World Regional Scenarios Described with the 11R Model of Energy-Economy-Environment Interactions

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Working Paper

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IIASA International Institute for Applied Systems Analysis □ A-2361 Laxenburg □ Austria
Telephone: +43 2236 807 □ Fax: +43 2236 71313 □ E-Mail: info@iiasa.ac.at

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*Leo Schrattenholzer**
*Andreas Schäfer**

1 Introduction

IIASA's Environmentally Compatible Energy Strategies (ECS) project has developed three families of scenarios of the development of the global energy-economic system and its major environmental impacts. The families are known under different descriptors, but they represent a High (H), a Reference (R), and a Low (L) set of cases. By design, these sets correspond, respectively, to Cases A, B, and C of *Energy for Tomorrow's World* (WEC, 1993). Characterized briefly, Set H represents an optimistic future with massive technological improvements and high economic growth. Set R describes what may be regarded as a more realistic future with slower technological improvements and lower economic growth. Set L pictures a "cooperative and green" future. It includes both substantial technological progress and unprecedented international cooperation for global environmental protection. Of the three, Set L is by far the most normative, and Set R comes closest to a descriptive, i.e., business-as-usual set of projections. A brief quantitative and qualitative description of the three sets is given in Table 1. For more background information, readers are referred to WEC and IIASA (1995).

The scenarios were formulated within an integrated framework for assessing environmental consequences of regionalized global energy developments. The energy systems part of this framework consists of two formal models and one spreadsheet, called "Scenario Generator". One of the two models, 11R, describes the interaction between the overall economy, the energy system and carbon emissions. It consists of a macroeconomic and an energy supply module. 11R is a modification of Global 2100 as described by Manne and Richels (1992).

Besides including macroeconomic development in the overall picture of the scenarios, an important role of 11R in the integrated assessment of scenarios is to ensure consistency between energy price and energy demand. This function drives the main feature of the ecologically-driven L scenario, in which carbon and energy taxes are used as a modeling tool to decrease the overall energy intensity of the global economy in an effort to drastically reduce the environmental impact of energy use (in comparison with the H scenario). In addition, tax revenues generated in the OECD countries are used to compensate the developing countries for the GDP losses due to the introduction of taxes. Although the language describing this scenario uses policy terms, it must be emphasized that scenario L is a normative experiment, quantifying the consequences

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*Leo Schrattenholzer is a Research Scholar and Andreas Schäfer is a Guest Research Scholar at the Environmentally Compatible Energy Strategies Project at the International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria; telephone no. (+43-2236) 807; telefax no. (+43-2236) 71313, e-mail leo@IIASA.ac.at and schafer@IIASA.ac.at.

Table 1: A summary description of three 11R scenarios.

	Scenario		
	H	R	L
Population in 10^9			
1990	5.3	5.3	5.3
2050	10.1	10.1	10.1
2100	11.7	11.7	11.7
GWP in $10^{12}\text{US\$}(1990)$			
1990	20.9	20.9	20.9
2050	102	72	94
2100	308	207	277
Energy intensity decline	medium	low	high
PE/GDP, %/yr			
World (1990–2050)	-1.0	-0.7	-1.8
World (1990–2100)	-1.1	-0.8	-1.7
Primary energy demand, Gtoe			
1990	9	9	9
2050	25	20	14
2100	41	36	19
Resource availability			
Fossil	high	medium	low
Non-fossil	high	medium	high
Technology costs			
Fossil	low	medium	high
Non-fossil	low	medium	low
Technology dynamics			
Fossil	high	medium	medium
Non-fossil	high	medium	high
Carbon emissions, GtC			
1990	6	6	6
2050	13	11	4
2100	17	18	1
Environmental taxes	no	no	yes

of one hypothetical assumption of unprecedented global cooperation aimed at achieving environmental benignness and global equity. WEC and IIASA (1995) are not suggesting that this scenario is likely to be implemented. The costs of a particular form of global cooperation have simply been calculated within the integrated framework.

