Conventional technologies, which are primarily coal-based, predominate other forms of generation, accounting for 78% of total production from 2060 to 2100. The advanced gas technology expands to a maximum share of 18% by 2020, however, rising natural gas prices reduce this share to 4% by 2050. Nuclear power generation changes very little as expansion of capacity is limited by a fixed factor whose growth is severely limited. The limited growth of the fixed factor represents regulatory limits to the expansion of nuclear power capacity. Limited penetration of wind and solar is modeled as imperfect substitutes for electricity from other generation sources. This treatment reflects the fact that they are intermittent, and could only penetrate further with investments in storage, redundant capacity, or through use of a reliable back-up technology (Fig. 5).

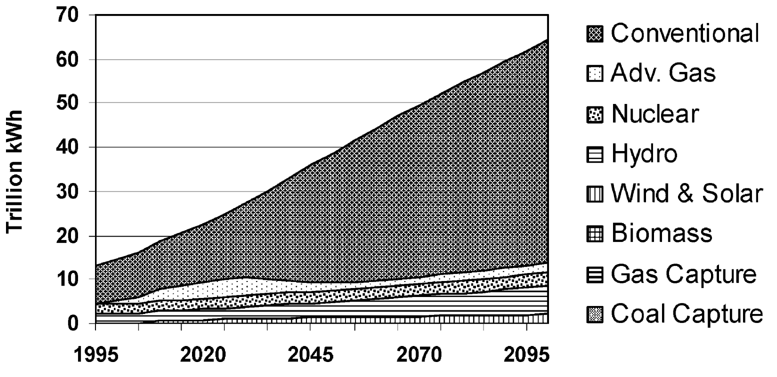

Fig. 5. Global electricity production—reference scenario.

In the tax scenario, aggregate electricity generation drops only 11% from reference levels by 2100, but the mix of generation technologies changes dramatically. Similar to the reference case, the advanced gas technology accounts for 15% of total electricity generation by 2020. The gas and coal CCS technologies enter the market in 2020 at a carbon price of $100/mtC. The CCS technologies enter into production at or above the partial equilibrium carbon prices calculated from Eq. (2) above for conventional pulverized coal technology yet well below the equivalent carbon prices based on the advanced gas technology. Greater displacement of conventional generation by the advanced gas technology would raise the carbon entry price of CCS technologies, however, limits on the penetration rate of the advanced gas technology mitigate this effect. Gas CCS generation reaches 4.5 trillion kWh by 2040, 16% of total generation. The coal CCS technology penetrates more slowly with only a 7% share by this time. Subsequently, rising natural gas prices lead to a decline in both gas technologies. Growth in the coal CCS technology then expands rapidly to surpass conventional fossil fuel technologies as the dominant form of generation by 2075 and accounts for 50% of total generation by 2100 (Fig. 6).

All regions except the European Union (EU) and Japan exhibit similar technology adoption patterns of introducing the gas technologies first and switching to the coal CCS

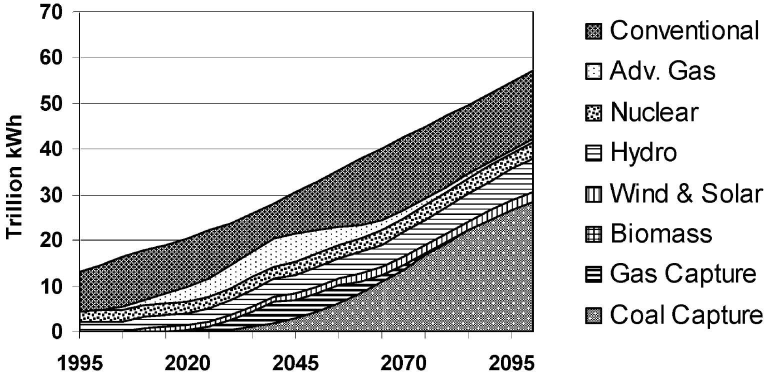

Fig. 6. Global electricity production—tax scenario.

technology in response to rising gas prices. In the EU, the advanced gas technology displaces 30% of the conventional generation by 2045. However, instead of transitioning to CCS technologies, rising natural gas prices spur a return to conventional generation over the remainder of the time horizon. This reversion to conventional technologies results from a relatively high factor share of labor in the EU's conventional electric sector as represented in the GTAP data compared with other regions and with our specification for the CCS technologies. With Harrod-neutral (i.e. labor augmenting) technical change as the main source of improving productivity in EPPA, real labor cost decline and the conventional electricity technology remain less costly than the CCS technologies. Further work should investigate the reasons for the high labor share in the EU electricity sector, and if there are structural reasons for this, whether the labor share in the CCS technologies should be similarly high. If so, then CCS technologies may compete more effectively with conventional technologies. In Japan, a different effect explains deviations from the general adoption trend. The adjustment made to the fuel factor share for advanced gas as discussed in Section 5 increases Japan's adoption of the advanced gas without capture technology. This adjustment leads to a low fuel factor share parameter of only 0.05. Thus, the competitiveness of advanced gas in Japan is much less affected by rising natural gas prices than in other regions where the adjusted fuel factor share parameter averages 0.22. Advanced gas increases its market penetration throughout the simulation and accounts for 27% of all electricity production by 2100, second only to conventional technology.

Under the CO_2 stabilization scenario, the CCS technology adoption pattern is broadly similar to the tax scenario, but with more dramatic changes in the mix of generating technologies. The stabilization scenario does not restrict greenhouse emissions until 2035 as economic growth reduces emissions intensities to target levels. After 2025, implicit carbon prices increase rapidly as greenhouse gas emissions are constrained to meet intensity targets. As in the reference scenario, the advanced gas technology expands to account for 4 trillion kWh, a fifth of total generation, by 2020. However, the rapidly rising carbon price allows this technology to expand to nearly 7 trillion kWh by 2040. The coal CCS technology enters in 2040 at carbon prices of \$100/mtC_{eq}. This technology gradually displaces the advanced gas and conventional generating technologies and generates over half all electricity produced by 2070 as shown in Fig. 7. The gas CCS technology also enters in 2040, but accounts for a maximum of 5% of global generation and does not account for a significant share of production in any region. Fixed factor scarcity for the coal CCS technology constrains its penetration and allows the gas CCS technology to compete at the margin. Rising gas prices lead to declining production from gas-based technologies beyond 2050. All regions except Japan generate a portion of their electricity with the coal capture technology by 2060. As in the tax case, Japan generates the majority of its electricity using the advanced gas technology for the reason described above.

A comparison of greenhouse gas stabilization scenarios with and without CCS technologies illustrates the potential effect of these technologies on electricity generation and economic welfare, measured as equivalent variation.[8] Including CCS technologies in

[8] Equivalent variation is the preferred measure of economic impact. To convert these to an absolute dollar amount, one would multiply the percentage change by aggregate consumption for the economy, and so these savings are substantial.

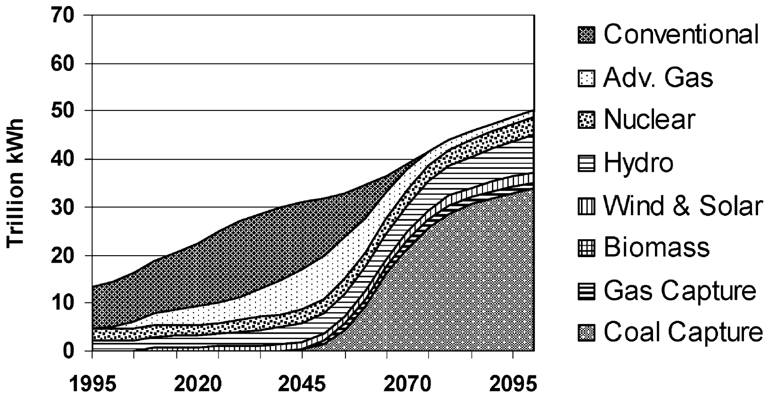

Fig. 7. Global electricity production—stabilization scenario.

the model, global electricity production reaches 50 trillion kWh in 2100 compared with only 36 trillion kWh without CCS technologies, a 38% increase in generation. The additional electricity output and lower carbon prices due to the widespread adoption of the coal capture technology improve welfare in all regions except Brazil, which relies heavily on hydropower, and so carbon sequestration is of little value there. By 2100, annual welfare improvements in China, India, and Eastern Europe exceed 3%. Annex B regions exhibit annual welfare improvements between 0.4% and 1.4% in this period.

7.3. Sensitivity analysis

We evaluated many different scenarios and sensitivities, the most interesting of which was the treatment of capital vintaging. Vintaging affects both the initial penetration rates of new technologies when they become competitive and their decline when they become less competitive relative to other technologies. To examine the importance of this feature of the model, we compare three cases: (1) complete capital malleability across all technologies and sectors, (2) technology/sector specific capital but with malleability of capital within a specific technology, and (3) the specification as presented in Section 6 that included vintaged and sector-specific capital. We report results from the reference scenario, with no emission penalties, and focus on the advanced gas technology.

With complete capital malleability across technologies and sectors, the advanced gas technology exhibits greater penetration and more rapid exit versus the reference scenario previously discussed. Generation from the advanced gas technology grows to 5.7 trillion kWh, or 26% of total electricity generation, by 2020 as shown in Fig. 8. By 2040, however, rising natural gas prices reduce the output from this technology over 60% to 2 trillion kWh. The maximum single-period decline in advanced gas generation reaches 40% from 2030 to 2035. Without limitations on capital mobility, once the advanced gas technology becomes uneconomic, the capital is redeployed in other economic sectors.

Treating capital as a technology-specific investment raises the maximum level of penetration and slows the decline witnessed in the above case. In this second case,

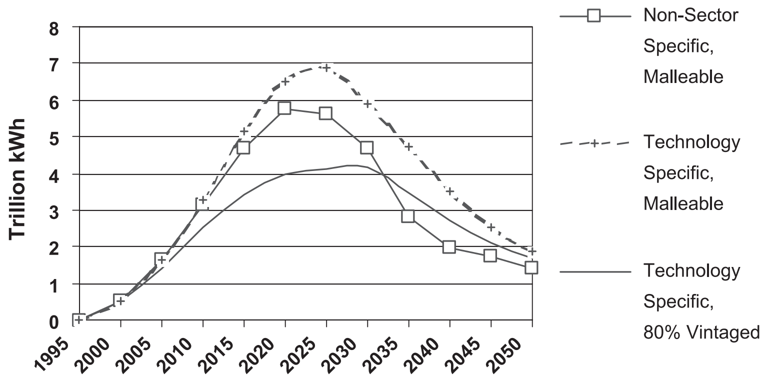

Fig. 8. Effects of vintaging and malleability on advanced gas generation.

capital invested in the advanced gas technology cannot be redeployed to other sectors yet the capital remains malleable subject to the nested production structure in Fig. 1. Generation from this technology peaks in 2025 at nearly 7 trillion kWh, or 20% above that in the previous case. Use of the technology-specific capital stock explains the higher peak production. Lacking an alternative use, the price of the malleable, technology-specific capital stock remains below that of the non-sector-specific capital and thus encourages continued investment in the advanced gas technology. After 2025, rising gas prices lead to declining output from advanced gas generation. However, use of the technology-specific capital stock yields a more gradual drop in output than in the previous case.

Finally, we turn to the case of technology-specific vintaged capital described in Section 6. Recall that in addition to restricting the redeployment of invested capital, a fraction θ of the invested capital, where $\theta = 0.8$, becomes rigid with fixed input shares as defined in the initial period of investment. This vintaged representation reduces the maximum generation of the advanced gas technology by 46% from the second case. The fixed share parameters of the vintaged capital prohibit input substitution in the vintaged capital stock. Unable to utilize less expensive capital and labor inputs, the advanced gas generation is limited to only 3.7 trillion kWh by 2035 due to rising natural gas prices. Again the technology's output gradually declines reflecting the depreciation of the technology-specific capital stock.

8. Conclusions

We described a consistent method for integrating bottom-up engineering data on new technology into the EPPA model, a top-down CGE model. We presented the link between the production function representation of a technology and its thermodynamic efficiency. This allowed us to parameterize the production function to reflect regional differences and to better constrain elasticities of substitution to assure that limits to thermodynamic efficiency were not exceeded, and instead reflected engineering estimates of feasible potential. We also developed and parameterized model components to represent market penetration, and eventual exit, of technologies as their competitiveness changes. It is a pattern of market penetration that is often observed for such technologies. This result was achieved while retaining consistency with theoretical underpinnings of a CGE modeling framework.

In developing an approach for incorporating bottom-up information into the EPPA model, we applied it to the electricity sector where we add three new large-scale technologies that could contribute to meeting a carbon constraint. These were an advanced gas generation technology without carbon capture and sequestration (CCS), advanced gas with CCS, and an advanced coal technology with CCS. The advanced gas technology was less costly than the pulverized coal generation and so, even without constraints on carbon emissions, this technology penetrated. Its success in the market was of limited duration because rising gas prices meant that eventually it could not economically compete. It played a slightly larger role when carbon constraints were present, but was again limited by rising gas prices. The CCS technologies could play a substantial role in reducing carbon emissions, but they would only be economically viable with policy constraints on carbon dioxide emissions. However, the carbon price at which CCS technologies entered was much lower than would be expected given a partial equilibrium comparison of them with today's best available technology, the advanced gas technology, because of the rising price of gas.

Our underlying assessment of the cost of CCS technologies is based on the technology as it exists today with only modest improvements. There are large research projects in industry and in the US government with the aim of greatly advancing the technology and lowering its costs even further, and if these are successful, then CCS could enter at lower carbon prices than found in our simulations. We find, however, that the CCS does not provide a backstop cost for a carbon policy if, as we have modeled it, it is limited to electric generation technologies. This is because even at the costs we specify for CCS, it is competitive with nearly all fossil electric generation by 2100, so that the carbon price depends on marginal costs of abatement elsewhere in the economy. The coal CCS technology offers the most cost-effective long-term source of low-carbon emitting electricity, as the gas technologies are limited by gas resource availability reflected in high gas prices that make the technology non-competitive. Benefits of using the CCS technologies are seen through increased electricity production and lower electricity prices, and this is reflected in lower welfare costs of the climate policy in most regions. The availability of CCS technologies in the policy scenarios raises the demand for gas and coal resources versus policy scenarios without the CCS technologies.

The two policy cases we investigated illustrate that the timing and ultimate penetration of the CCS technology depend on specifically how climate policy is formulated, and this is a major uncertainty in forecasting when CCS will be implemented at a significant level. As with any projection, there are many uncertainties including the potential for technological improvements in CCS technologies. Also, the uncertainties that go into creating a reference forecast in the EPPA model include the specification of fossil fuel resources that directly determines future fuel prices, the level of economic growth, energy efficiency improvement in the economy, and the other mitigation options available in the electric sector and in the economy in general.

