Costs of Reducing Carbon Emissions: An Integrated Modeling Framework Approach

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COSTS OF REDUCING CARBON EMISSIONS: AN INTEGRATED MODELING FRAMEWORK APPROACH

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Abstract. This paper presents an approach to estimating world-regional carbon mitigation cost functions for the years 2020, 2050, and 2100. The approach explicitly includes uncertainty surrounding such carbon reduction costs. It is based on the analysis of global energy-economy-environment scenarios described for the 21st century. We use one baseline scenario and variants thereof to estimate cumulative costs of carbon mitigation as a function of cumulative carbon emission reductions. For our baseline for estimating carbon mitigation cost curves, we use the so-called IIASA F scenario. The F scenario is a high-growth, high-emissions scenario designed specifically to be used as a reference against which to evaluate alternatives. Carbon emissions and energy systems costs in the F scenario are then compared with (reduced) emissions and (higher) costs (including macroeconomic adjustment costs) of alternative scenarios taken from the IIASA scenario database. As a kind of sensitivity analysis of our approach, we also present the results of a scenario involving assumptions on particularly rapid technological progress.

1. Introduction

One objective of the ICLIPS (Integrated Assessment of Climate Protection Strategies) model system is to improve the estimation of long-term carbon abatement costs by using insights emerging from recent research on technological development. A long period of such research is captured in an integrated modeling framework – and accompanying databases – developed at the International Institute for Applied Systems Analysis (IIASA). This paper presents an approach to estimating world-regional carbon mitigation cost functions for the years 2020, 2050, and 2100 for use in the ICLIPS integrated assessment model. These dynamic cost curves are of key importance in computing long-term global and regional emission corridors under different climate change and mitigation cost constraints.

Our approach is designed to amend most existing studies and surveys of long-term carbon mitigation costs (e.g., Nordhaus (1991), based on the analysis of more than 11 models, and Weyant (1993, 1996), summarizing results from 14 models), in which abatement cost curves are static and do not provide regional details. Also, we explicitly include the uncertainty surrounding such carbon reduction costs. Recent development in studies of climate mitigation costs and technological options to reduce carbon emissions are reviewed by Chapter 8 (Hourcade et al., 2001) and Chapter 10 (Toth et al., 2001) of the contribution of Working Group III to the Third

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Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). A good overview of existing modeling approaches that deal with technological as well as other uncertainties with respect to climate change is presented in a recent article by Papathanasiou and Anderson (2001).

In the following we present detailed descriptions of the assumptions behind our baseline scenario and its variants. As an illustration of the importance of the baseline scenario, we present – in addition to the scenarios on which our cost curve estimates are based – a scenario involving assumptions on technological progress that may appear extreme, but which we argue are still plausible. That ('dynamic') scenario quantifies the effect of particularly successful research and development in the the area of mitigation technologies on all levels of the energy system.

For our baseline for estimating carbon mitigation cost curves, we use the so-called IIASA F scenario. The F scenario is a high-growth, high-emissions scenario designed specifically to be used as a reference against which to evaluate alternatives (McDonald, 1999). Carbon emissions and energy systems costs in the F scenario are then compared with (reduced) emissions and (higher) costs (including macroeconomic adjustment costs) of alternative scenarios taken from the IIASA scenario database. These alternative scenarios include, among others, one scenario that specifically aims at carbon mitigation (FC scenario) and one aiming at sulfur mitigation (FS scenario).

Section 2 of this article introduces IIASA's modeling framework. Section 3 describes the scenario set used to derive the mitigation cost estimates. Section 4, the central part of the paper, analyzes carbon mitigation costs in more detail and presents dynamic mitigation cost curves derived from statistical analyses of the scenarios introduced in previous part. Section 5 provides some conclusions.

2. The Modeling Framework

Although most of the numerical results used for the derivation of mitigation cost curves come from the MESSAGE-MACRO model, we present here an overview of the full IIASA Integrated Modeling Framework. This way the readers can appreciate the context in which the modeling results are derived, in particular sources of the crucial input data ('scenario variables').

Figure 1 shows the models and databases (represented as rectangular boxes) constituting the integrated assessment modeling framework and how they are linked to generate the scenarios. The boxes with the rounded edges represent formalized procedures involving the use of judgement on the side of the users as an important element. The most important example of such a procedure is the scenario Generator (SG). The SG is the central tool for formulating fundamental scenario features such as economic development rates and energy intensities. Energy model runs are made for eleven world regions as shown in Figure 2.

Let us describe each of the models and procedures in turn.