The WEC-IIASA scenarios focussed on the time period until 2050, worldwide as well as in the three macro world regions: OECD, the Reforming Economies of Eastern Europe and the Former Soviet Union, and the Developing Countries. The underlying model results were derived for 11 world regions and the time horizon through 2100. Some of the results reported in WEC and IIASA (1995) referred to the extended time period, but no explicit results were given in 11-region detail. Future work will be devoted to further refining the scenarios for each of the 11 world regions.

The main purpose of this paper is to document the inputs and outputs of 11R that correspond to three representative scenarios – one each of the Sets H, R, and L[1]. After an overview of the model set used at IIASA, the 11R model is described in some detail. The rest of the paper describes and discusses model inputs and outputs. The concluding section describes plans for continuation of the work described here.

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[1] Our H scenario corresponds to A1 of WEC-IIASA (1995), R corresponds to scenario B, and L to C1. Since confusion is not likely to arise, in this paper, the three scenarios will be denoted as "scenario H", "scenario R", and "scenario L", i.e., referred to exclusively by their family names.

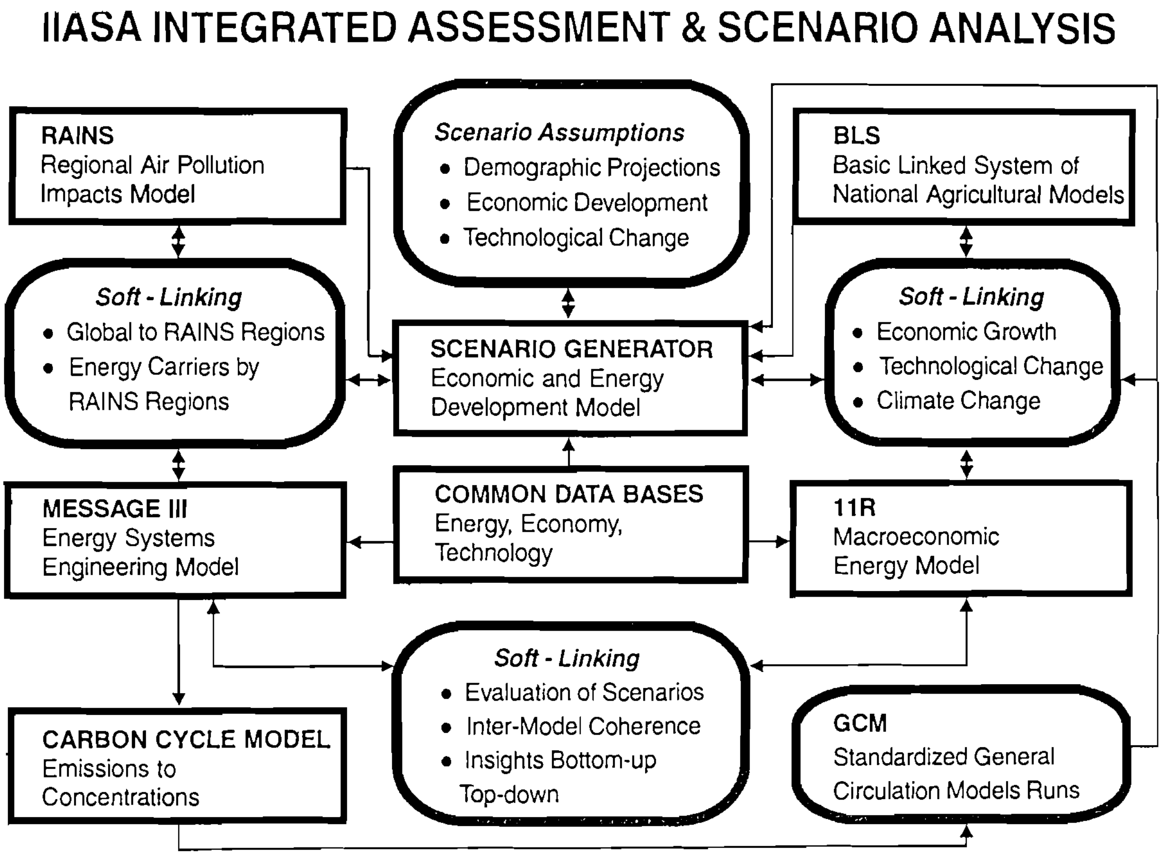

Figure 1: IIASA's modeling framework for integrative assessments.