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Analysis of global warming stabilization scenarios: the Asian-Pacific Integrated Model

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Abstract

This paper analyzes the economic and climatic impacts of the EMF 19 emission scenarios. A reference scenario, three emission scenarios targeting 550 ppmv atmospheric concentration, and three tax scenarios are analyzed. The profiles of energy consumption and economic losses of each policy scenario are compared to the reference scenario. The model also estimates that global mean temperature will increase 1.7–2.9 °C in 2100, and the sea level will rise 40–51 cm, compared to the 1990 levels under the EMF scenarios. Impacts on food productivity and malaria infection are estimated to be very severe in some countries in the Asian region.

PACS: C53, Forecasting and other model applications; F18, Emission trading and environment; Q2, Renewable resources and conservation; Environmental management

Keywords: Global warming; Economic model; Impact model; Climate policy; Environmental management; Emission trading; Model application

1. Introduction

It is predicted that global warming will have significant impacts on the society and economy of the Asia-Pacific region, and that adoption of measures to tackle global climate change will force the region to carry a very large economic burden. Also, if the Asia-Pacific region fails to adopt such countermeasure, it has been estimated that its greenhouse gas emissions will increase to over one-half of total global emissions by the year 2100. In

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order to respond to such serious and long-term threats, it is essential to establish communication and evaluation tools for policy makers and scientists in the region. The Integrated Assessment Model provides a convenient framework for combining knowledge from a wide range of disciplines, and is one of the most effective tools to increase the interactions among these groups.

The Asian-Pacific Integrated Model (AIM) is a large-scale computer simulation model developed to promote the integrated assessment process in the Asia-Pacific region. The main goal of this model is to assess policy options for stabilizing the global climate, particularly in the Asia-Pacific region, from the two perspectives of reducing greenhouse gas emissions and avoiding the impacts of climate change (Matsuoka et al., 1995).

We have evaluated the economic impacts of the Kyoto Protocol using the AIM model (Kainuma et al., 1999). Although the Kyoto Protocol is very important as a milestone in climate policy, it is necessary to reduce emissions by more than the reduction target specified by the Protocol to achieve the long-term goals of the Framework Convention. Considerable efforts have been devoted to estimating the different stabilization pathways in the post-SRES experiments (IPCC, 2001). EMF 19 extended these experiments and analyzed several scenarios including stabilization scenarios of atmospheric concentrations.

Stabilization emission pathways and economic as well as climatic impacts are studied by the AIM model. The emission model examines several important variables such as GDP changes, energy consumption, carbon emissions, and marginal costs. Outputs of the emission model are fed as input to the climate model. Estimated climate changes under different scenarios are used to estimate the climatic impacts on food production and infectious diseases focusing on the Asia-Pacific region.

2. Structure of the AIM model

AIM comprises three main models: the greenhouse gas emission model (AIM/emission), the global climate change model (AIM/climate), and the climate change impact model (AIM/impact).

The AIM/emission model consists of country-level, bottom-up type energy models and global-level, top-down type energy and land-use models. A variety of global and regional assumptions, such as on population and economic trends as well as government policies, are entered into the emission model to provide estimates of energy consumption, land-use change, etc., and provide predictions of greenhouse gas emissions. Emissions of SO_2, NO_x, and SPM are also calculated within the AIM/emission model, and they are input into the AIM/climate model and a regional environmental model that was developed in order to reinforce the interaction with local atmospheric pollution problems.

With the exception of CO_2, GHGs emitted into the atmosphere are gradually transformed by chemical reactions, which are calculated within the AIM/climate model. We divided these chemicals into two groups based on their reaction rates: long-life chemicals such as CFCs and halons, and short-life chemicals such as ozone and OH radicals. A pseudo-equilibrium state is assumed for the latter group, and the oxidation and photochemical reactions of CH4 and other molecules are represented by simple kinetic equations. The absorption of CO_2 and heat by the oceans is calculated using an upwelling-diffusion model (part of the AIM/climate model) with the oceans divided into a surface mixed layer and an intermediate layer that extends down to about 1000 m.

Global mean temperature changes are calculated with an energy balance/upwelling-diffusion ocean model, and used as input into the regional models. Data from the GCM experiments are used in order to estimate the regional distribution of climate parameters. They are coupled with the global mean temperature change calculated in the AIM/climate model. The interpolated climate distributions are used in the AIM/impact model, which calculates global and regional climatic impacts. The AIM/impact model mainly treats the impact on primary production industries, such as water supply, agriculture, forest products, and human health. It can also be used to assess higher-order impacts on the regional economy.

3. Simulation with EMF 19 scenarios

AIM was run under seven scenarios: a reference scenario, three 550 ppmv scenarios, a TAX+$10 scenario, a TAX+$25 scenario, and a TAX+$100 scenario. As a reference scenario we used the driving forces used by the SRES B2 scenario. It is assumed that carbon emissions can be traded without quantitative limitations on trading cases within the allowable emissions. The global allowable emissions are specified in the 550 ppmv scenarios and they are allocated according to the population.

3.1. Reference scenario

Future greenhouse gas emissions are the products of systems having very complex dynamics, determined by driving forces such as demographic development, socioeconomic development, and technological change. Their future evolution is highly uncertain. Many future alternative images can be drawn depending on how driving forces change and how they influence future emission outcomes. The IPCC SRES (IPCC, 2000) examined a variety of emission scenarios and presented a set of scenarios focusing on different socioeconomic developments.

The IPCC SRES used four families of scenarios (A1, A2, B1, B2) to illustrate business-as-usual pathways. The A1 family has the highest rates of technological change and economic development. The A2 family describes a very heterogeneous world where per-capita economic growth and technological change are more fragmented and slower than in other storylines. The B1 family emphasizes global solutions to economic, social, and environmental sustainability. The B2 family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability.

This study uses the storylines of the B2 family without additional climate initiatives as a reference scenario. Fig. 1 shows a projection of the world GDP from 2000 through 2100. World growth rates during this period vary from 1.25% to 3.16%, with an average of 2.1%. The highest is that of China, which varies from 1.5% to 6.4%.

Fig. 2 shows a projection of world CO_2 emissions. It is projected that China will become the top CO_2-emitting country after 2020. The growth rate of world CO_2 emissions will follow a downward curve, whereas that of China will increase. The growth rate of

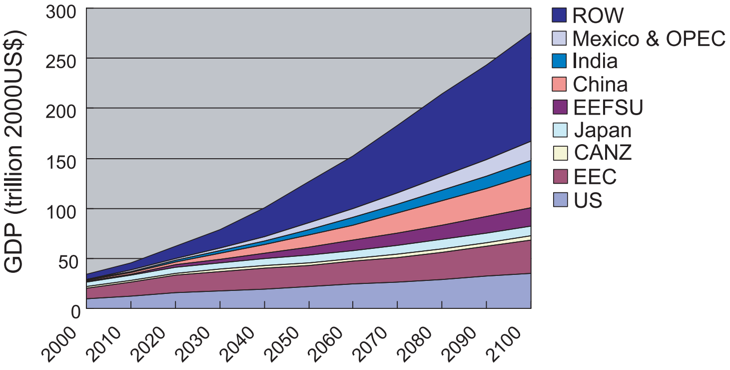

Fig. 1. Projection of world GDP under the reference scenario.

CO_2 is much higher than the growth rate of GDP in China under this reference scenario. This is because the energy efficiency of China is estimated to be lower than that of the developed countries in this case.

3.2. Policy scenarios

The results of the reference scenario are compared with those of the six policy scenarios; namely, the three 550 ppmv scenarios and three carbon tax scenarios. The 550 ppmv scenarios limit the atmospheric concentration of CO_2 at 550 ppmv. There are three 550 ppmv scenarios: WRE 550, WGI 550, and MID 550. The WRE scenario was proposed by Wigley et al. (1995) to find the optimal path to 550 ppmv from the economic point of view. WGI 550 is a scenario proposed by IPCC Working Group I (IPCC, 1995). It is a path aimed at avoiding an abrupt change in emissions in achieving the 550 ppmv target. The MID 550 scenario is proposed representing the mean of these two scenarios.

The three other scenarios are tax scenarios. The first is TAX+$10/tC, which begins at $10/tC in 2010 and increases at $10/tC per decade up to $100. The second is TAX+$25/tC, starting at $25 in 2010. The third is TAX+$100/tC, which adopts a constant $100/tC tax from 2010. These scenarios are used to calculate marginal abatement curves.

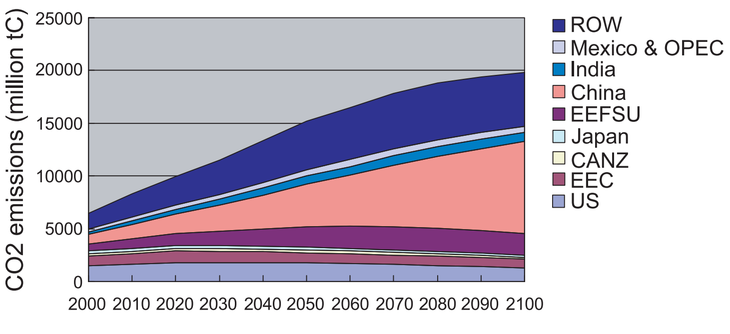

Fig. 2. Projection of world CO_2 emissions under the reference scenario.

Fig. 3 shows world energy demand in end-use sectors. The left-hand figure shows the result in the reference scenario and the right-hand figure shows the WRE 550 scenario. In the reference scenario, the use of solid energy increases from 18% in 2000 to 48% in 2100, and more than half is used in China in 2100. The world final energy demand in the WRE 550 scenario decreases to nearly half that in the reference scenario in 2100. This reduction comes about mainly from cutting coal use. The share of coal in the WRE 550 scenario becomes 29% in 2100. Electricity demand will increase in the policy scenarios. The share of electricity will increase from 17% in 2000 to 29% in 2100 in WRE 550.

Fig. 4 shows the results of projecting marginal costs to reduce emissions. The marginal cost of the WGI 550 scenario is the highest through the year 2060, that of MID 550

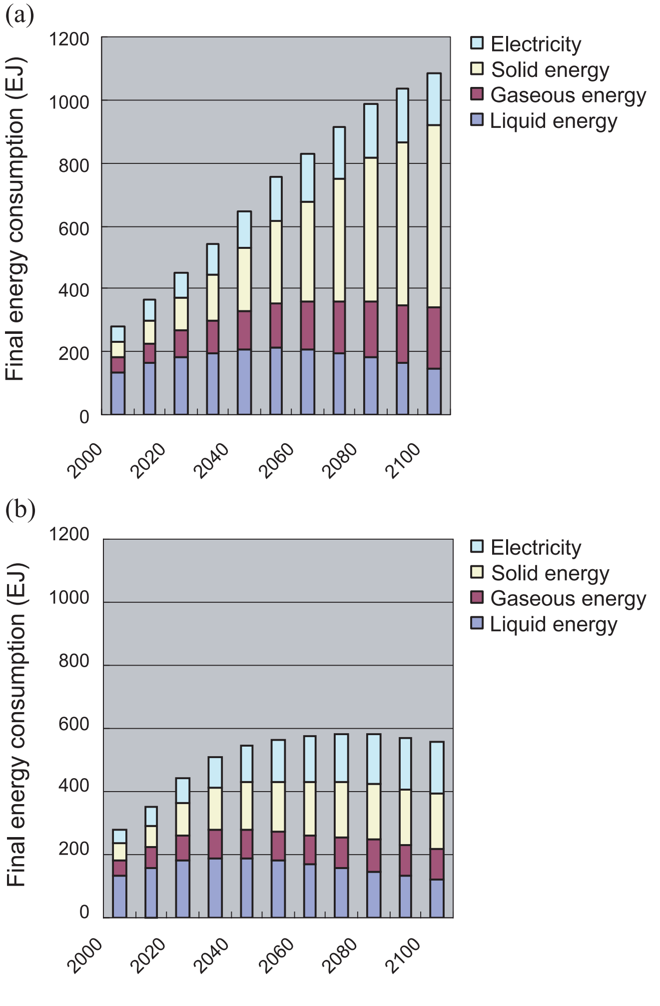

Fig. 3. World energy demand in end-use sectors under (a) the reference scenario and (b) the WRE 550 scenario.

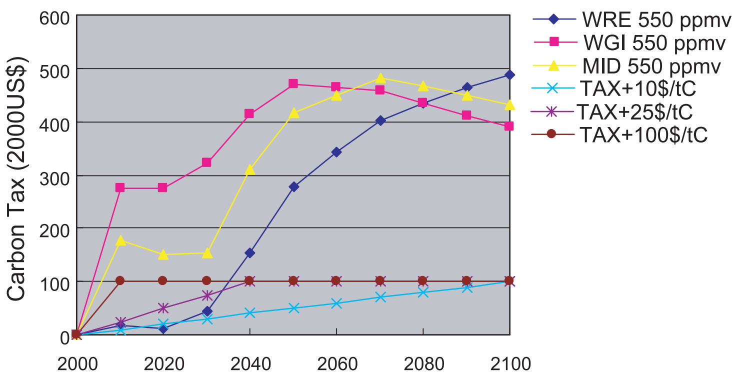

Fig. 4. Projection of marginal costs to reduce emissions.

becomes the highest from 2060 through 2080, and then that of WRE 550 becomes the highest from 2090 onwards. Although the constraint of the WGI 550 scenario is the severest until 2070, the marginal cost becomes the second highest in 2060. The restructuring of the energy system at an early stage will decrease the marginal costs after 2050.

Fig. 5 shows a projection of GDP changes compared to the reference scenario. The magnitude of the economic impact of the WGI 550 scenario decreases from 2050, while that of WRE 550 continues to increase until 2080. The impacts of the tax scenarios are not significant.

Fig. 6 shows the consumption changes relative to the reference scenario. The values shown are the present discounted values of macroeconomic consumption change with respect to the reference scenario in trillion 2000 US$ through 2050. The discount rate is 5%. Consumption in India will grow at the highest level, especially in the WGI 550 scenario. Consumption will decrease in Annex I countries and China. The severest

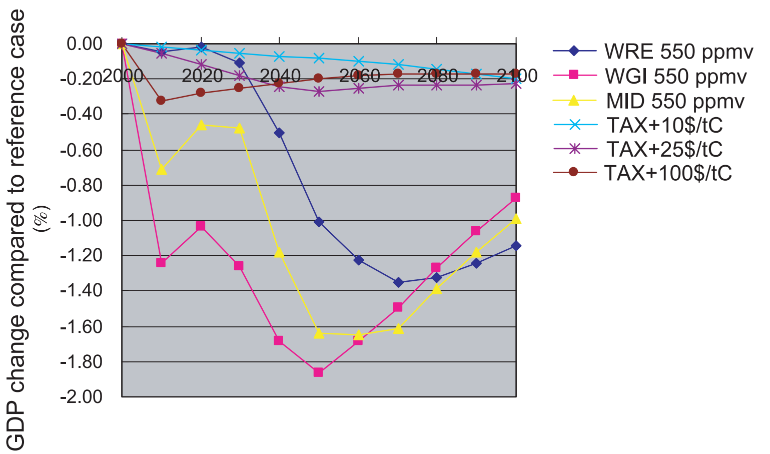

Fig. 5. Projection of GDP changes compared to the reference scenario.