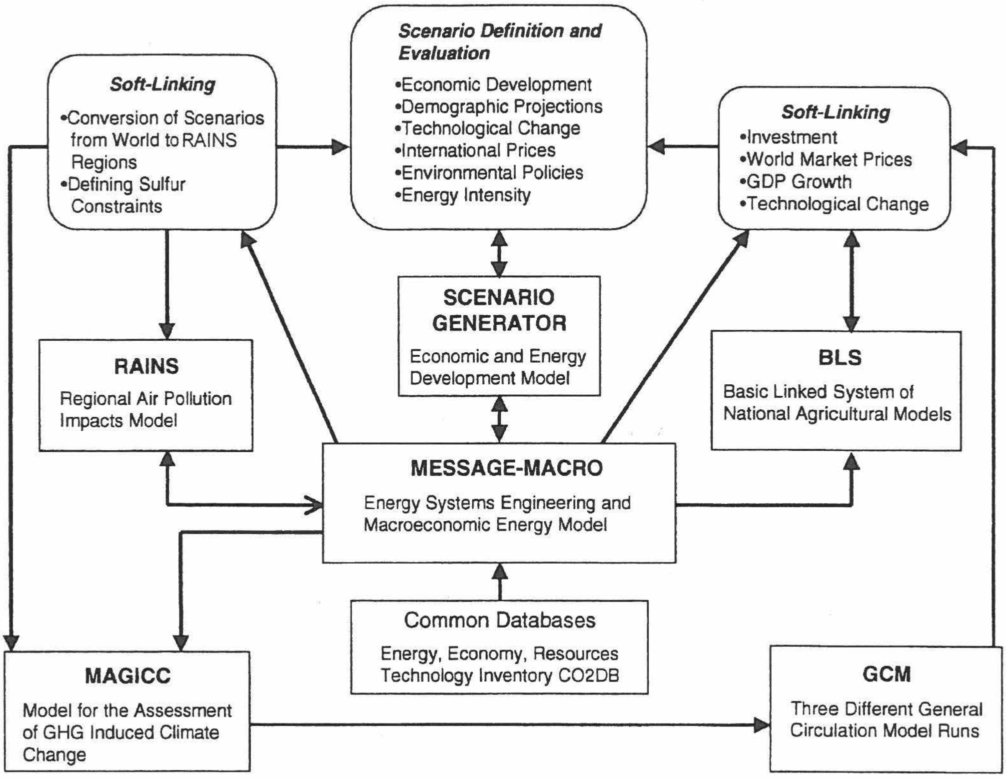

Figure 1. The IIASA integrated assessment modeling framework.

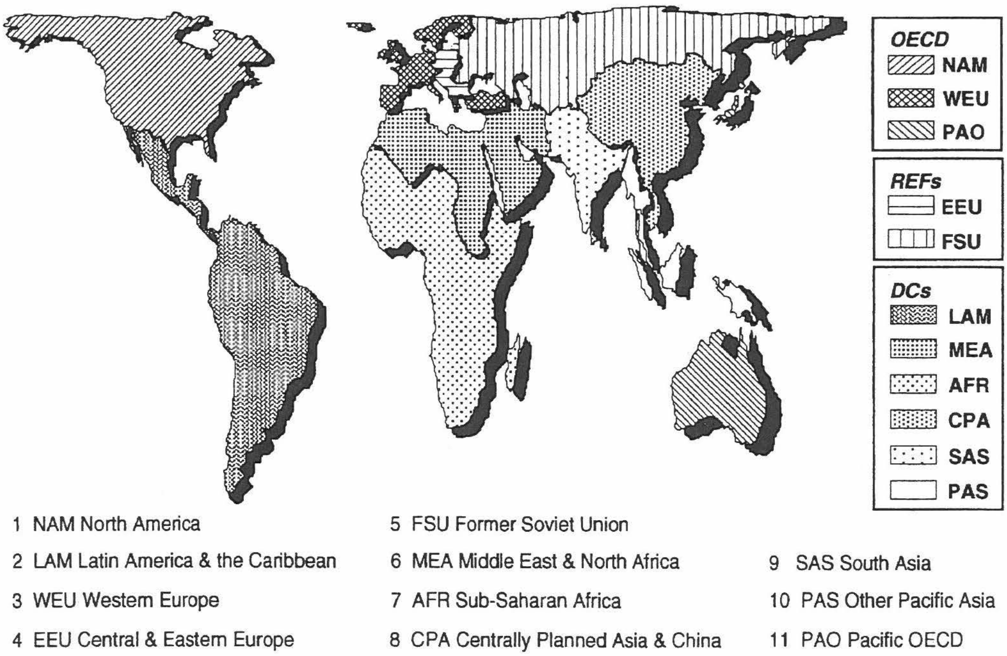

Figure 2. World regions used in the study.

The Scenario Generator

The Scenario Generator (SG) is a simulation tool to help formulate scenarios of overall economic and energy development at the level of the study's eleven world regions (Nakicenovic et al., 1998a; Gritsevskyi, 1996). It produces input data for the MESSAGE-MACRO model by generating initial 'reference' paths for economic growth and energy intensity. The reference data of the SG become final, or 'realized', data emerging from the operation of the full modeling loop.

The basis for the SG consists of economic and energy data for the base year of 1990 plus time series of energy and economic data. With these data, the user can employ pre-formulated regression equations to estimate future trends from many different, partly heuristic, relationships between the historical data.

MESSAGE

Although MESSAGE and MACRO are integrated into the single MESSAGE-MACRO model, it is still best to describe the two separately. This not only permits a clearer description, but also emphasizes that both models can also run in a stand-alone mode.

MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) is a dynamic systems engineering optimization tool used for medium to long-term energy system planning, energy policy analysis, and scenario development. The objective function is to minimize energy system costs. The 'backbone' of the model is the reference energy system (RES) describing all interdependencies from resource extraction, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services such as light, space conditioning, industrial production processes, and transportation.

The model's output includes information on the utilization of domestic resources, energy imports and exports and related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions, interfuel and energy-capital substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy. The model outputs are the result of given energy demand, available energy supply, and descriptions of the performance over time of a large set (over 400) energy conversion technologies. A detailed model description is given in Messner and Strubegger (1995).

MACRO

MACRO is a macroeconomic model representing the so-called 'top-down modeling' approaches. It employs a production function in which energy use is combined with capital and labor to generate economic output, GDP. MACRO's objective function is to maximize the total discounted utility of a single representative producer-consumer. The maximization of the model's utility function determines a sequence of optimal savings, investment, and consumption decisions. Other model outputs include internally consistent projections of world and regional realized GDP including the disaggregation of total production into macroeconomic investment, overall consumption, and energy costs.

The main determinants of the model outputs are the reference GDP growth input and the assumed development of the overall energy intensity of GDP. The link with the energy system is provided by cost functions describing energy supply. The macroeconomic equations of MACRO are, with minor modifications, the same as those in the dynamic nonlinear macroeconomic optimization model developed by Manne and Richels (1992).