The authors gratefully acknowledge the comments and suggestions they received from János Gacs, Alan Manne, and Nebojša Nakićenović on the draft of this paper. Many thanks are also due to Linda Kneucker for her careful and dedicated editing word.

2 IIASA's Energy Modeling Framework

Five models constitute the framework used for formulating global energy scenarios and their impact on the global climate, local acid depositions, as well as their interaction with the global agricultural system. Figure 1 is a graphical representation of the models and the information flows between them.

A spreadsheet simulation model called *Scenario Generator* (SG) is the principal tool for scenario formulation. The other four models cover different areas of the system under consideration. They are used to enrich the original scenario assumptions with more detail, and they permit an analysis of the consequences of these assumptions in the models' respective domains. In an informal iterative process the original assumptions are refined until a plausible state of the scenario is reached.

The four formal models are a systems engineering energy model, MESSAGE III; a macroeconomic energy model, 11R; a regional acidification model, RAINS; and a world agriculture model, BLS. There is some overlapping between MESSAGE and 11R since both of them include a description of the primary energy mix. The two energy models and the *Scenario Generator* are defined for 11 world regions, graphically represented in Figure 2. This figure also shows an

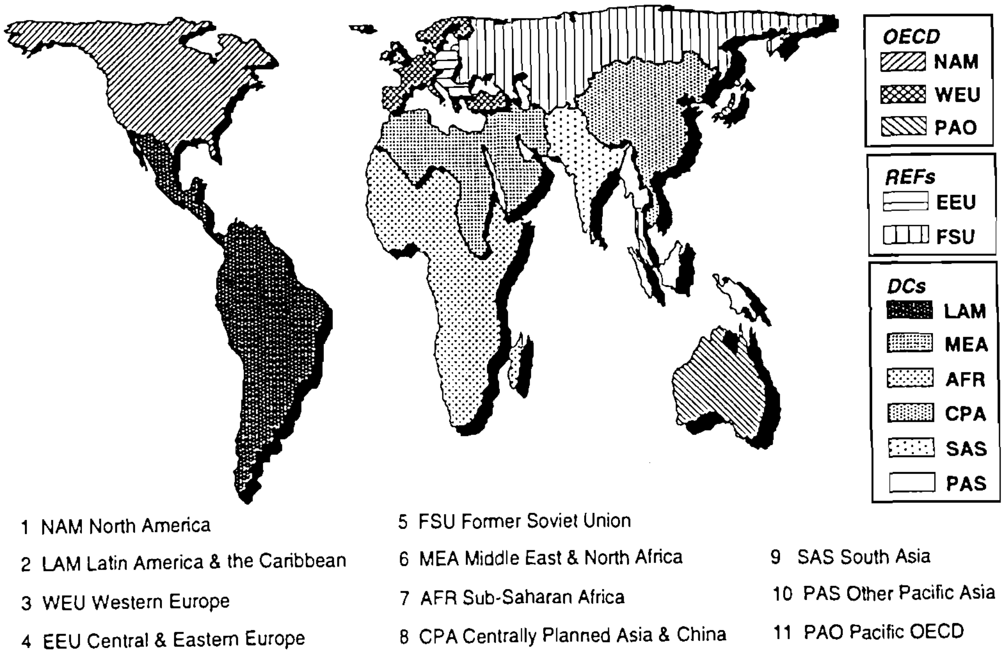

Figure 2: The 11 World Regions of 11R.

aggregation of the 11 regions into three macro regions, i.e., the OECD countries, the Reforming Economies (REF) of Eastern Europe and the former Soviet Union, and the Developing Countries (DC). For most of the input and output descriptions in this paper, the macro regions were chosen as the geographical disaggregation level.