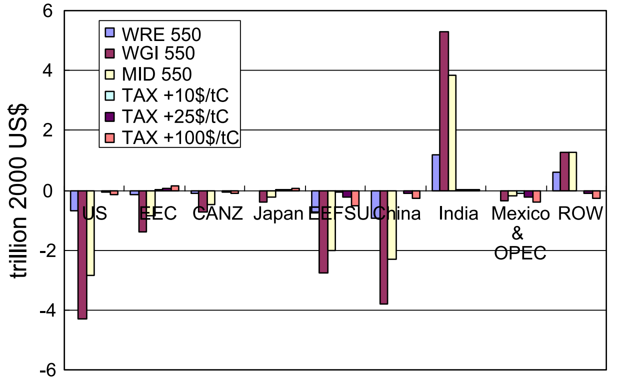

Fig. 6. Present discounted values of macroeconomic consumption loss with respect to the reference scenario.

decrease is in the US followed by China under the assumptions taken by the policy scenarios.

3.3. Global climate change

The impact on the global mean temperature is shown in Fig. 7. The results of the IPCC SRES range from 1.4 to 5.8 °C by 2100 from the 1990 value. The temperature rises to 2.9 °C in the reference case, which is lower than the average of the SRES range, but a little higher than the SRES B2 range. The reference emission projection is 21.9 GtC which is higher than the SRES B2 emissions. They range from 10.8 to 21.8 GtC in 2100. This is because the reference scenario takes the assumptions of population and GDP from SRES B2, but does not focus as much on environmental sustainability.

The temperature increase in the WGI 550 scenario is the lowest, at 1.7 °C. The increase in the WRE 550 scenario is 1.9 °C. Although the targets of these two scenarios are the same, there is a 0.23 °C difference in temperature increase in 2100. These 550 ppmv scenarios can decrease temperature by 1.04 to 1.26 °C compared to the reference scenario.

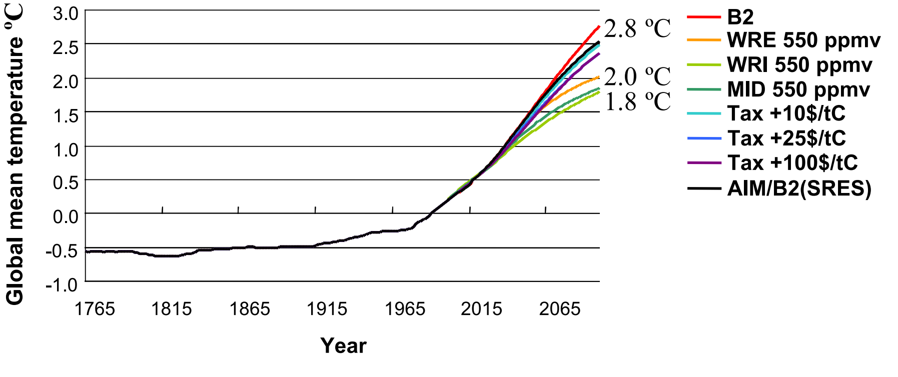

Fig. 7. Global temperature increase for different policies from 1990.

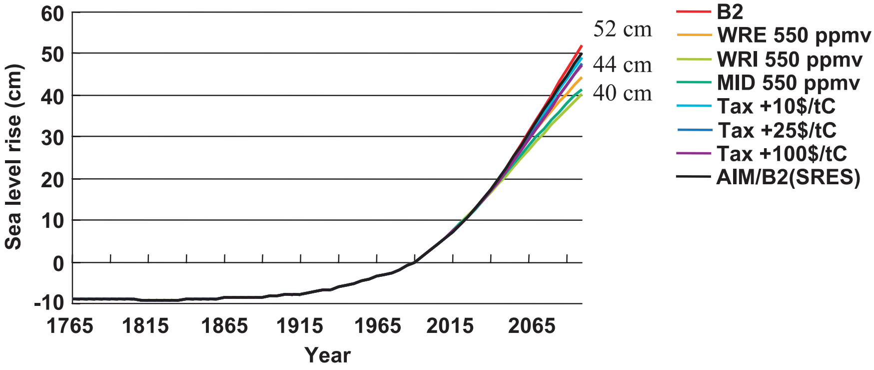

Fig. 8. Global sea level rise for different policies from 1990.

Although the macroeconomic consumption loss of the WRE 550 scenario is lower than that of the WGI 550 scenario, the change in global mean temperature by 2100 is greater.

The globally averaged sea level rise is shown in Fig. 8. It ranges from 39 to 54 cm. The global sea level is projected to rise by 9 to 88 cm for the full range of SRES scenarios. The sea level in the WRE 550 scenario rises higher by 3.8 cm than that in the WGI 550 scenario.

3.4. Potential impacts in the Asian region

Climate change has direct or potential impact on water resources, agricultural production, natural ecosystems, and human health, even if we do not consider socioeconomic interaction. In the actual world, global trade, immigration, and measures for adaptation modify direct impacts. Hence, there are two stages of impact study: the direct and indirect stages. In this study, we analyzed the direct impact under the EMF 19 scenarios.

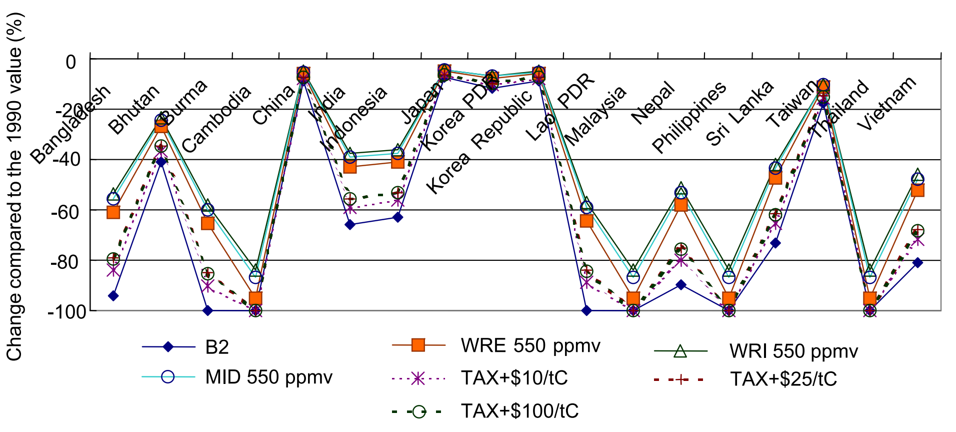

Fig. 9. Changes in winter wheat productivity in 2100 compared to the 1990 values.

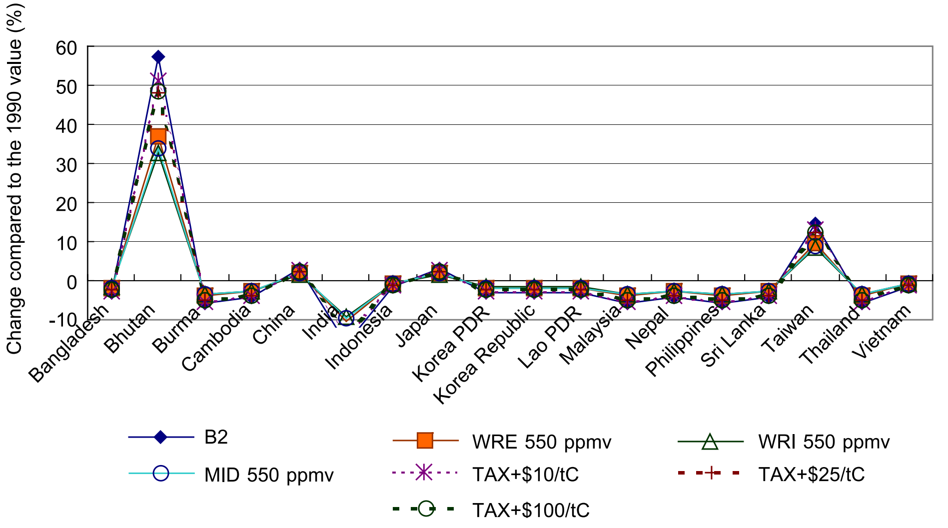

Fig. 10. Changes in rice productivity in 2100 compared to the 1990 values.

Fig. 9 shows the changes in winter wheat productivity in 2100 compared to 1990. The productivity of wheat will decrease significantly in Sri Lanka, Malaysia, Korea-PDR, Burma, and other tropical countries.

Fig. 10 shows changes in rice productivity in 2100 compared to 1990 under the EMF scenarios. A slight decrease in rice production is expected in most countries, while a slight increase is expected in Bhutan and Taiwan. The productivity decrease in India is projected to be the highest.

Air and water pollution, as well as solid and hazardous wastes, affect human health directly. Global climate change will also affect human health in the future in many ways.

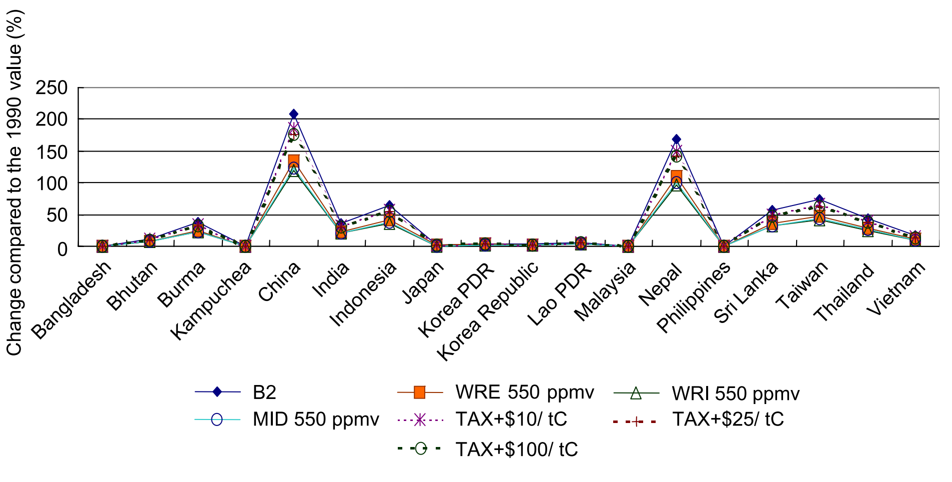

Fig. 11. Changes in populations living in areas at malaria risk in 2100 compared to 1990.

For example, global warming will result in increasing temperature and changing vegetation close to the ground. This will allow the habitat of the anopheles mosquito, which is the malaria vector, to expand. In addition, the development period of malaria protozoa will shorten and their reproductive potential will increase. As a result, it is expected that the global malaria risk will increase.

Fig. 11 shows the changes in populations living under endemic malaria under the EMF 19 scenarios. Under the reference scenario, malarial risk in China, Nepal, Taiwan, Indonesia, and Sri Lanka will increase due to environmental change. Although China may be little affected by climate change in terms of food productivity, the impact it experiences in terms of malaria risk will be the highest in the Asian region. Even under the 550 scenarios, the population living in areas at malaria risk will be double in 2100 compared to 1990.

4. Conclusion

Several climate change stabilization pathways are examined by the AIM model. It is an urgent task to take action against global warming, as it is an irreversible process and once it occurs, the probability is very high that it will have a multiplicative effect that further enlarges its impact. It is necessary to consider many uncertainties in human activities such as population growth, economic development, and technological innovation as well as uncertainties in natural processes to estimate future CO_2 emissions and to make plans for climate stabilization. The scenario approach is a practical means of analyzing the policy options under such uncertainties.

Although the emissions of developing countries were lower than those of developed countries in 2000, it is expected that they will grow much faster than those of developed countries in the future. The estimated impacts in developing countries in the Asian region under the EMF 19 scenarios are serious. The model projects that the early timing of emissions reductions can reduce the amount of impacts in the future.

Acknowledgements

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Dynamics of carbon abatement in the Second Generation Model

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Abstract

The Second Generation Model (SGM) is a collection of computable-general-equilibrium models developed for analysis of policies to reduce greenhouse gas emissions. Behavior of the Second Generation Model, with respect to changes in carbon prices, can be summarized using marginal abatement cost curves. Marginal abatement costs vary over time, as capital stocks adjust to a new set of prices, and across countries, depending in part on the mix of fuels in the existing energy system. This paper documents the production structure in SGM, marginal abatement cost curves derived from SGM with constant-carbon-price experiments, an application to several Energy Modeling Forum scenarios, and a methodology for including carbon capture and disposal in SGM.

JEL classification: C68; Q40

Keywords: Climate policy analysis; General equilibrium modeling

1. Introduction

The cost of meeting any particular carbon emissions constraint depends on the amount of time available for capital stocks to adjust to a new set of equilibrium energy and carbon prices required to meet the constraint. This suggests that top-

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down economic models should partition capital stocks into old and new capital to capture variations between short-run and long-run responses to carbon constraints. The Second Generation Model (SGM), developed at Pacific Northwest National Laboratory, is often used to simulate emissions trading during time periods (e.g. 2010 or 2015) that are within the useful lifetimes of capital stocks already in place.

This paper documents some of the changes to the Second Generation Model (SGM) since publication of *The Energy Journal* special issue on the cost of meeting the Kyoto Protocol (MacCracken et al., 1999). In particular, this paper focuses on the representation of energy technologies in a computable general equilibrium (CGE) model. The first part of this paper provides background on producer behavior in SGM and how vintages of capital affect the dynamics of marginal abatement cost curves. This section also presents long-run marginal abatement curves for each of the 13 SGM regions. The second part of this paper provides an application of SGM to several scenarios specified by the Energy Modeling Forum (EMF-19). In one of these scenarios, carbon prices by 2050 are comparable to published costs of carbon capture from electricity generation. The third part of this paper provides an indication of how marginal abatement cost curves might shift in the United States with carbon capture and disposal as an option for electricity generation.

2. SGM background

The SGM operates in 5-year time steps, from its 1990 base year through 2050. SGM is a collection of 13 CGE models that can be run independently or as combinations of regions trading carbon emissions rights. As a CGE model, most of the producing sectors in SGM are represented by a constant-elasticity-of-substitution (CES) production function. A production sector exists in SGM for each unique product, with its own unique price. Therefore, for most of the SGM production sectors, a CES production function represents the range of possible production methods, and relative prices determine the mix of inputs.

Capital stocks in the SGM are grouped into 5-year vintages, each corresponding to 5 years' worth of investment. Once capital is created it must remain with its original industry until that vintage of capital is retired. An unanticipated price change, such as the introduction of a carbon price, will not be fully effective until all capital stocks in place before the price change have retired. Therefore, achieving short-term emissions targets is expensive, relative to longer-term targets, because old capital is less responsive to a change in prices than new capital.