MESSAGE-MACRO

MESSAGE and MACRO are linked by the energy supply cost functions. In the version used for this report, these cost functions are calibrated so that they approximate MESSAGE's cost functions in the neighborhood of the optimal solutions of both MESSAGE and MACRO. A detailed description of MESSAGE-MACRO is given in Messner and Schrattenholzer (2000).

The linked MESSAGE-MACRO model is particularly suited to calculate mitigation costs in a consistent way, i.e., by considering the feedback of increased energy prices on energy demand. MACRO's production function substitutes other production factors (capital and labor) for energy if and when the relative prices of energy increase. This substitution generates mitigation costs in the form of GDP loss relative to a reference case. The other cost component of mitigation consists of the difference of energy supply costs in the two scenarios (reference and mitigation) that are compared. Energy supply costs are calculated by MESSAGE. In order to characterize macroscopic features of energy supply, we disaggregate energy supply costs into net energy sector costs (all costs of energy extraction and conversion up to the point of final energy costs including net trade) and end-use costs. As total economic costs, we report energy supply costs plus income (GDP) losses relative to the baseline scenario.

The Climate Change Model MAGICC

The original climate change model MAGICC (Model to Assess Greenhouse-gas Induced Climate Change) was developed by Wigley et al. (1994). The IIASA version of the MAGICC model uses CO_2, CH_4, SO_2, and NO_x energy-related emissions from MESSAGE-MACRO and the IPCC IS92a scenario's emissions profiles for other greenhouse gases and non-energy-related activities. From this information, the model calculates, among others, atmospheric CO_2 concentrations, global mean temperature change relative to 1990, and sea level rise.

Other Models

The models described above are used to produce the main results for estimating our dynamic mitigation cost curves. Other models are also used in the process of scenario generation (Figure 2). Acidification impacts of energy strategies are studied by using the IIASA RAINS (Regional Air Pollution Information and Simulation) model (Alcamo et al., 1990; Amann et al., 1995). The Basic Linked System of National Agricultural Policy Models (BLS) is a global general-equilibrium model system generating global agricultural scenarios of overall economic and agricultural development (Fischer et al., 1996). A projection of global temperature change only, as calculated by MAGICC, provides insufficient information to assess the impact of climate change on agriculture. Therefore, climate change simulations under doubled CO_2 concentrations relative to the pre-industrial levels of three general circulation models are included in the IIASA Integrated Modeling Framework.

3. The Scenario Set

In our derivation of abatement cost curves, a crucial role is played by the baseline scenario. For the purposes of this article, a scenario with high carbon emissions seems particularly suitable because it facilitates a clear distinction between the baseline and the abatement cases. The two most important mitigation cases include one that specifically limits carbon emissions (the FC scenario) and another that specifically limits sulfur emissions (the FS scenario).

The topic of technological change and its major driving forces is so fundamental and complex that its detailed elaboration goes far beyond the original scope of this paper. Nonetheless, to give a flavor of what appears possible if technological change is radical during the 21st century, we include a brief description of the D Scenario here. The main purpose of the D Scenario is purely 'illustrative', based on a sort of 'what-if' approach. Assumptions about energy technologies' key improvements, like cost and efficiency, are derived from the scientific and the applied literature on R&D and captured in IIASA's tool CO2DB (Strubegger et al., 1999). They are also consistent with a number of studies conducted in that area. As a good source, see Capros (2000). These assumptions are clearly subjective, but based on estimates provided by recognized experts in that field.

The following description will focus on those scenarios that are used for the generation of the Dynamic Cost Curves (DCCs), but with the 'D' scenario we also include an 'illustrative case'.

3.1. THE F SCENARIO

The baseline scenario is dubbed 'F' (for 'fossil energy'). This scenario is very similar to the A2 IIASA-WEC scenario (Nakicenovic et al., 1998b). It assumes no major deviations from long-term trends of economic growth and carbon emissions even as some environmental impacts build up to what may turn out to be intolerable levels. It is thus not necessarily intended to be plausible. Rather, it permits to emphasize the effects of alternative assumptions about efforts to protect the environment.

Although economic growth in the F scenario is projected to follow long-term trends, it must be considered high because it assumes that developing countries 'catch up' with industrialized countries. This is to say that the ratio between the highest and the lowest per-capita income (average per world region) decreases from a 1990 value of 68 to about 5 in the year 2100. By 2050, total Gross World Product increases to more than five times its 1990 value, 21 trillion (10^{12}) U.S. dollars of 1990 purchasing power. By 2100, it increases by a factor of 18.

Population growth in the 'F' scenario is medium, based on the central scenario of IIASA's revised set of demographic scenarios (Lutz et al., 1996). According to this medium scenario, world population grows to almost 11 billion in 2100. Technological progress is assumed to be relatively modest, with energy intensity reductions on the order of 1% per year for the world as a whole. Primary-energy resources are assumed to be limited to currently estimated ultimately recoverable resources of conventional oil and gas, and to currently identified *reserves* of unconventional oil and gas. In our view, this represents a low, cautious range on future fossil resource availability, reflecting 'conventional wisdom'. The result of these assumptions in terms of energy supply developments and environmental impact is given in Figure 3.

The result of high economic growth, modest technological change, and no policies to limit emissions is a substantial increase in energy demand, and in sulfur and carbon emissions. For Europe, this would mean, for example, that the F scenario's sulfur emissions would exceed constraints that countries have already agreed to under international agreements that have excellent records of success. In Asia, acid deposition would be higher than observed in the 1980s even in the most heavily polluted regions of Central Europe. The high CO_2 emissions of the F scenario are estimated to lead to an atmospheric CO_2 concentration of 800 ppmv in 2100.