2.1 Short Model Descriptions

In this subsection, very brief descriptions of the constituent models of IIASA's Modeling Framework and the links between them are given. Only 11R, the main subject of this paper, is described in a separate subsection and in more detail.

The Scenario Generator (SG)

The main function of the *Scenario Generator* (SG) is to develop many alternative scenarios quickly and consistently (Gritsevskii, 1996). There are two exogenous variables that are inputs to the SG: population growth and per capita GDP growth. All other variables are endogenous, in particular, primary and final energy demands, and the disaggregation of total final energy into different end-use sectors and activities. Within the SG, calculations can always be performed in two ways. Primary energy requirements, for example, can be combined with per capita GDP to calculate energy intensity changes. Alternatively, energy intensity changes can be considered as the strategic scenario variables, and the SG used to calculate resulting primary energy demands. The SG then converts primary into final energy demands, which in turn are converted into useful energy, based on final-to-useful conversion efficiencies derived from the energy database. Useful energy demands are input to the MESSAGE III model.

The Systems Engineering Model MESSAGE III

MESSAGE III is a dynamic systems engineering optimization model used for medium to long-term energy system planning, energy policy analysis and scenario development (Messner and Strubegger, 1994). The model provides a framework for representing an energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services. From useful energy demands, MESSAGE III calculates corresponding final and primary energy requirements under constraints on the availability of energy resources, given a menu of energy conversion technologies.

The RAINS Model of Acidification

The Regional Acidification INformation and Simulation (RAINS) model was developed as a tool for the integrated assessment of alternative strategies to reduce acid deposition in Europe (Alcamo et al., 1990). Its present version, RAINS 7.0, describes the pathways of emissions and mechanisms of acidification in the environment for sulfur dioxide (SO_2), which is a major acidifying component. The various sub-models are organized into three modules, i.e., the energy-emissions module (ENEM), the acid deposition module (ATMOS), and the ecosystems impact module (IMPACT). For their use by RAINS, MESSAGE III's continental-scale primary energy supply projections are translated into projections with much more spatial detail. From these, RAINS determines SO_2 emission patterns in those world regions for which it is defined (Europe and Asia), the resulting environmental impacts of acidification, and the costs of abatement strategies.

The World Agriculture System Model BLS

The Basic Linked System of National Agricultural Policy Models (BLS) is a world-level general equilibrium model system developed at IIASA in the 1970's and 1980's by the Food and Agriculture Program (Fischer et al., 1988). BLS incorporates all economic activities, but its main emphasis is on the agricultural sector, which is divided into 9 subsectors. Important for its coupling with the energy models, BLS contains information on world-regional land use so that the feasibility of biomass-intensive energy scenarios can be checked.

BLS uses scenario assumptions jointly with 11R. These include GDP, overall energy intensity, capital stock, labor, and population. In runs involving both models, the values of these variables are harmonized by adjusting the production factors in the BLS to match 11R output. The other coupling variables are CO_2 concentrations, influencing future agriculture productivity. The parameters describing productivity in BLS are chosen to be consistent with the carbon emissions generated by the energy models.

2.2 The Macroeconomic Energy Model, 11R

11R is a dynamic, nonlinear macroeconomic optimization model used for the analysis of long-term CO_2-energy-economy interactions. It is based on the Global 2100 model developed by Manne and Richels (1992), and has been modified to cover 11 world regions and extended to include features that are useful for the scenario generation described here. 11R's objective function is the total discounted utility of a single representative producer-consumer in each region. 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 CES (constant elasticity of substitution) production function.