The electricity production sector differs from other producing sectors in SGM in that it contains several explicit generating technologies. Each of the generating technologies is represented by a separate production function. The market share of each generating technology is determined by either the rate of return per dollar of investment or by the cost per kilowatt-hour (kWh) generated. The generating technology with the highest rate of return, or the lowest cost per kWh, receives the greatest share of investment in new capital for electricity generation.

Here we describe the mathematical foundation of the production structure in the SGM. All goods are produced with either a Constant-Elasticity-of-Substitution (CES) or a fixed-coefficient (Leontief) production function. Production in any sector or subsector is split among vintages, where each vintage of capital is the accumulated capital stock over 5 years of investment. Once capital stock is created, it must remain with its original production sector. The primary advantage of this vintage structure is that we can better describe technical change over time, and it provides the capability for putty-clay behavior in the capital stock.

2.1. CES production function

The Constant-Elasticity-of-Substitution production function can be written[1],

$$q(\mathbf{x}) = \alpha_0 \left[\sum_{i=1}^{N} (\alpha_i x_i)^{\rho} \right]^{1/\rho} \tag{1}$$

where gross output q is a function of inputs $\mathbf{x}$ and technical coefficients α_0, α_i, $i=1,\ldots, N$. N is the number of inputs to production. Many subscripts have been suppressed for clarity; each sector, subsector, and vintage combination has its own set of technical coefficients. ρ is a parameter that determines the elasticity of substitution σ according to

$$\sigma = 1/(1-\rho) \tag{2}$$

The corresponding CES cost function is

$$g(\mathbf{p}) = \frac{1}{\alpha_0} \left[\sum_{i=1}^{N} \left(\frac{p_i}{\alpha_i} \right)^{r} \right]^{1/r} \tag{3}$$

where $r = \rho/(\rho - 1)$ and p_i is an element of the price vector $\mathbf{p}$. (4)

Eq. (5) provides an expression for input–output coefficients in the case where all inputs are variable. This expression is used to determine capital requirements for new investment when output is known in advance, and provides the optimal capital-output coefficient for a given set of prices. At any time when the SGM is running, we always have a trial set of prices.

[1] This CES production function is written in a slightly different form than in Edmonds et al. (1993). This functional form makes it easier to describe technical change in the SGM, and more clearly shows the relationship between CES production and fixed-coefficient (Leontief) production.

The physical input–output coefficients are functions of prices and technical coefficients of the production function.

$$a_{ij}(\mathbf{p}) = \alpha_{0j}^{-r}\alpha_{ij}^{-r}\left[\frac{p_j}{p_i}\right]^{1-r} \tag{5}$$

where a_{ij} is the amount of input i required per unit of output j. Note that these CES input–output coefficients always depend on prices. Also note that the above equation uses subscripts for inputs and outputs, except for the exponent r. This exponent actually does vary by producing sector, but all subscripts on r have been suppressed.

2.2. Fixed-coefficient production

The Leontief, or fixed-coefficient, production function can be written as

$$q_j(\mathbf{x}) = \alpha_{0j}\ \min(\alpha_{1j}x_{1j}, \ldots, \alpha_{nj}x_{nj}) \tag{6}$$

Fixed-coefficient production is useful for modeling sectors that have a very narrow range for the energy-output ratio (e.g., petroleum refining). The corresponding cost function is linear in prices.

$$g_j(\mathbf{p}) = \frac{1}{\alpha_{oj}}\sum_{i=1}^{n}\frac{p_i}{\alpha_{ij}} \tag{7}$$

where the input–output coefficients are given by

$$a_{ij} = \frac{1}{\alpha_{0j}\alpha_{ij}} \tag{8}$$

Note that Eq. (8) can be derived from Eq. (5) by setting r equal to 1, which corresponds to a zero elasticity of substitution. Also note that the input–output coefficients do not depend on prices.

2.3. Vintages and the elasticity of substitution

Elasticities of substitution must satisfy the following relationship

$$0 \leq \sigma_{j,jj,\mathrm{old}} \leq \sigma_{j,jj,\mathrm{new}} < 1 \tag{9}$$

Where j is the sector index and jj is the subsector index. For each sector and subsector combination, old and new vintages may have different elasticities of substitution. New capital is more flexible than old capital and its elasticity of substitution must be greater than or equal to the corresponding elasticity of substitution for old capital. New vintages have more flexibility to substitute among inputs, in response to changes in relative prices, than do old vintages. However, there is a practical lower limit to σ of about 0.05, where computations using CES production and cost functions approach the numerical limits of double precision Fortran. If σ is specified to be less than 0.05, the SGM switches from CES to a fixed-coefficient production function.

Depending on the selection of elasticities of substitution, any subsector may be set up to operate in one of the following modes:

$$\text{putty} - \text{putty}, \quad 0 < \sigma_{j,jj,\text{old}} = \sigma_{j,jj,\text{new}} < 1$$

$$\text{putty} - \text{semiputty}, \quad 0 < \sigma_{j,jj,\text{old}} < \sigma_{j,jj,\text{new}} < 1$$

$$\text{putty} - \text{clay}, \quad 0 = \sigma_{j,jj,\text{old}} < \sigma_{j,jj,\text{new}} < 1$$

$$\text{clay} - \text{clay}, \quad 0 = \sigma_{j,jj,\text{old}} = \sigma_{j,jj,\text{new}}$$

Typical SGM elasticities are presented in Table 1. Short-run elasticities of substitution for producers are always small (zero for energy transformation sectors and 0.10 for other sectors). Long-run elasticities of substitution are small for energy transformation but larger for other sectors.

Table 1
Typical producer and consumer elasticities in the Second Generation Model

Sector no.	Activity (producers), consumption good (consumers)	Long-run elasticity of substitution for producers	Short-run elasticity of substitution for producers	Own-price elasticity of demand for consumers	Income elasticity of demand for consumers
1	Agriculture	0.30	0.10	– 0.38	0.32
2	Services	0.40	0.10	– 1.02	1.01
3	Crude oil	0.28	0.10		
4	Natural gas	0.28	0.10		
5	Coal	0.28	0.10	– 0.21	0.50
6	Coke	0.28	0.10		
7	Electricity	0.10	0.00	– 0.21	0.50
8	Refined petroleum	0.10	0.00	– 0.21	0.50
9	Distributed gas	0.10	0.00	– 0.21	0.50
10	Paper and pulp	0.28	0.10	– 1.02	1.01
11	Chemicals	0.28	0.10	– 1.02	1.01
12	Non-metallic minerals	0.28	0.10	– 1.02	1.01
13	Primary metals	0.28	0.10	– 1.02	1.01
14	Food processing	0.28	0.10	– 1.02	1.01
15	Other industry	0.28	0.10	– 1.02	1.01
16	Passenger transport	0.28	0.10	– 1.02	1.01
17	Freight Transport	0.28	0.10	– 1.02	1.01

2.4. Technical change

All of the alpha parameters in the CES production function, as well as the corresponding parameters in fixed-coefficient production, can be specified to have a growth rate γ during each of the SGM's 5-year time steps (NSTEP = 5). This is similar to the Autonomous Energy Efficiency Improvement (AEEI) used in some other energy models; but in the SGM, exogenous rates of technical change can be specified for all inputs to production, not just energy. For example, the labor productivity parameter is used primarily for calibrating the SGM to a GDP growth path. The energy productivity parameters are then used to adjust energy consumption. Technical change growth rates can either change smoothly over time or vary between time steps.

2.4.1. Non-neutral technical change

All alpha parameters in the production function corresponding to input i in production activity j may have independent growth rates. An increase in the alpha parameter represents increasing technical efficiency.

$$\alpha_{ij}(T) = \overline{\alpha}_{ij} \prod_{S=1}^{T} (1 + \gamma_{ij}(S))^{\mathrm{NSTEP}} \tag{10}$$

T is an integer that represents the model time period, where $T = 0$ during the base year of 1990. Since the model runs in five-year time steps, $T = 1$ represents 1995. If t is the number of years since 1990, then

$$t = T \times \mathrm{NSTEP}$$

The flexibility provided by non-neutral technical change is used extensively for calibrating an SGM baseline.

2.4.2. Neutral technical change

Technical change is neutral if all of the alpha parameters from Eq. (10) change at the same rate. This can be captured by changing only the alpha-zero parameter and leaving the other alpha parameters constant.

$$\alpha_{0j}(T) = \overline{\alpha}_{o,j} \prod_{S=1}^{T} (1 + \gamma_{oj}(S))^{\mathrm{NSTEP}} \tag{11}$$

2.5. Electricity sector

The electricity sector in SGM is not a single production function, but is instead a collection of production functions representing individual generating technologies. Each electric generating technology is represented by a fixed-coefficient production function or by a CES production function with a very low elasticity of substitution. The set of technologies includes oil-fired, gas-steam, coal-steam, hydropower, and nuclear. A logit sharing algorithm allocates investment among electric generating technologies, providing a way for fuels to shift in response to changes in relative prices. For any particular generating technology, heat rates remain in a limited range with limited response to changes in fuel prices. Output of the electricity sector is the sum of output across generating technologies.

Generation shares are based on either the rate of return to invested capital, or on the levelized cost per kWh. The technology with the highest rate of return to capital, or with the lowest levelized cost per kWh, receives the greatest share of investment during each model time step. The amount of electricity generated by nuclear and hydropower/renewables is usually set exogenously and not determined by a logit algorithm. In most SGM regions, the potential for new hydropower is limited. The economics of nuclear power are difficult to capture within a simple logit mechanism based only on cost per kWh. As with other production functions in SGM, capital stock within each generating technology is spread among 5-year vintages.

3. Constant-carbon-price experiments

Marginal abatement cost curves are a convenient way to characterize the response of a model to a carbon price. Marginal abatement cost curves can be constructed as either a reduction in carbon emissions measured in million metric tons of carbon (million tC), or as a percentage reduction in carbon emissions from the baseline emissions scenario. The percentage reduction format is useful because it allows the user to substitute alternative baseline emissions scenarios.

However, marginal abatement cost curves depend on time and on the time path of previous activities. Of the infinite number of carbon price time paths that could be used to construct marginal abatement cost curves, we use a step function at various carbon prices. Marginal abatement cost curves for SGM were constructed by running a series of constant-carbon-price experiments with the carbon price first applied in 2005. SGM operates in 5-year time steps, so one could think of the 2005 time step as covering 2003 through 2007. Carbon prices begin in 2005 for each of the 13 SGM regions, and are held constant through 2050.[2] Because of the vintage capital stock structure of SGM, the full impact of a carbon price is not felt until at least the third full time period after the start period. Most of the producing sectors in SGM have a capital lifetime of 20 years, or four full SGM time periods.

Because of the time it takes for capital stocks to turn over, we have a family of marginal abatement curves. Fig. 1 shows a family of marginal abatement cost curves for the United States expressed as a percentage reduction from reference carbon emissions.

The first marginal abatement curve, labeled "start," represents the percentage reduction in carbon emissions during the same time step that the carbon charge is first applied. The second curve, "plus 5 years," is the percentage reduction in emissions in the time step after the carbon charge is applied. The marginal abatement curve farthest to the right, labeled "long run," is the percentage reduction after capital stock has had 20 years (the initial time periods of 5 years, plus three more SGM time periods) to adjust to the carbon

[2] The carbon prices are 10, 20, 30, 40, 50, 100 and 150 dollars per metric ton of carbon in 1990 US$. Carbon prices were converted to 2000 US$ in Figs. 1–3.

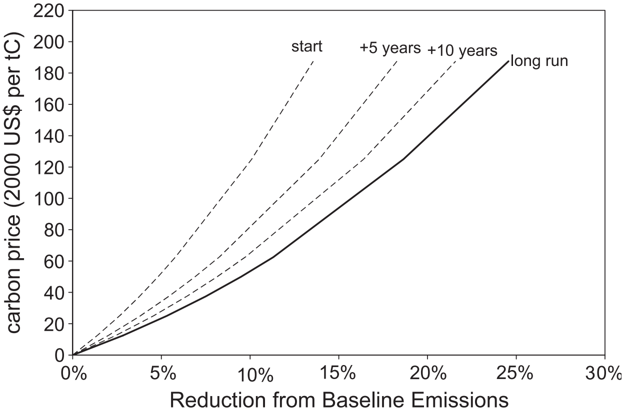

Fig. 1. Marginal abatement cost curves from SGM-USA. These curves are expressed as a percentage reduction from baseline so that they can be applied to alternative baseline scenarios.

price. Therefore, we have one long-run marginal abatement curve accompanied by a set of short-run marginal abatement curves.

Capital stocks in SGM can be parameterized anywhere from putty–clay to putty–semiputty to putty–putty, so the family of curves in Fig. 1 shows the range of response to carbon prices that the SGM generates. Dynamics of capital stock turnover limit the short-run response to a carbon policy.

Marginal abatement curves of the type shown in Fig. 1 turn out to be quite useful in reduced-form simulations of programs to trade carbon emissions rights, either within a country or among a group of countries. Marginal abatement curves from Fig. 1 represent abatement opportunities for carbon dioxide in the US energy sector, but it is difficult to endogenize abatement opportunities for non-CO_2 greenhouse gases or terrestrial carbon sinks within a single computable general equilibrium model. For some time, analysis of a full suite of greenhouse gas abatement opportunities will require comparison of marginal abatement cost curves derived from multiple sources and models.

Graphics similar to Fig. 1 could be created for each of the thirteen SGM regions. If we take only the long-run marginal abatement curves and compare them across Annex I regions, we have the set of curves in Fig. 2.[3] Relative abatement costs vary greatly among Annex I regions. Japan and Western Europe have the highest costs, or steepest marginal abatement cost curves, while the former Soviet Union has the lowest costs. Determinants of marginal abatement cost include the level of pre-existing energy taxes and the amount of coal in the energy system that can be replaced with less carbon-intensive fuels.

[3] The Western Europe, Eastern Europe, and former Soviet Union regions in Fig. 2 are approximations of Annex I regions and include some countries that are not in Annex I. For example, the fSU region in SGM includes Russia and all newly independent states. Of these countries, Russia, Ukraine, Latvia, Lithuania, and Estonia are in Annex I.

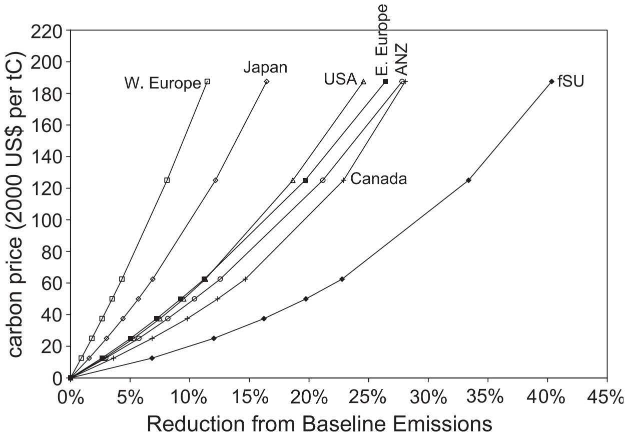

Fig. 2. Long-run marginal abatement cost curves for Annex I regions: Western Europe, Japan, United States, Eastern Europe, Australia/New Zealand (ANZ), and former Soviet Union (fSU).