On the energy supply side, the energy future of the F scenario is dominated by coal use, in particular for electricity generation and, after 2050, increasingly for synthetic liquid and gaseous fuel production. Beginning around 2020, synfuels derived from biomass, and to a lesser extent from natural gas and coal, expand rapidly. Electricity use grows by a factor of five between 1990 and 2050 and by a factor of almost ten by 2100. In addition to the dominating coal, electricity generation is relying increasingly on renewables and nuclear power with natural gas supplying the balance. By the end of the simulation period, 53% of global electricity production is powered by coal. The share of renewables is almost 30%. The F Scenario is rather similar to the A2 IIASA-WEC scenario. Readers interested in further detail are therefore referred to Nakicenovic et al. (1998b) for a more comprehensive description of the relevant features of the F Scenario.

3.2. THE FC SCENARIO

In the FC scenario, carbon emissions are constrained to stabilize atmospheric CO_2 at 550 pmmv by 2150. This stabilization level is in the middle of the range of 450 to 650 ppm analyzed by the Second Assessment Report of the IPCC (1996). Assumptions about population growth, technological change, reference economic growth,

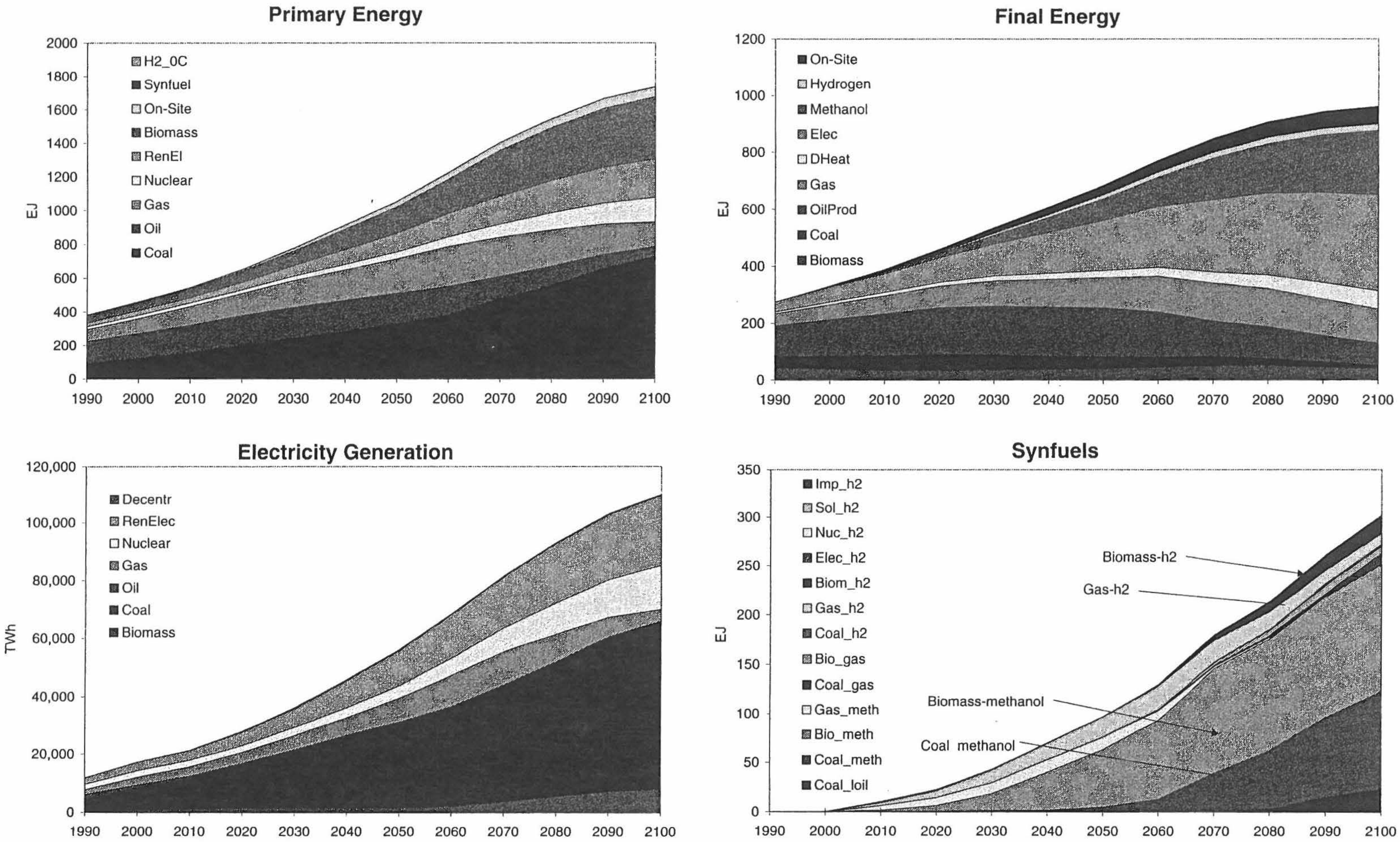

Figure 3. Total primary energy, final energy use, electricity generation, and synfuels production for the world, F scenario.

and resource availability in the FC scenario are the same as in the F scenario. As a result of the FC scenario's carbon constraint, emissions drop to 3 GtC in 2100. The CO_2 concentration in 2100 is 556 ppmv and underway to reach 550 ppmv by 2150.

Through 2050, carbon mitigation in the FC scenario is dominated by a 30% (93 EJ) reduction in coal use relative to the F scenario, and a slightly lower utilization of oil and natural gas. The decline in fossil fuel combustion is offset in almost equal parts by (1) increased use of nuclear power, renewable electricity generation, and biomass, and (2) overall energy demand reduction. CO_2 scrubbing and disposal from synfuel production contributes by more than 10% to carbon mitigation by 2050 and gains importance after 2050. CO_2 scrubbing is the only way to meet the FC scenario's carbon limits in view of an increase in coal use from 90 EJ in 1990 to 230 EJ in 2100. Altogether, 6 GtC are scrubbed by 2100. This accounts for 30% of carbon emission reductions. The rest is due to reduced coal use and, to a lesser extent, reduced waste use.