A similar set of long-run marginal abatement curves can be created for all non-Annex I regions, and is shown in Fig. 3. Marginal abatement curves for four of the six regions fall with the range of Annex I regions. However, marginal abatement curves for India and China are far to the right of the other regions. One of the reasons is that energy resources in India and China are dominated by coal. Another reason is the divergence of market exchange rates and purchasing power parity exchange rates in these two countries. Both SGM-India and SGM-China operate in local currency, so it is necessary to choose an exchange rate for converting US dollars to rupees or yuan when comparing marginal abatement cost curves across countries. The SGM uses base-year

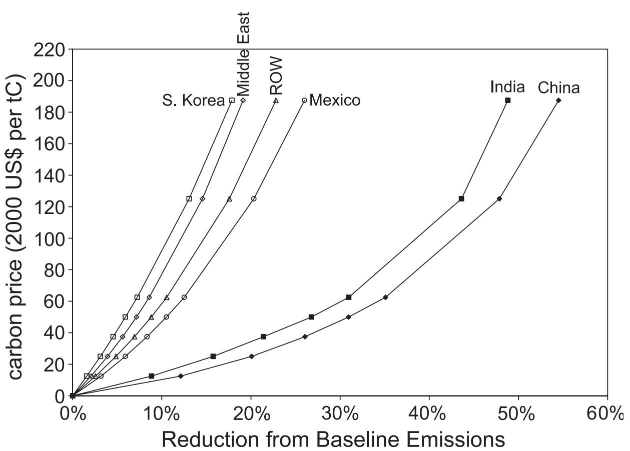

Fig. 3. Long-run marginal abatement cost curves for non-Annex I regions: South Korea, Middle East, Rest of World (ROW), Mexico, India, and China.

(1990) market exchange rates for this conversion. US dollars, when converted to rupees or yuan using market exchange rates, result in relatively large internal price increases for coal. If market exchange rates for these two countries converge over time to purchasing power parity exchange rates, then the marginal abatement curves will shift to the left.

4. Examples from EMF-19 scenarios

Modeling groups participating in EMF-19 were asked to run a number of scenarios. Some of the scenarios were designed to determine model response to either a constant carbon price or a gradually increasing carbon price.

Five global scenarios using SGM were reported to EMF-19: (1) SGM baseline; (2) carbon price starting at \$10 per tC in 2010 and increasing by \$10 per decade; (3) carbon price starting at \$25 per tC in 2010 and increasing by \$25 per decade, with a maximum price of \$100; (4) carbon price of \$100 per tC starting in 2010 and held constant thereafter; and (5) global carbon emissions limited to the WRE 550 time path, with full global trading of carbon emissions rights.

Baseline carbon emissions through 2050 for selected SGM regions are shown in Fig. 4. Carbon emissions in India and China increase rapidly, although India starts at a much lower base-year level. Carbon emissions in the former Soviet Union begin to increase again after year 2000, getting back to 1990 levels sometime between years 2020 and 2030. Emissions growth after 2030 in the former Soviet Union is limited due to declining population and labor force. The United States baseline is constructed to generally follow projections from the U.S. Energy Information Administration (2002) until 2020, and then continue with the same rates of change in energy and labor productivity through 2050.

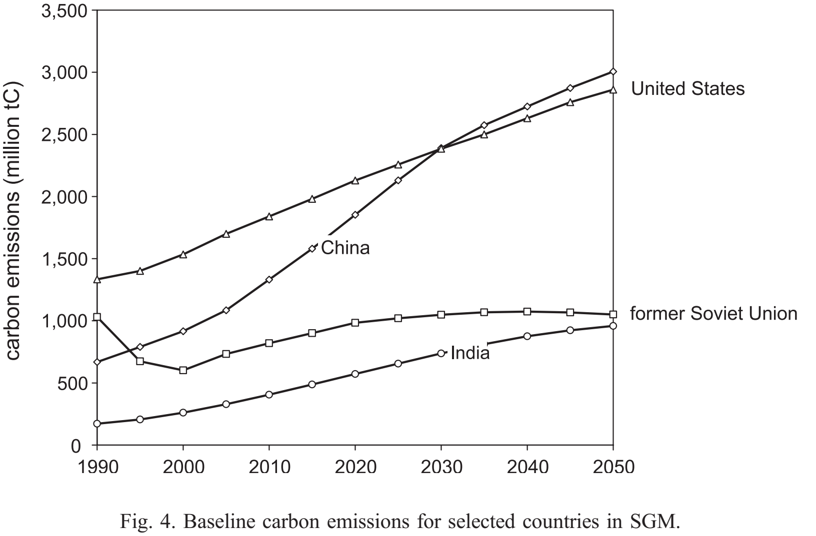

Fig. 4. Baseline carbon emissions for selected countries in SGM.

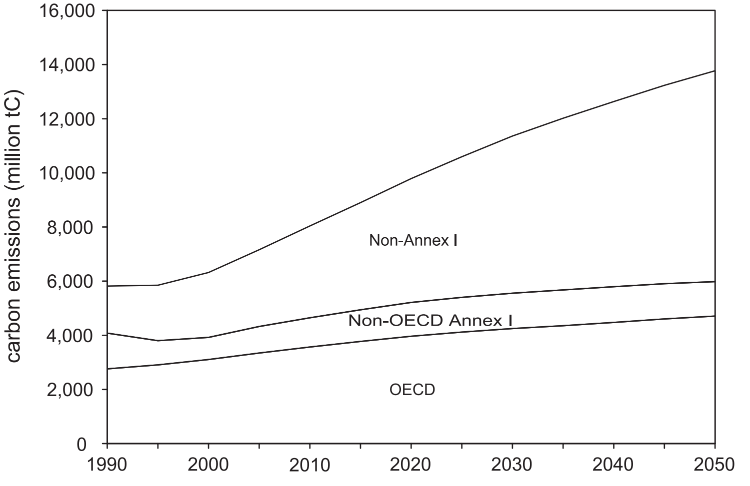

Fig. 5. Baseline carbon emissions for regional aggregates.

Baseline carbon emissions for thirteen SGM regions are combined into three regional aggregates in Fig. 5. Most of the growth in global carbon emissions occurs in the non-Annex I regions. Fig. 6 describes the case where global carbon emissions are limited so that the CO_2 concentration never exceeds 550 ppmv. The global emissions target was specified in advance by EMF-19, and the SGM determines a time series of global carbon prices, with full global trading of carbon emissions rights, to meet the WRE 550 ppmv target. The bulk of emissions mitigation occurs in non-Annex I countries, as would be expected from the baseline share of carbon emissions in non-Annex I countries, and because the marginal abatement cost curves for India

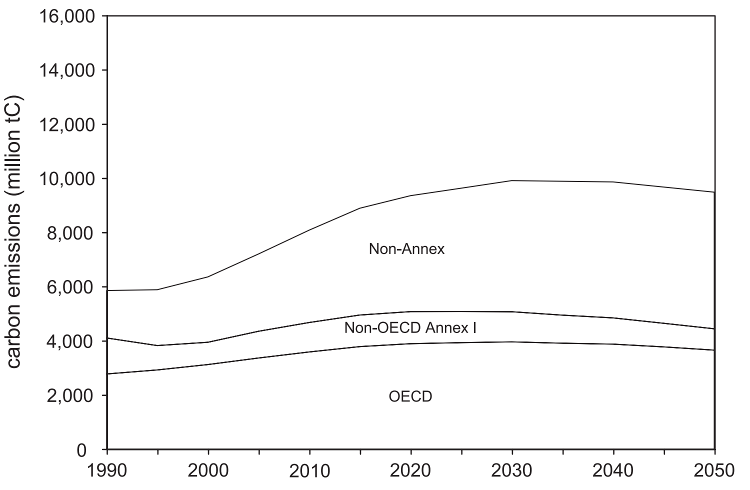

Fig. 6. SGM carbon emissions with global WRE-550 ppmv target and full global emissions trading.

Table 2
Carbon prices (2000 US$ per tC) in EMF-19 global carbon mitigation scenarios using SGM

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
$10/decade (A)	0	5	10	15	20	25	30	35	40	45	50
$25/decade (B)	0	13	25	38	50	63	75	88	100	100	100
$100 constant (C)	0	50	100	100	100	100	100	100	100	100	100
WRE 550 ppmv	0	0	0	3	28	50	55	82	102	164	215

and China are to the right of comparable cost curves of other SGM regions, as shown in Fig. 3.

Carbon prices for the four SGM mitigation scenarios are shown in Table 2. Since the SGM operates in five-year time steps, the 2005 time step was used to gradually introduce each carbon policy. Note that the marginal cost of meeting the WRE 550 target increases rapidly after year 2040. The marginal cost of emissions reductions from baseline become progressively more expensive.

Global SGM carbon emissions for all five scenarios are shown in Fig. 7. After 2040, the WRE 550 target is falling while baseline emissions are still rising, with a relatively high marginal cost to meet the target. If we had run the SGM scenarios beyond 2050, the baseline and WRE target would continue to diverge, resulting in even greater marginal costs of carbon mitigation.

5. Excursion: carbon capture and disposal in the United States

Top-down economic models are often used for analysis of climate policy, but there is an increasing demand for these models to simulate the introduction of specific

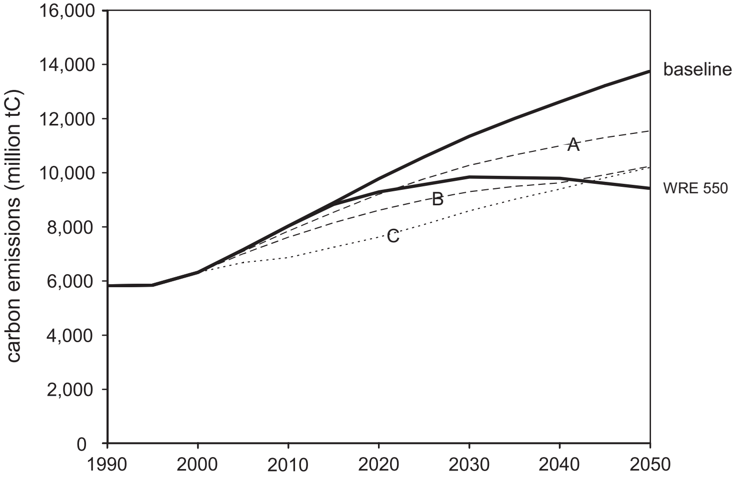

Fig. 7. Global SGM carbon emissions for EMF-19 scenarios. (A) Carbon prices start at $10 per tC in 2010 and increase by $10 per decade. (B) Carbon prices start at $25 per tC and increase by $25 per decade until a maximum of $100 per tC. (C) Carbon prices start at $100 per tC and are held constant thereafter.

energy technologies while maintaining the essential features of an engineering cost model. None of the global SGM scenarios described in the previous section allow for carbon capture and disposal in electricity generation, nor was any other advanced technology included that could serve as a backstop to limit the increase in the marginal cost of emissions mitigation. With a WRE 550 target, SGM carbon prices in 2050 are comparable to published costs (David and Herzog, 2000) per tC for carbon capture in electric power plants. This section demonstrates a methodology for including carbon capture and disposal in a computable general equilibrium model such as SGM-USA, and is a small step toward bridging the gap between top-down economic models and engineering cost models.[4] See Biggs et al. (2000) for an alternative approach to include engineering cost data on carbon capture into a computable general equilibrium model.

Two electric generating technologies, natural gas combined cycle with capture and disposal (NGCCcd) and coal IGCC with capture and disposal (IGCCcd), were added to the set of electric generating technologies. The full set of technologies is shown in Fig. 8.

At each nest in the fossil fuel investment allocation tree in Fig. 8, generation shares are calculated using Eq. (12).

$$\text{share}_i = \frac{b_i C_i^{\lambda}}{\sum_j b_j C_j^{\lambda}} \tag{12}$$

where C_i is the levelized cost per kWh, b_i is a calibration parameter to match base-year generation, and λ determines that rate that one technology can substitute for another. The b_i are all set to 1.0 in the base load nest and below of Fig. 8, so that the capture and disposal technologies compete only on cost with the corresponding technology without capture and disposal. This formulation prevents knife-edge switching into capture and disposal.

A common way to compare costs among electric generating technologies is to plot cost per kWh against carbon price. This is done in Fig. 9 for NGCC and IGCC, with and without carbon capture. Costs in Fig. 9 include a \$40 per tC disposal cost.[5] A similar option for pulverized coal generation was not included because its levelized cost with carbon capture is greater than IGCC with capture.

Fig. 9 was constructed using engineering cost models of the four electric generating technologies. Data for the capture plant are based on David and Herzog (2000). The relative cost of electricity from coal and natural gas depends on the relative prices of these fuels and on the interest rate. IGCC generating technology is more capital intensive than NGCC, and a lower interest rate would narrow the gap in costs. A higher price of

[4] Results in this section are from a new object-based version of SGM designed to facilitate the introduction of advanced electric generating technologies. Analysis in this section covers only the United States.

[5] This assumption of a constant \$40 per tC disposal cost oversimplifies the question of how much disposal is available at what cost and in what year. However, it is instructive to see how the disposal cost affects the break-even cost of capture and disposal in Fig. 9.

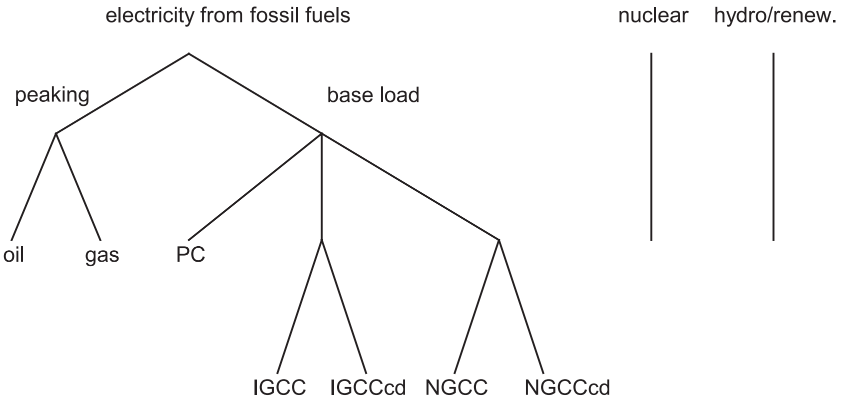

Fig. 8. Electric generating technologies: oil-fired (oil), natural gas single cycle (gas), pulverized coal (PC), coal integrated gasification combined cycle (IGCC), coal IGCC with carbon capture and disposal (IGCCcd), natural gas combined cycle (NGCC), NGCC with carbon capture and disposal (NGCCcd), nuclear, and hydropower/renewables.

natural gas would increase the cost of electricity generated from natural gas. Note the crossover point for each technology, where the cost of electricity is the same with or without capture. This occurs at $131 per tC for IGCC, but at $226 per tC for NGCC.[6] However, we cannot fully exploit the lower cost of carbon mitigation with IGCC because its cost per kWh is greater than that of NGCC over the entire range of carbon prices.

Electricity production in the SGM baseline case is split among the generating technologies in Fig. 10. The two capture and disposal technologies acquire no market share with a zero carbon price. Pulverized coal loses market share over time to both NGCC and IGCC. Market share in the model is determined mainly by cost per kWh, but the shift among technologies is gradual as the relative cost of generation varies by technology. This scenario assumes a capital lifetime of 40 years for electric power plants, so new technologies are phased in gradually over time. Note the strong growth in electricity generation through 2050. This scenario roughly matches projections by the U.S. Energy Information Administration to 2020 (EIA, 2002). One important difference is that the projections in Fig. 10 include rapidly growing shares for IGCC.

Electricity scenarios in Figs. 10 and 11 include a carbon disposal charge of $40 per ton of carbon. This has the effect of increasing the break-even carbon price with carbon capture and disposal to at least $40 more than the break-even carbon price with carbon capture alone. Fig. 11 shows how the mix of electric generating technologies changes

[6] The break-even carbon price consists of a capture component and a disposal component. For IGCC, the capture component is $84 per tC and the disposal component is $47 per tC. For NGCC, the capture component is $180 per tC and the disposal component is $46 per tC. In each case the disposal component is greater than the assumed $40 per tC direct cost of carbon disposal because of the energy penalty associated with carbon capture.

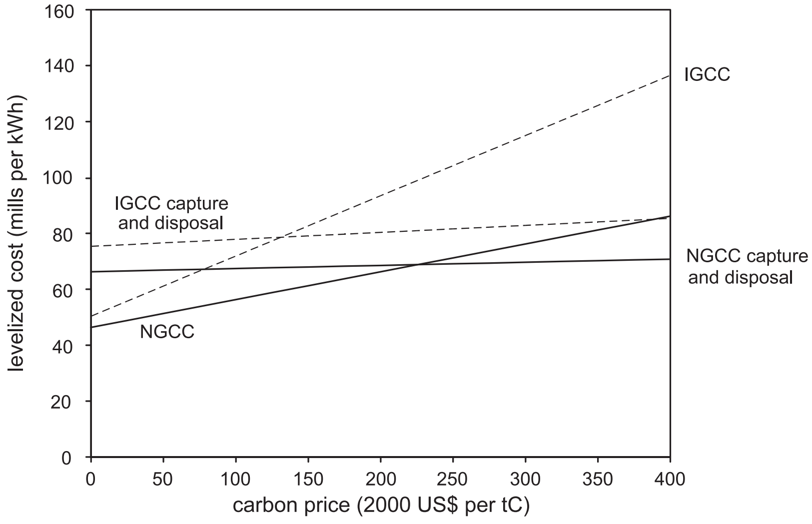

Fig. 9. Levelized electricity cost as a function of carbon price for four electric generating technologies: natural gas combined cycle (NGCC), NGCC with carbon capture and disposal, coal integrated gasification combined cycle (IGCC), and IGCC with carbon capture and disposal.

with a carbon charge of $200 per tC applied in 2005 and held constant thereafter. Electricity is more expensive with the carbon charge, so the total amount of electricity generation falls.

The $200 carbon price in Fig. 11 is greater than the break-even price for adding carbon capture and disposal ($131) to a new IGCC plant, so most of the generation from IGCC is with capture and disposal. The $200 carbon charge is still less than the break-even price for adding carbon capture and disposal to a new NGCC plant ($226), so less than half of new NGCC capacity uses capture and disposal in this SGM scenario.[7]

An alternative view of the impact of carbon capture and disposal on the cost of reducing carbon emissions is shown in Fig. 12. Here, constant-carbon-price experiments, with the carbon price starting in 2005, were run up to $300 per tC. The impact of carbon capture and disposal is minimal at low carbon prices, but is significant at carbon prices near the break-even prices for carbon capture and sequestration in IGCC and NGCC. Year 2030 was chosen for Fig. 12 because it is far enough in the future that most of the electric generation capacity existing before 2005 would have been replaced (with a capital lifetime of 40 years).

This excursion considered carbon capture from new NGCC and new IGCC generating plants, but did not consider capture from pulverized coal (PC) plants. David and Herzog

[7] At the break-even carbon price of $131, 50% of new IGCC plants would be constructed with carbon capture and disposal. Similarly, 50% of new NGCC plants are built with carbon capture and disposal at the break-even carbon price of $226. The share of new plants with capture and disposal adjusts smoothly as the carbon price approaches break-even for IGCC or NGCC.

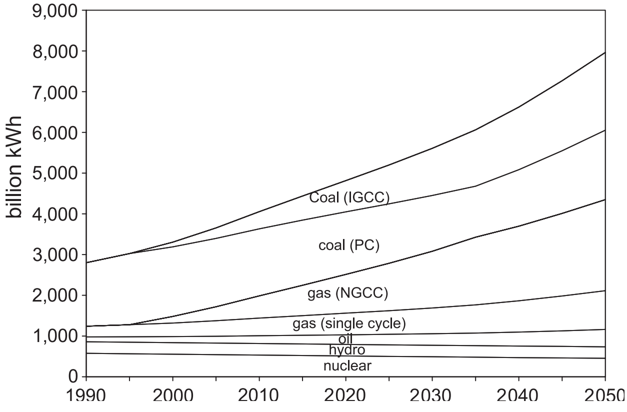

Fig. 10. Electricity generation by technology (SGM-USA baseline).

(2000) provide an engineering cost model for new PC plants with capture, but electricity generating costs in a new PC plant with CO_2 capture are much higher than in a new IGCC plant with capture. However, given the very long lifetime of existing PC plants, retrofit of a PC plant to capture CO_2 is an option that should be considered in future analysis.

6. Conclusions

This paper explores some possibilities for representing energy technologies, especially for electricity generation, in a computable general equilibrium model such as SGM. It is

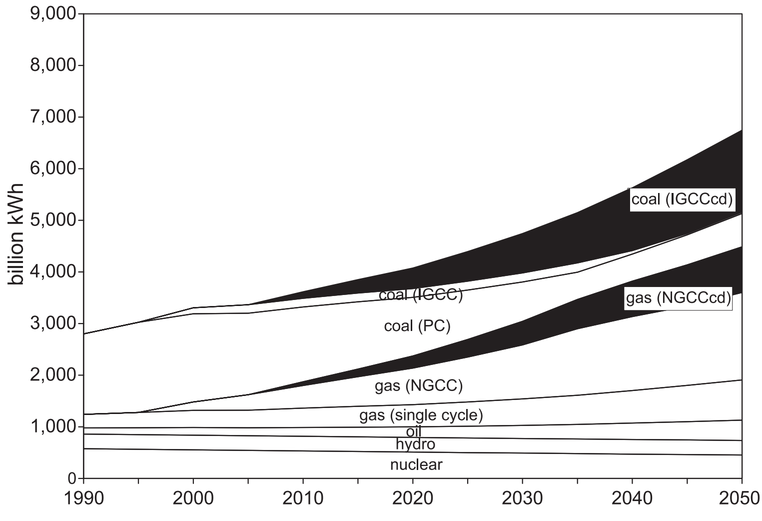

Fig. 11. Electricity generation by technology in SGM-USA at $200 per tC.

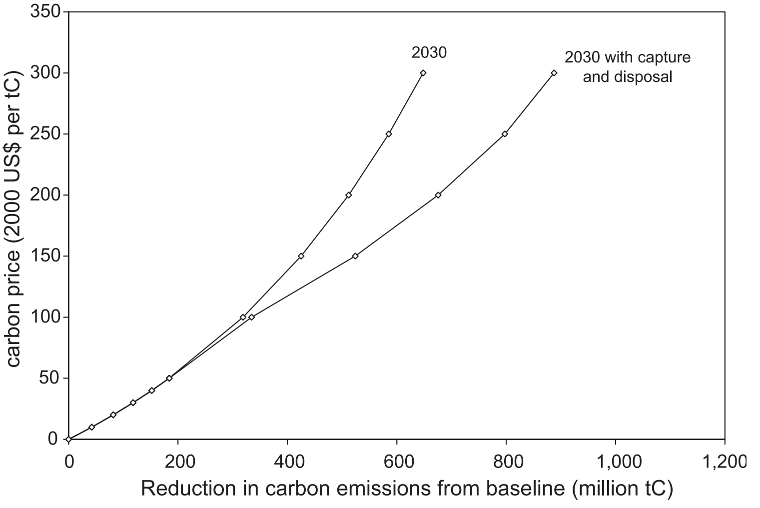

Fig. 12. Effect of carbon capture and disposal on SGM-USA marginal abatement cost curve in 2030.

possible to start with engineering cost models, derived by others, and accurately represent those technology characteristics in the operation of a computable general equilibrium model. In this case, it was helpful to have a separate production function for each electricity generation technology, as the cost of carbon capture varies across these technologies.

Outside of the electricity sector, the SGM represents technology choice by smoothly varying substitution possibilities in a CES production function. Here, it is useful to partition capital stocks into 5-year vintages. New capital has a greater elasticity of substitution than old capital, which implies greater marginal abatement costs in the short run than in the long run.

Another objective of this paper was to document SGM marginal abatement cost curves, both over time and across SGM regions. These curves, generated by constant-carbon-price experiments, have been useful in reduced-form analysis of emissions trading within individual countries or groups of countries.

Future model development will extend the representation of other sectors, especially agriculture, land use, and buildings. These sectors offer substantial opportunities for reductions in net carbon emissions, and direct use of technical data for these activities can improve the realism of economic models used for analysis of climate policy.

Acknowledgements

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An integrated analysis of policies that increase investments in advanced energy-efficient/low-carbon technologies

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Abstract

A new analysis by the EPA Office of Atmospheric Programs and the Argonne National Laboratory (ANL), using the *All Modular Industry Growth Assessment* (AMIGA) system, indicates that a technology-led investment strategy, can secure substantial domestic reductions of carbon emissions at a net positive impact on the U.S. economy. However, a moderate energy policy, even supported by a carbon charge ranging from US$48 to US$93 per metric ton, is insufficient to reach the so-called Kyoto targets.
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Keywords: AMIGA; Climate policy; Technology

1. Introduction

The evidence is slowly accumulating that increased atmospheric concentrations of heat-trapping gases are causing global climate change. Concerns over the potentially adverse impacts of global climate change led to the Kyoto Protocol to the United Nations Framework Convention on Climate Change in December 1997. The agreement was a watershed event in the history of environmental policy. For only the second time in history, national governments have agreed to seek binding targets for pollutants that have global

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effects. Because of serious economic concerns, however, the United States has chosen not to ratify the treaty which would require greenhouse gas (GHG) emissions reductions to 7% below the nation's 1990 levels within the 5-year period from 2008 to 2012. Nonetheless, there is growing recognition that cost-effective energy policies may reduce carbon emissions in ways that benefit the economy and that provide significant reductions in greenhouse gas emissions.

In this article, we quantify some of the macroeconomic benefits that can result from increased investments in energy-efficient and renewable energy technologies by the year 2050. Such investments are the result of a moderate set of programs and policies designed to overcome the many institutional and organizational barriers that slow the adoption of energy-efficient, low-carbon technologies. We also compare these results with a scenario that largely emphasizes pricing policies rather than other cost-effective program options.

For the analysis presented in this article, we used the Argonne National Laboratory (ANL)'s general equilibrium model, the *All Modular Industry Growth Assessment* (AMIGA) system, to evaluate the effects of a successful expansion of well-designed energy efficiency and renewable energy policies and programs (Hanson, 1999). The results from numerical simulations show that: (1) although the policies and programs evaluated in this review never achieve the Kyoto targets, energy-related carbon emissions are substantially reduced compared to the reference case; and (2) the investments in cost-effective energy efficiency and low-carbon energy supply technologies will tend to provide a small increase in overall economic activity within the United States.

2. Scenario of a moderate energy policy

Driven by an average annual economic growth rate of 2.7% between the years 2000 and 2050 (measured by changes in the nation's Gross Domestic Product, or GDP), the reference case projections developed for this exercise indicate that carbon emissions will increase from 1582 million metric tons (MtC) in 2000 to 2342 MtC by 2050 (see Table 1). Following an analysis by Edmonds (2002), it appears the reference case projections are following a path that would lead to carbon dioxide (CO_2) concentrations of about 550

Table 1
Incremental expenditures in the moderate energy policy scenario compared to the reference case

	Moderate policy case					
Variable (in billions of US$2000)	2000	2010	2020	2030	2040	2050
Government program expenditures	0	4	17	15	14	12
Efficiency investments	0	16	66	69	66	78
Power generation investments	0	– 11	– 8	– 14	– 12	– 15
Other business investments	0	– 3	– 6	– 16	– 24	– 30
Carbon revenues	0	85	106	110	118	126
Energy expenditures	0	29	– 29	– 124	– 191	– 257
Energy expenditures net of carbon payments	0	– 56	– 135	– 230	– 308	– 383
Petroleum imports	0	– 12	– 49	– 93	– 125	– 159

Source: EPA Office of Atmospheric Programs, Argonne National Laboratory AMIGA Modeling System Moderate Policy Runs, 08-12-2002.

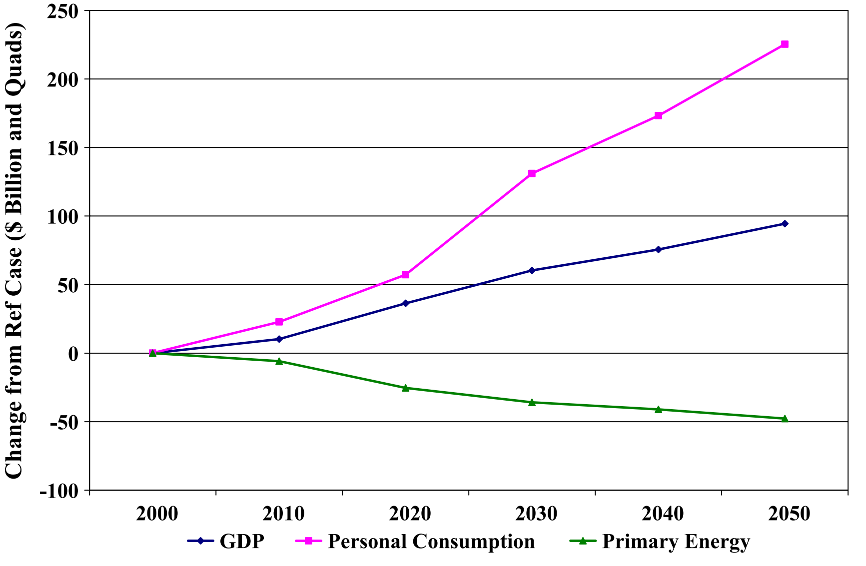

Fig. 1. Key energy and GDP changes for a moderate energy policy scenario.

parts per million by volume (ppm) if his calculated least-cost carbon reduction path were adopted by all nations in the future.[1] The question posed in this analysis is what economic impacts and climate benefits might be expected should the United States implement a series of moderate energy policies and programs that lower energy use by businesses and consumers? In this case, a "Moderate Energy Policy" is defined as one in which cost-effective technology investments are made that increase the nation's overall energy efficiency, and that reduce the carbon intensity with respect to the nation's energy supply technologies.