In the FC scenario, high energy costs due to carbon mitigation reduce energy demand sufficiently to reduce total cumulative discounted energy system costs – as calculated by MESSAGE – by U.S. $810 billion relative to the F scenario. But cumulative discounted income losses of U.S. $2.2 trillion – as calculated by MACRO – outweigh these savings by a factor of more than 2.5.

3.3. THE FS SCENARIO

The difference between the F and FS scenarios is that while the F scenario allowes unabated emissions, the FS scenario includes strict SO_2 limitations, designed to provide high levels of protection against acidification for managed and unmanaged ecosystems alike. Assumptions in the FS scenario about population growth, technological change, and resource availability are the same as in the F scenario. Although potential economic growth rates are also identical, realized economic growth rates are slightly lower. In contrast to the drastically reduced sulfur emissions, carbon emissions in the FS scenario are only marginally lower than in the F scenario, leading to an atmospheric CO_2 concentration of 766 ppmv in 2100.

Because technological change in the FS scenario proceeds at the same moderate pace as in the F scenario, the FS scenario's sulfur constraints lead to higher energy service costs. These in turn cause demand-side responses such as capital substitution for energy (efficiency improvements and energy conservation), fuel switching, and behavioral changes. All these lead to lower specific energy use. Global primary-energy use falls behind the F scenario by 0.7%, or 4.6 EJ, in 2020, by 2.7% or 29 EJ in 2050, and by 3% or 54.3 EJ in 2100.

Coal use is affected much more significantly, of course. Compared to the F scenario, the world consumes 6%, or 8 EJ, less coal in 2020, 17% or 54 EJ less in 2050, and 6% or 42 EJ less in 2100. Nevertheless, coal's dominance in the primary energy supply structure is not seriously challenged by the sulfur emission constraints, and

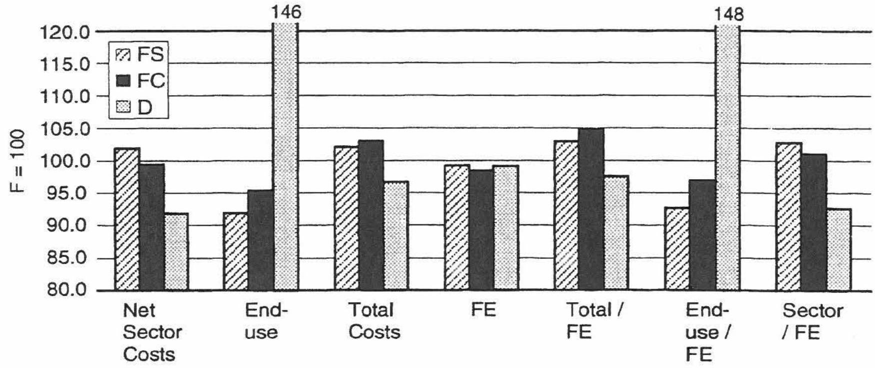

Figure 4. Cost comparison across four scenarios for the world – for net energy sector costs, energy end-use costs, and total economic costs (energy supply costs plus income losses). The figure also shows a comparison of total final energy demand (FE), total economic costs per unit of final energy demand, end-use costs per unit of final energy demand, and net energy sector costs, also per unit of final energy demand. All costs are discounted and cumulative for the period 1990–2100 and all indices are defined relative to the F scenario, i.e., F = 100.

coal still supplies 41% of primary energy in 2100. In the early decades of the 21st century, this is achieved by end-of-the-pipe techniques such as coal cleaning and sulfur scrubbing. Later, other approaches take on more importance, particularly advanced coal conversion technologies with low sulfur emissions.

This is reflected in Figure 4, which shows the costs of three alternative scenarios relative to the F scenario. For each alternative, the bars of the figure show, from left to right, net direct costs in the energy sector, direct costs at the level of end-use, and total costs including indirect income losses. The rightmost three groups show each of these divided by final energy use. As in the FC scenario, end-use costs in the FS scenario are lower than in the F scenario. The costs of mitigation are reflected in direct energy sector costs and total costs, which are higher than baseline costs as expected.*

3.4. THE D SCENARIO

We have added the D scenario ('D' for dynamic technologies) to the three scenarios described above. It resembles the A3 IIASA-WEC scenario (Nakicenovic et al., 1998b), but assumes even more rapid technological change. More recently, a scenario has been published that – in terms of technological assumptions – is very similar to the D Scenario. The A1T Scenario is described in great detail in the IPCC Special Report on Emissions Scenarios (IPCC, 2000).

* Scenario D shows quite a special case here. Very high level of technological progress assumed in the scenario D as well as 'aggressive' introduction of new energy technologies (in comparison to Scenario F less binding market penetration constraints) reduces total cost substantially even versus base case F. But this is not a 'free lunch'. End-use cost in scenario D is almost 50% higher. This is clear indication of quite high investment requirements for advanced technology deployment that is necessary for such substantial changes in energy services structure to be achieved.

The D scenario's assumptions about population and economic growth, as well as on resource availability are the same as in the F scenario. Emission constraints are also the same – there are none. The most pronounced difference between the two is that the D scenario assumes more rapid technological progress, which results in increased competitiveness of new and renewable energy technologies and in faster decreases of energy intensities. For a detailed description of theses dynamics, see also (IPCC, 2000). The results of the D scenario, which reveal significant advantages relative to the F, FS, and FC scenarios, argue for (1) additional attention to be given to policies that broadly accelerate technological progress, and (2) further research to improve the capacity of models to endogenize technological change and thereby analyze such policies.