To provide a context for such an analysis, we used the policy and program cost information specified in the U.S. Department of Energy (DOE) sponsored study, *Scenarios for a Clean Energy Future* (Interlaboratory Working Group, 2000) as the basis to reduce carbon emissions approximately to 1990 levels by 2050. In other words, while the business-as-usual (BAU) scenario assumes a continuation of current energy policies and a steady pace of technological progress, the Moderate Energy Policy scenario is defined by a set of program options that are consistent with increasing levels of public commitment and political resolve to solving the nation's energy-related challenges. Some of the public policies and programs that define the scenarios are cross-cutting; others are designed individually for each sector (buildings, industry, transportation, and electric generators). A broad number of policies are examined, including increased fiscal incentives, expanded voluntary programs, efficiency performance standards and regulations, improved vehicle choice and information programs, and increased research and development activities. Fig. 1

[1] This compares to pre-industrial CO_2 concentrations of 280 ppm, and to present-day concentrations of about 380 ppm.

illustrates the GDP, personal consumption, and primary energy impacts of these assumptions over the period 2000 through 2050 compared to the reference case.

3. Overview of the AMIGA system

Over the last few years, a new economic impact modeling system, the *All Modular Industry Growth Assessment* (AMIGA) system, has been developed with the capability to represent many of the specific policy options for reducing carbon emissions. The system has household and government demand modules, a transportation vehicle choice module, gas supply and electricity generation modules, a unit inventory of power plants in the United States, and five other modules in which various production activities and industrial processes are represented, including demand functions for energy.

The system represents capital stock accumulation, depreciation and utilization for transportation equipment including 48 types of light-duty vehicles, for 20 categories of electrical generation equipment, and for a broad range of buildings, appliances, and industrial processes. Capital is not treated as homogeneous; rather many separate stocks are included providing different services and having different characteristics. Stock characteristics include equipment vintage, energy efficiency, and operating costs. Some key capital services are energy-intensive such as transportation services or industrial processes. Capital investment can be directed at expanding the quantity of service or lowering its energy-intensity through substitution.

The full set of modules that make up the AMIGA system provide a comprehensive representation of more than 200 production sectors and the absorption of goods and services within the U.S. economy. The modules include additional detail on technology, employment, and trade. Flows of these goods and services are modeled from production to consumption, investment, or trade. In most cases these flows are measured by constant dollar indices, but where appropriate for energy commodities the flows are measured in physical units such as kilowatt-hours (kW h) or British thermal units (Btus). An aggregation module calculates various performance measures and macroeconomic concepts, such as national income and consumer price indices. The system is run annually, in this case from the years 2000 to 2050.

An important feature of the system is that the household demand module uses a household production function approach, based on the consumer demand theory of Lancaster (1971). Consumer demand related to durable goods depends on the attributes of the services derived from the use of these goods, i.e., vehicles, housing, and appliances. Thus, if an attribute such as home heating comfort can be provided with less energy and at lower cost with improved technology, then the household would be financially better off. Some household income will become available to save or to spend on other goods and services. The functional forms used to specify demand are consistent with microeconomic theory and are structured hierarchically. As an example, transportation services can be met with different size vehicles that are not perfect substitutes. Resulting changes in consumer welfare from policies that promote the development and adoption of energy efficient technologies can be measured by equivalent variation, the change in income at which the representative consumer would have the same welfare. The demand functions are estimated using the Department of Commerce National Income and Product Account (NIPA) time series data. These NIPA accounts provide annual data by detailed product categories with adjustments made to impute services derived from stocks of durable goods.

In all the modules, purchased energy and capital can combine to provide energy-related services and to represent opportunities for pushing the technology and decision-making frontiers in these areas. Hence, specific modeling routines have been developed for energy-capital substitution opportunities and technology adoption that supports the demand for major energy services. Trends in government spending are exogenously determined, except for programs related to climate and energy policy as well as changes in energy demand that results from the government's own energy efficiency measures.

All the AMIGA modules are programmed in C-code. The operating shell for the AMIGA system controls the execution of all the modules. First, a preprocessor module sets up the base year databases for each module. A modified, enhanced Gauss-Seidel type algorithm is used to find a general equilibrium solution to the system of equations. After convergence, information can be accessed from any of the modules and output reports are prepared.

In AMIGA, price and quantity indices are associated with each activity; expenditures equal price times quantity. Quantities are measured either in terms of real dollars or, where appropriate, in physical units. The AMIGA system passes price data into a module that purchases an external material and puts back the total quantity of intermediate demand. Total costs of producing each product are calculated. In equilibrium, supply and demand balance for each good or service.

For production sectors, a constant elasticity of substitution (CES) aggregator function is used to combine labor in efficiency units with capital services from producer durable equipment and structures, creating value added as the output. The standard theory of expenditure functions is used to obtain the derived demands for the factors of labor and capital. Investment demand is derived from demand for capital services.

Regarding international trade, some goods, such as crude oil, are considered perfect substitutes whether they are produced domestically or abroad. However, AMIGA uses the Armington assumption that most final and semi-finished goods are differentiated, i.e., that these imports are close but not perfect substitutes for domestically produced goods. The model also uses elasticity of substitution values based on the MIT Emission Prediction and Policy Analysis (EPPA) model. Then demand for a sector's product is interpreted as a demand for the aggregated combination of the domestic and imported goods. Again, the CES function is used as the aggregator for the imported and the domestic goods. The elasticity of substitution is taken in most cases to be 0.70, somewhat less elastic than what is assumed in the MIT EPPA model, which uses a Cobb–Douglas (C–D) function as the Value-Added aggregator (Babiker et al., 2001).

In terms of programming implementation, a module consists of one or more files containing C-code programs (or in older terminology, "subroutines"). Each module has at least one "header" file, which defines the names of variables and structural groups of variables, to be used within the module (but these variables are not accessible to other modules unless the two modules are explicitly linked). User control inputs may be attached as arguments to the execution command or read in from a user inputs control file in text data format. The module may also read in data tables from other text files to initialize its data base structures. The model has a flexible, user friendly interface.

There are hundreds of different materials, semi-finished goods, business services, and production processes modeled in AMIGA. Currently, the model takes the simple approach of using Leontief technologies regarding the demand for these intermediate inputs, but with the opportunity for time trends and with the introduction and materials characterization of future products, e.g., hybrid vehicles, hydrogen infrastructure, or carbon capture and sequestration. Hence, materials substitution occurs through the choice of substitute products with different materials composition.

Product outputs, material inputs, labor, capital, and energy are all related though production processes and technology. Expansion of labor input, investment, and technical advances drive economic growth over time.

The basic representation for the model of ''ideal'' factor demands is obtained from the following production structure: for each sector *i*:

$$Sector\ Output = f^{\mathrm{CES}}\ (Utilized\ Capital,\ Labor\ Input)$$

$$Utilized\ Capital = f^{\mathrm{LEON}}\ (Production\ Capital,\ Energy\ Services)$$

$$Energy\ Services_j = f_j^{\mathrm{CES}}\ (Energy - Saving\ Capital,\ Energy\ Input)$$

where *Energy Services* can be provided by multiple energy forms, denoted by *j*.

Sector output is given by a CES functional form, with industry-specific substitution elasticities obtained from estimates in the literature (Varian, 1992). Services from utilized capital are represented by a quantity index number calibrated to the base year (1992), with the price index normalized to one in the base year. This index number includes both capital rental plus energy services, where energy services themselves are given by combining energy-saving capital with energy input. The equation above for *Utilized Capital* can be taken in the long run to be Leontief, since the capital-energy substitution possibilities are captured in the third equation. However, over the business cycle, there may be periods in which demand for output decreases and then typically the ratio, *Energy Services*/*Utilized Capital*, increases. (AMIGA does not currently include this effect because the reference forecast is one of smooth economic growth.) The management of energy flows to a process is slightly sensitive to the price of energy with short-run price elasticities of energy demand between 0.10 and 0.15.

The CES energy service equation is adapted from the Ross 18-sector LIEF model (Ross et al., 1993). These equations are specific to the sector and energy form (electricity and fossil fuels). Side conditions are used to account for combined heat and power (co-generation) systems. Some electricity can be self-generated by using by-product fuels or purchased natural gas. Also, some of the heat demands otherwise supplied by gas-fired furnaces can be met from the waste heat from co-generation systems.

The production model shown above combined with technology penetration equations gives rise to investment demands. Investment spending is a component of GDP. This model is sensitive to energy prices and to information and voluntary agreement programs. The latter are represented by increased penetration rates for energy-efficient capital and/or by reduced hurdle rates, which reflect the higher priority being attached to energy management. The programs are win–win opportunities, since the voluntary agreements encourage adoption of cost effective measures.

As we noted earlier, AMIGA uses a household production function approach to represent consumer energy demand. This is analogous to using industry production functions (Lancaster, 1971). Household transportation services are "produced" using vehicle capital stocks and fuel. Energy-related housing services such as heating, cooling, and hot water are also viewed as being produced by the household. When the technology used to provide energy-related services improves (e.g., more efficient electric heat pumps or vehicles with greater fuel economy), then these household services can be provided with less energy and possibly at lower life-cycle costs.

4. Investment-led efficiency improvements

The scenario evaluated in this analysis is driven by the technology resource potentials characterized in the CEF study. The authors of that report describe their analysis as an attempt to "assess how energy-efficient and clean energy technologies can address key energy and environmental challenges facing the US" (Brown et al., 2001). In that regard, they evaluated a set of about 50 policies to improve the technology performance and characterization of the residential, commercial, industrial, transportation, and electricity generation sectors. The policies include increased research and development funding, equipment standards, financial incentives, voluntary programs, and other regulatory initiatives. These policies were assumed to change business and consumer behavior, result in new technological improvements, and expand the success of voluntary and information programs.

The selection of policies in the CEF study began with a sector-by-sector assessment of market failures and institutional barriers to the market penetration of clean energy technologies in the U.S. For buildings, the policies and programs include additional appliance efficiency standards; expansion of technical assistance and technology deployment programs; and an increased number of building codes and efficiency standards for equipment and appliances. They also include tax incentives to accelerate the market penetration of new technologies and the strengthening of market transformation programs such as Rebuild America and Energy Star labeling. They further include so-called public benefits programs enhanced by electricity line charges.

For industry, the policies include voluntary agreements with industry groups to achieve defined energy efficiency and emissions goals, combined with a variety of government programs that strongly support such agreements. These programs include expansion and strengthening of existing information programs, financial incentives, and energy efficiency standards on motors systems. Policies in the CEF analysis were assumed to encourage the diffusion and improve the implementation of combined heat and power (CHP) in the industrial sector. For electricity, the policies include extending the production tax credit of 1.5 cents/kW h over more years and extending it to additional renewable technologies.

Broadly speaking, the CEF moderate scenario can be thought of as increasing the funding for programs that promote a variety of both demand-side and supply-side technologies. They include, for example, increased funding for cost-shared research, development, and demonstration of efficient and clean-energy technologies. These also include production incentives and investment tax credits for renewable energy, energy efficiency and transportation technologies. They further include increased spending for programs such as DOE's Industrial Assessment Centers and EPA's Energy Star programs.

The combined effect of the R&D and program expenditures, together with other policies described in the CEF report, implies a steady reduction in total energy requirements over the period 2000 through 2050.[2] By the year 2050, for example, the nation's primary energy consumption and electricity sales as summarized in Table 1 were projected to decrease by 30% and 22%, respectively, compared to the reference case.

Table 1 summarizes the changed spending patterns that emerge from the funded programs and resulting technology investments. The moderate scenario anticipates increased program spending of US$4 for the year 2010, rising to about US$17 billion in 2020, and then declining somewhat to US$12 billion by 2050. Consumer and business efficiency investments increase from US$16 billion in 2010 and rise steadily throughout the time horizon, reaching US$78 billion by 2050. At the same time, however, the efficiency gains tend to offset the need for additional electricity supply technology which, although still growing, is about US$15 billion less in 2050 compared to the reference case. Similarly, Table 1 also shows reduced energy-related investment in other sectors of the economy. In the year 2010, when efficiency savings have yet to accumulate, the investment savings are on the order of US$3 billion. By 2050 this rises to US$30 billion when energy bill savings (including the carbon payments) peak at US$257 billion.

Yet, even with the technology assumptions reflected in this scenario, programs alone are not enough to reduce carbon emissions to 1990 levels even by 2050. Hence, a further policy introduced into the scenario is an auction of carbon permits beginning in 2007 and phased in over a 7-year period such that it is fully in place by 2014. In Table 2, the decadal permit prices are shown as US$48 and US$69 per metric ton for the years 2010 and 2015, respectively. This is assumed to increase approximately 1% per year through 2050 which, together with the other programs and policies reflected in the CEF study, is sufficient to reduce carbon emissions to roughly their 1990 levels by the year 2050.[3]

Under the design of this scenario it is assumed that permits are auctioned which, in turn, generates a revenue stream from the sales of the permits which can be used to pay for the programs and policies. The balance of the revenue is then returned to consumers and businesses either as lump sum rebates or as incentives to increase their production or

[2] The Clean Energy Future Study actually covers a time horizon through 2020. For purposes of this analysis, however, we extend the assumptions of the moderate energy policies through the year 2050.

[3] Again following the Edmonds analysis, it appears the emissions of the Moderate Energy Policy scenario will put the U.S. on a trajectory that will stabilize at a 450 ppm CO_2 concentration by 2100. This assumes, of course, that other nations achieve similar reductions.