Rapid technological change in the D scenario extends current trends towards energy market deregulation and liberalization to the point where distributed and on-site electricity production dominate long-term electricity supply. In the short run, on-site electricity involves small-scale natural-gas fueled combined heat and power generation using gas turbines with heat recovery or phosphoric acid fuel cells operating on natural gas or methanol. Later, solar-based electricity first augments and then replaces fossil-sourced distributed power generation. In addition, advances of fuel cell technology make it possible to integrate cars into residential and commercial energy service supply systems. (At present North America's vehicle fleet represents approximately 10 TW of power capacity, which is more than 10 times the total installed power generating capacity.) Key technology and infrastructure components of such a dispersed energy supply future include electricity, hydrogen, and methanol production from non-carbon sources, both centralized and decentralized (Figure 5). See also McDonald (1999).

3.5. COMPARATIVE DISCUSSION OF ALL SCENARIOS

Due to the costs of mitigating sulfur emissions, cumulative discounted net energy sector costs from 1990 to 2100 are U.S. $660 billion higher in the FS scenario than in the F scenario, and cumulative discounted income losses relative to the F scenario are an additional U.S. $1.4 trillion. These costs are partially offset by discounted cumulative end-use costs, which are U.S. $1.0 trillion lower than in the F scenario.

We choose the D scenario as an illustration of the sensitivity because we believe that flexibility in the energy system as a whole and broad technological progress could lead to emission reductions equal to or more than reductions through targeted control of specific pollutants. The D scenario was developed to examine this possibility in detail. It therefore investigates what might be accomplished by general technological progress rather than specific emission reductions.

The first important feature of the D scenario is that it simultaneously achieves the low sulfur emissions of the FS scenario and the low carbon emissions of the FC scenario – without explicit sulfur or carbon constraints. It therefore provides

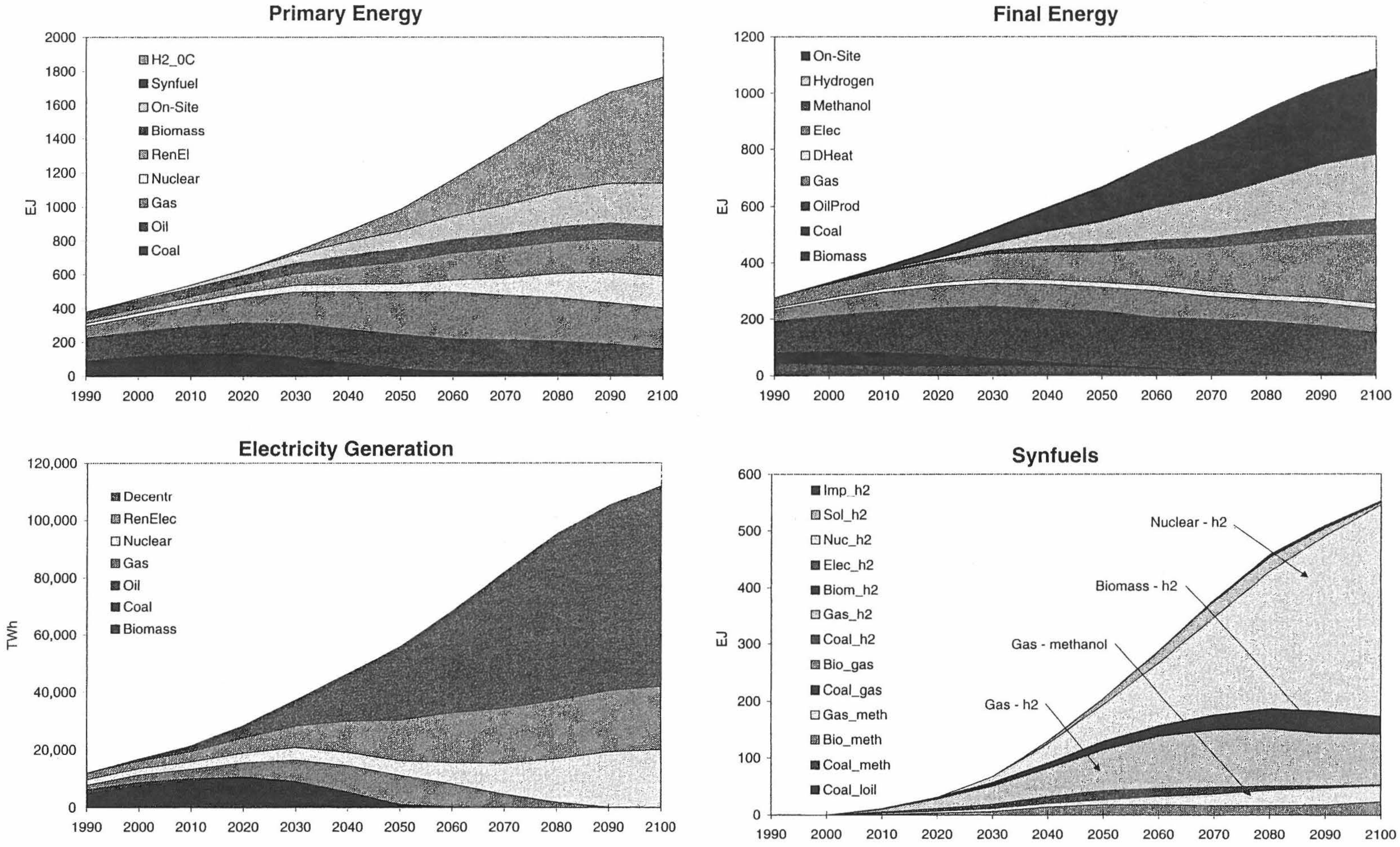

Figure 5. Total primary energy, final energy use, electricity generation, and synfuels production for the world, D scenario.

the same ecosystem protection from acidification as the FS scenario and the same climate protection as the FC scenario, limiting atmospheric CO_2 concentrations in 2100 to 556 ppmv and heading toward 550 ppmv by 2150. However, the timing of carbon reductions is different in the FC and D scenarios with near-term reductions being greater in the D scenario and long-term reductions being greater in the FC scenario. However, both meet the same cumulative carbon constraint leading to stabilization at 550 ppm by 2150.