Table 2
Key price variables in the reference and moderate energy policy scenarios

Variable	Reference case						Moderate policy case					
	2000	2010	2020	2030	2040	2050	2000	2010	2020	2030	2040	2050
Carbon charge (US$2000 per metric ton)	0	0	0	0	0	0	0	48	69	76	84	93
World oil price (US$2000 per barrel)	27.72	23.36	24.68	26.20	27.82	29.53	27.72	22.89	22.87	22.91	23.57	24.39
(Change from reference case)	–	–	–	–	–	–	0.00	− 0.47	− 1.81	− 3.39	− 4.25	− 5.14
Electricity price (2000 cents per kilowatt-hour)	6.7	6.0	6.1	6.2	7.0	7.9	6.7	6.6	7.5	7.6	8.5	9.3
(Change from reference case)	–	–	–	–	–	–	0.0	0.6	1.4	1.4	1.5	1.4
Wellhead natural gas price (US$2000/1000 ft^3)	3.60	2.75	2.93	3.95	4.81	5.38	3.60	2.45	2.48	2.97	3.65	4.03
(Change from reference case)	–	–	–	–	–	–	0.00	− 0.30	− 0.45	− 0.98	− 1.16	− 1.35

Source: EPA Office of Atmospheric Programs, Argonne National Laboratory AMIGA Modeling System Moderate Policy Runs, 08-12-2002.

consumption efficiencies. Table 1 shows the magnitude of those revenues, rising from US$85 billion in 2010 to US$126 billion by 2050.

But lower energy consumption can also mean reduced energy bills for businesses and consumers. Table 1 also shows that energy expenditures, with the carbon charge embedded within the cost of energy, first increases by US$29 billion in 2010 and then decreases by US$257 billion in 2050. Since the carbon revenues are used to provide either technology investment incentives or consumer and business rebates, the net energy expenditures are shown to decline more significantly. In 2010, the energy expenditures net of carbon payments are reduced by US$56 billion. The savings continue to grow throughout the period, reaching US$383 billion by 2050. Reduced petroleum import expenditures provide yet another benefit to the economy.

Part of the reason for the lower energy expenditures is that the efficiency investments create a downward pressure on energy prices. Table 2 highlights these trends. By 2050, for example, world oil prices are down by US$5.14 per barrel of oil, a 17% decline compared to the reference case. Electricity prices are up 1.4 cents per kilowatt-hour, an increase of 18% over the reference case, while natural gas prices at the wellhead are down US$1.35 thousand cubic feet, a drop of 25% compared to the reference case.[4]

Incorporating the set of cost-effective policies and technologies characterized in the CEF study's Moderate Energy Policy, AMIGA estimates a total carbon reduction of 113 million metric tons (MtC) of carbon by the year 2010, growing to 992 MtC by 2050. In effect, this allows carbon emissions to fall to 1990 levels by 2050.[5] These macroeconomic impacts are summarized in Table 3. Almost all of the emission reductions are due to gains in energy efficiency by 2010. By 2050, however, about two-thirds of the carbon reductions are from efficiency improvements while one-third are the result of low- or non-carbon energy supply technologies. Though less aggressive than other scenarios, both the savings and the macroeconomic impacts are similar to the results published in other recent studies done elsewhere. See, especially, Bailie et al. (2001), Barrett et al. (2002), Hanson and Laitner (2000), Hanson et al. (2004), Koomey et al. (2001), Krause et al. (2002), Laitner (2001), Peters et al. (2002), and Sanstad et al. (2001). The section that follows describes the macroeconomic impacts in more detail.

5. Impact on economic activity

In addition to both energy and carbon savings, Table 3 also shows that an investment-led strategy can lead to slightly higher gains in the nation's Gross Domestic Product

[4] Since energy expenditures are a function of both prices and quantities, total electricity expenditures might be lowered if the efficiency gains are sufficient to offset the price increase. Reviewing the electricity consumption figures for 2050 in Table 1 suggests that total electricity use is reduced by nearly 22% compared to the reference case. Hence, we would expect that under this scenario electricity expenditures would be reduced. And although these totals are not provided separately in this analysis, this is the case.

[5] Assuming a 7% below 1990 level to comply with the Kyoto protocol—in effect, lowering U.S. domestic emissions to about 1252 MtC in 2010—the domestic mitigation strategies outlined in this analysis would provide the United States with about 18% of its needed energy-related carbon reductions.

Table 3
Summary of key macroeconomic variables in the reference and moderate energy policy scenarios

Variable	Reference Case						Moderate Policy Case					
	2000	2010	2020	2030	2040	2050	2000	2010	2020	2030	2040	2050
Gross Domestic Product (Billion 2000 Dollars)	9870	13,174	17,681	22,577	28,828	36,811	9870	13,184	17,717	22,637	28,904	36,905
(Change from Reference Case)	–	–	–	–	–	–	–	10	36	60	76	94
Personal Consumption (Billion 2000 Dollars)	6696	8834	11,760	14,762	18,531	23,262	6696	8857	11,817	14,893	18,704	23,487
(Change from Reference Case)	–	–	–	–	–	–	–	23	57	131	173	225
Total Energy Consumption (Quadrillion Btu)	100.3	115.6	129.6	140.7	149.3	159.9	100.3	109.7	104.3	104.8	108.3	112.2
(Change from Reference Case)	–	–	–	–	–	–	–	– 5.9	– 25.3	– 35.9	– 41.0	– 47.7
Total Electricity Consumption (Billion kilowatt-hours)	3569	4371	5078	5778	6575	7481	3569	4143	4151	4390	5067	5853
(Change from Reference Case)	–	–	–	–	–	–	–	– 228	– 927	– 1388	– 1508	– 1628
Carbon Emissions (Million Metric Tons)	1582	1893	2100	2222	2255	2342	1582	1780	1536	1453	1400	1350
(Change from Reference Case)	–	–	–	–	–	–	–	– 113	– 564	– 769	– 855	– 992

Source: EPA Office of Atmospheric Programs, Argonne National Laboratory AMIGA Modeling System Moderate Policy Runs, 08-12-2002.

(GDP). By 2010, GDP is up US$10 billion (0.08%). By 2050, this grows to US$94 billion (0.26%). At the same time, household personal consumption also increases significantly (see also Fig. 1).

Three features about the incremental investment paths are important. First, both the programs and the price signal grow over time, which encourages an increase in the level of private sector spending for new technology. Second, there is a tendency to select the least-cost measures (with the highest rates of return) first. By taking the opportunities with the highest payoffs early, a substantial savings on energy bills is realized within the first few years. This savings in energy expenditures from the initial energy efficiency investments is available to re-invest in additional energy efficiency measures, basically leading to "internal financing" of future measures for many firms. Finally, the revenues generated from a US$48–93 per metric ton carbon charge (see Table 2) are used to support R&D programs as well as a variety of other policies designed to accelerate investment in energy-efficient, low-carbon technologies. This positive investment, together with reduced oil imports and lower energy expenditures (from Table 1), all tend to increase, albeit it in a very small way, the overall level of GDP within the U.S. economy. The key macroeconomic impacts of the Moderate Energy Policy scenario, compared to the reference case analysis, are described more fully in the paragraphs that follow.

5.1. Gross domestic product

Overall efficiency improvements in the economy imply that more goods and services can be produced from the labor and other resources that are available. The growth path in incremental GDP (i.e., changes from a business-as-usual scenario) closely follows the growth path in total efficiency investments, avoided investments in energy supply, energy expenditure savings, and reduced petroleum imports. These are all shown in Table 1. There is an economic rationale for this close relationship. These expenditures represent the economic value (at least approximately) of the inputs used to produce energy. Hence, the reduction in the cost of energy services (including utilized capital and energy consumption) approximates the opportunity cost of the input factors that are freed up to produce other goods and services. This relationship is only approximate because of different sectoral factor intensities and adjustment costs. Compared to the reference case, this entire set of changes generates a net increase of US$10 billion for the nation's GDP in 2010, rising to US$94 billion by 2050. But again, the changes are relatively small, amounting to an increase of only 0.08% and 0.26% in years 2010 and 2050, respectively. GDP is not a strict welfare concept; rather, it is a measure of the total value of output of the goods and services produced within a country. Output includes investment goods produced as well as consumption goods and services. Therefore, the incremental investment in energy efficient technologies adds to the investment component of GDP.

5.2. Household consumption and savings

The net energy-related savings shown in Table 2 does not translate into household consumption increases as a fixed share over time because households tend to borrow to smooth out their consumption paths (or add to their wealth if they receive a transient increase in income). A vast amount of theoretical and empirical literature supports this smoothing behavior (Merton, 1992). In the year 2010, household consumption increases only slightly as a consequence of the more efficient durable goods purchased by consumers and the energy-related savings (net of the carbon payments) in that year. Thereafter, the increase in consumption continues to grow, but not as quickly as the net energy-related savings because of the consumption smoothing effect. Soon the first-year borrowing by households is paid back, and after that, some of the net energy-related savings go into increases in accumulated wealth (Shell et al., 1969).

5.3. The capital stock

The incremental investments in energy-efficient and renewable energy capital add to the nation's total capital stock. The composition of the capital stock also changes somewhat. There is less investment in conventional energy supply capacity, which represents intended commitments to produce more energy in the future. But there is more investment in "clean energy supply technologies" such as combined cycle natural gas generation units, combined heat and power systems, and renewable energy technologies. There is also more investment in energy efficient buildings, appliances, vehicles, and industrial processes. Without these incremental investments in energy efficiency, there would be less efficient buildings, appliances, vehicles, and industrial processes that would require increased future streams of energy production.[6] Investments in energy efficient technologies promote energy security and hedge against situations of higher energy prices in the future.

6. Price versus non-price policies

Much of the modeling emphasis to date has been one of generating the correct price signal as a means of promoting the more efficient use of technology or correcting for so-called "missing markets." In contrast, the approach taken by this analysis provides a framework in which both price and non-price programs might be seen as a complementary approach toward achieving more cost-effective emission reductions.

To test the effectiveness of this "complementary approach" with a price only approach, we developed two sensitivity runs. The Low Price scenario eliminates all programs, but institutes a carbon charge equal to that found in the Moderate Energy Policy scenario. The High Price scenario again eliminates all program impacts but doubles the carbon charge found in the Moderate Energy Policy scenario. For example, a pure carbon pricing approach would have the carbon charge flowing through into fuel prices. Anticipating higher fuel expenditures, consumers would then purchase vehicles with improved fuel economy, followed by reduced miles traveled. Whereas a new vehicle efficiency program,

[6] Strictly speaking, consumer investments in more energy efficient cars and appliances are purchases of durable goods that increase consumption rather than add to the nation's capital stock. However, the larger point remains.

as was included in our moderate case simulation, could be designed around the cap-and-trade concept, using tradeable equipment efficiency permits. It would focus the choice process on the important vehicle purchase decision since, once on the road, a light duty vehicle is typically driven for 14 years. Table 4 summarizes the key comparisons of these different approaches.

Several important results emerge in comparing moderate policy scenario with the price only runs. First, and perhaps most intuitive, total emission reductions are generally greater in the Moderate Energy Policy scenario, especially in the later years. In 2050, for example, the moderate case reaches total emission reductions of 992 MtC compared to 365 MtC in the Low Price case and 629 MtC in the High Price case. At the same time, the High Price case obtains about the same level of reductions in the year 2020 as the moderate case, 551 MtC versus 564 MtC for the two cases, respectively. But as we shall see, the cost-effectiveness of the moderate policy reductions is significantly greater than for the high price reductions.

The test for cost-effectiveness is straightforward. It is the sum of carbon revenues (permit price times the quantity of emissions) plus program costs (if any) divided by the tons reduced. As Table 4 illustrates, the Moderate Energy Policy case shows a cost-effectiveness of US$139 per ton of carbon saved in 2050 (compared to the reference case in that same year). The low price case has a cost-effectiveness of US$185/tC while the high price increases the cost to US$321/tC. In other words, the combination of both price and program policies achieves larger reductions for a significantly greater level of cost-effectiveness. This makes sense when we recall that price elasticities tend to remain low, and that energy costs are a very small part of the overall cost of living or the cost of doing business. Given the existence of the many little inefficiencies in the economy (Boyd, 2001; Krause et al., 2002), and the success of voluntary programs that encourage emission reductions (Laitner and Sullivan, 2001), it seems reasonable to conclude that reducing the size of both the inefficiency and the information gaps may generate a higher level of return compared to an economy that remains relatively unresponsive to pricing signals alone.

Table 4
Evaluating scenario effectiveness

	Reference case		Moderate policy case		Low price case		High price case	
Variable	2020	2050	2020	2050	2020	2050	2020	2050
Carbon emissions (MtC)	2100	2342	1536	1350	1781	1977	1549	1713
Carbon permit price (US$/tC)	–	–	69	93	69	93	138	186
Program spending (billion US$)	–	–	17	12	0	0	0	0
Tons saved compared to reference case (MtC)	–	–	564	992	319	365	551	629
Policy effectiveness (US$/tC saved)	–	–	124	139	124	185	215	321

Source: EPA Office of Atmospheric Programs, Argonne National Laboratory AMIGA Modeling System Moderate Policy Runs, 08-12-2002.

7. Conclusion

For understandable reasons the United States has chosen not to ratify the Kyoto Protocol which would require greenhouse gas emission reductions to 7% below 1990 levels in the period 2008 through 2012. Yet, the analysis summarized briefly in this article indicates that a Moderate Energy Policy, supported by a technology-led investment strategy, can secure substantial domestic reductions of carbon emissions at a small but net positive impact on the U.S. economy. Although shown to be cost-effective, the policies as described here provide an insufficient basis to reach the so-called Kyoto targets.

At the same time, the estimation of economic benefits provided in this analysis tend to be understated in the sense that attendant co-benefits from adopting energy efficient technologies are not yet included in the exercise (Mills and Rosenfeld, 1994). For example, improved lighting and HVAC systems increase comfort in houses and increase worker productivity in businesses, yet these benefits are not accounted for with the standard accounting framework of policy models. Moreover, technologies are evaluated on the basis of many different attributes. There is a high probability that at least several characteristics of the adopted technologies are improvements over previously available models. One type of investment that often yields a particularly high economic return is one that improves the overall process efficiency of an existing industrial facility as well as its energy efficiency. A recent study of process industries by the Lawrence Berkeley National Laboratory's identified a number of these technology opportunities, especially in the heavy industries (Worrell et al., 2003). More broadly, a series of papers have indicated that including energy savings alone does not account for the full economic returns to industry when evaluating the cost-effectiveness of energy efficiency improvements (Finman and Laitner, 2001; Elliott et al., 1997; Sullivan et al., 1997).

There are also substantial conventional air pollution reduction benefits associated with carbon emission reductions. In light of these co-benefits, it is likely that further measures than those embodied in the moderate policy case described here would be desirable. From an insurance perspective as to what level of stabilization will ultimately be necessary, the moderate case described here would leave the economy better positioned at the end of the 2050 time horizon, having developed improved technologies and having passed through the early phases of learning and market transformation as well as having a capital stock that embodies substantially lower energy intensity than in the reference case. The modeling framework used in this paper can be a useful tool for fleshing out the details of a well-designed policy mix to achieve the full set of potential economic and environmental benefits. A key dimension for the development of an optimal energy (climate) policy mix will be the relative (and complementary) roles of pricing policies and other programs in inducing an investment-led technology strategy.

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