The second feature is that the D scenario is distinctly different from the FS and FC scenarios as it permanently shifts away from centralized energy conversion and large infrastructures toward decentralized end-use technologies and systems. This shift is reflected in Figure 4 that shows the shift from investments in the traditional energy conversion sector to investments in end-use technologies and infrastructures. The D scenario is not only cleaner than the F scenario, it also represents a net economic gain of U.S. \$1.6 trillion.

4. The Dynamic Cost Curves

In this section, we describe how we use the results obtained from the F, FC, FS, and other scenarios (analyzing the sensitivity of the FC and FS Scenarios with respect to carbon and sulfur constraints) to estimate direct costs of carbon mitigation. Relative to the baseline of the F scenario, we calculate carbon emission reductions and the related costs for each of the other scenarios. For three points in time, 2020, 2050, and 2100, we therefore have the point describing zero emission reduction and zero costs (from the baseline) and one point for each other scenario describing a given (cumulative) emission reduction at given (cumulative) costs. Given these points, we estimate a simple power function through them. We illustrate this method by focussing the discussion on FC, the carbon mitigation scenario (Figure 6).

Through the first half of the 21st century, carbon mitigation costs in the FC scenario are negligible. After 2050, when combustion-based carbon emissions have peaked and begin to decline as a consequence of a constraint on cumulative emissions, carbon mitigation costs begin to increase significantly. It is interesting to note, however, that the two cost components (i.e., energy system costs as calculated by MESSAGE and income losses caused by higher energy prices as calculated by MACRO) move into opposite directions. To illustrate, total cumulative direct energy system costs in the FC scenario are lower than in the F scenario while the economic adjustment costs are higher. The reason is that considerably higher specific energy costs induce drastic demand side responses and thus macroeconomic adjustment costs. The average cost of carbon mitigation, calculated over the entire study horizon, amounts to U.S. \$204/tC globally. The spread among regions, however, is quite significant. In Asia, these costs are U.S. \$229/tC while in Europe these costs are only U.S. \$86/tC. Obviously, carbon mitigation becomes more expensive

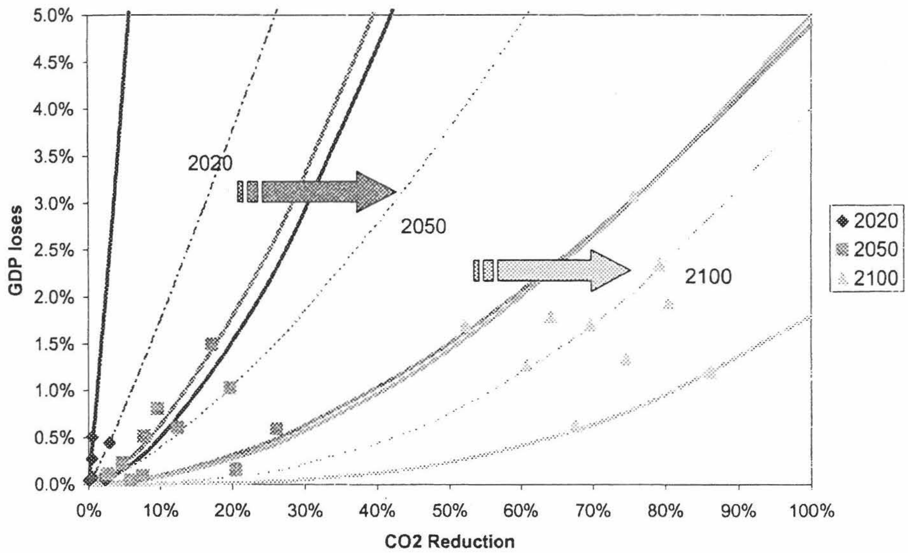

Figure 6. Dynamic mitigation cost curves. Different points represent different scenarios and world regions.

in the later decades of the 21st century with annual costs approaching U.S. $300/tC in Asia.

The analytical form we use for the carbon cost reduction is quite similar to the exponential form discussed in Nordhaus (1991) for total costs of reducing carbon emissions: $C(R) = \beta R^{\alpha}$ with α being an exponential term and β a constant for a given time interval and a given region. But there are some important differences. First of all, we suggest region-specific values for parameters. Moreover, these values are time-dependent. In order to capture the 'cumulative' nature of emitting carbon (what matters for climate change is the concentration of the corresponding GHG) and the rather long replacement time typical for energy systems, we use cumulative percentage reduction (*CPR*) and the re-normalized constant β in such way that the result is equal to cumulative GDP percentage losses, (*CPL*), rather than to absolute values: $CPL_{rt} = \beta_t CPR_{rt}{}^{\alpha_t}$, where r is the region-specific index, and t is the time index.

This form has an obvious advantage over using time-independent cost functions, an approach commonly used as a simplifying approximation. In particular, it views the mitigation process as a continuous dynamic process driven by logically interrelated policies rather than by independent actions performed in distinct time periods.

Statistical analyses and comparisons of alternative runs demonstrated that least-square estimates of α and β, without any indication of the corresponding uncertainty range could be quite misleading. Table I summarizes estimated values for the carbon mitigation cost function and includes uncertainty ranges obtained from analyzing alternative runs from the IIASA scenario database. Table I also

Table I

Estimated values for carbon mitigation cost curves and uncertainty bounds, 2020, 2050 and 2100, and suggested regional clusters based on the appropriateness of parameters

	2020		2050		2100	
				CPA		CPA
Maximum		FSU		FSU		FSU
α	1.05	MEA	1.50	MEA	1.80	MEA
β	1.00	PAS	0.20	PAO	0.05	PAO
						SAS
Median		All		NAM		NAM
α	1.10	others	1.40	PAS	2.40	PAS
β	0.22		0.10	EEU	0.04	EEU
						SAS
Minimum				AFR		AFR
α	1.60		1.80	LAM	2.90	LAM
β	0.20		0.05	WEU	0.02	WEU

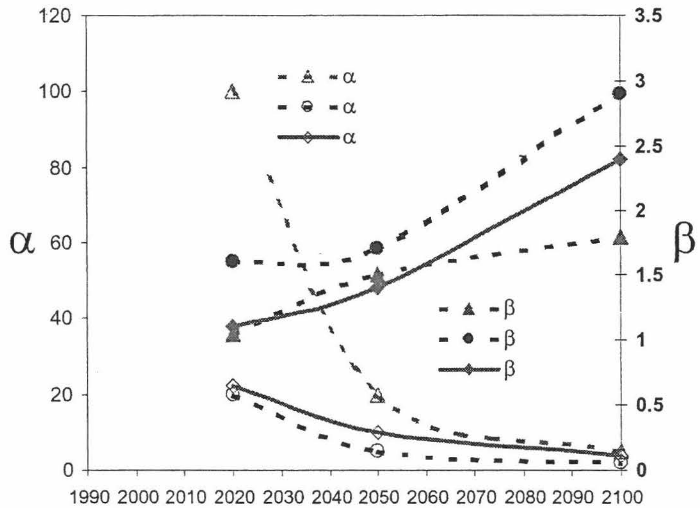

Figure 7. Suggested dynamics for the parameters of the mitigation cost curve over time.

suggests a possible regional clustering on the basis of regional 'similarities' among the appropriate values for mitigation cost parameters.

The dynamic development of the α and β parameters over time is given in Figure 7. Within our modeling framework, it would have been impossible to obtain reliable data for these parameters for non-OECD regions from 1990 to 2020. Given the accuracy of the models, emission reductions are sufficiently low that the associated impact on economic development cannot be estimated with the required degree of confidence. In these cases, more detailed and sophisticated short-term models (10–30 years) are more appropriate.

5. Conclusions

Much work has been dedicated to the problem of estimating future long-term carbon mitigation costs (Nordhaus, 1991; Weyant, 1993, 1996; Papathanasiou and Anderson, 2001; Toth et al., 2001; Hourcade et al., 2001). Unfortunately, in most approaches, the links between carbon reduction and the economic model components are static over time and do not provide regional details. With the exception of a few studies, there is no explicit evaluation of uncertainties involved in such carbon reductions. In most cases, carbon mitigation costs are incorporated in a 'generic' form without any real comparison of the assumptions behind baseline scenarios on the one hand and their variants on the other. This partially explains the extremely broad range of carbon reduction costs in the literature.

For the purposes of the ICLIPS project, and for reasons of consistency with the 'tolerable windows' approach, we narrow this broad range by choosing appropriate baseline and sensitivity scenarios. With the exception of the D Scenario, which was put here as an illustration, our scenarios are consistent with the precautionary spirit prevailing in ICLIPS. This spirit prevents the inclusion of particularly optimistic scenarios in the derivation of dynamic cost curves.

As illustrated in the previous section, baseline assumptions matter a lot, especially those on the development of energy technologies. They define baseline emissions and thus the amount of carbon to be mitigated, and even more importantly, they also provide technical and economic assumptions on the technology options available for mitigation.

We would like to emphasize that none of our scenarios is meant as a prediction. We did not choose them because we believe them highly likely. Indeed, we stress how unlikely we consider particularly the F scenario, which simply provides a reference for the assessment of alternatives and nothing else. The FC, FS, and D scenarios are such alternatives, each focussed on one particular strategy. The FC scenario focuses on limiting carbon emissions. The FS scenario focuses on limiting sulfur emissions. The D scenario focuses on speeding up technological progress in all parts of the energy system. Technology assumptions, as shown by the alternative technological D scenario, are particularly important and could drastically influence the cost and the amounts of carbon that must be mitigated. Carbon mitigation costs per se do not occur in the D scenario. Although direct energy systems costs in the D scenario are 7% higher than in the F scenario, higher incomes in the D scenario more than compensate for this increase.

Traditional energy sector costs are considerably lower than in any other scenario. In the D scenario, investments are progressively shifted to the level of end-use conversion by way of on-site electricity and heat generation, the integration of vehicle power into commercial and residential energy service, and energy efficiency improvements within energy end-use infrastructures. Still, the D scenario has the lowest specific final-energy costs and the highest GDP and meets, at the same time, the atmospheric carbon concentration objective of the FC scenario. It must be noted, however, that these benefits come at extra costs that are not included in the energy models. These costs are for accelerating technological progress in particular through research and development. In our model runs, we do not quantify R&D expenditures (because we believe that reliable numerical relationships describing the effect of R&D in terms of technology costs and energy efficiency are still in an experimental stage), but simply assume their success. A full cost-benefit analysis of enhancing technological progress through R&D is therefore not included in our analysis. Early experiments with introducing uncertainty of induced technological change into energy model indicate a strong bifurcation of the most 'cost-effective' energy development paths towards low and high possible emissions ranges even with single useful-energy demand trajectory (Gritsevskyi and Nakicenovic, 2000).

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