Energy demand in two categories (electricity and non-electric energy) is determined within the model, and is consistent with the development of energy prices and energy intensity of GDP. Energy supply is determined so as to minimize costs. In the description of the energy conversion sector, the capacity utilization rates are exogenous parameters (not decision variables as in MESSAGE), and assumed to be fixed. 11R includes a resources module that describes the dynamic transition from exhaustible energy resources to reserves. Oil trade is modeled by an international oil price and region-specific import and export limits. Inter-regional trade of natural gas is not explicitly modeled in the present version of the model. It is included nevertheless, by transferring some amounts of reserves and resources from the Former Soviet Union into Eastern and Western Europe.

The limited availability of renewable energy and of other energy conversion technologies is modeled through limits on annual production. Carbon emissions can be either constrained or taxed.

11R's outputs include internally consistent projections of global and world regional GDP, including the disaggregation of total production into macroeconomic investment, overall consumption, and energy costs. The most important outputs concerning the energy system and the environment are primary energy consumption by fuel, and CO_2 emissions.

The model's most important driving input variables are the projected growth rates of total labor, i.e., the combined effect of labor force and labor productivity growth. The model's GDP growth rates remain within relatively narrow limits around these labor growth rates (see Manne and Schrattenholzer, 1993). Therefore, labor growth is referred to also as reference GDP growth. In the absence of price changes, energy demands grow at rates that are the approximate result of GDP growth rates, reduced by the rates of energy intensity reduction, which are model inputs. Price changes can alter this path significantly.

As in most intertemporal comparisons of costs and benefits, a discount rate is used in 11R to account for the differences in the value of consumption at different points in time. Typically, this works out to 5% per year. The utility discount rate is determined by the capital-GDP ratio (KGDP), the annual depreciation of capital (DEPR), and the optimal value share of capital (KPVS) in the capital-labor aggregate (in the CES production function). For the scenario described here, the numerical values of these variables are the ones used by Manne and Richels (1995). The consumption discount rate is the sum of the utility discount rate and the economy-wide growth rate. (See, e.g., Manne (1995), for a more detail and for a discussion of the implications for the greenhouse debate of choosing alternative values of the discount rate.) The model is calibrated to the base year, 1990, by setting the marginal productivity of non-electric energy (i.e., the partial derivative of the production function with respect to non-electric energy) equal to the 1990 price of non-electric energy (PNREF).

The elasticity of substitution (ESUB) determines the response of the optimal allocation of the two aggregated production factors, capital plus labor and energy, to changes of the relative prices of these factors. Higher values of ESUB correspond to less costly substitution between these aggregated factors.

2.3 Running 11R Within the Integrated Model Set

Scenario development starts with exogenous assumptions on population and per capita GDP growth in the 11 world regions. From these inputs, the *Scenario Generator* calculates GDP, primary, final and useful energy requirements. In scenarios H and R, GDP and total primary energy are taken as targets that are matched by 11R's outputs. Scenario L is different. There, 11R takes the inputs describing reference economic growth and reference energy intensity reductions from scenario H and inflates energy costs by 1.2 percent (in the Developing Countries) and 2.4 percent (in the Industrialized Countries) annually. The difference between the inflated costs and the genuine costs is recycled within the subregions of the Reforming Economies and the Developing Countries. The OECD is assumed in this scenario to collect this difference and to transfer it into the Developing Countries. No particular targets of GDP or total primary energy are aimed at in scenario L.

MESSAGE III uses total primary energy as a target for its outputs. The difference between the two models is that MESSAGE III adjusts its useful-energy inputs to achieve the target whereas 11R uses inputs on reference GDP growth and on energy intensity reduction rates for that purpose. The general strategy for dealing with the overlapping parts of 11R and MESSAGE can be described as *harmonization*. This principle has been formally outlined by Wene (1995) in the course of presenting a general concept of linking models. Central to Wene's description are so-called *Common Measuring Points (CMPs)*. These are key variables that are common to both models. If these CMPs cannot be matched independently of each other, complete agreement of the key variables will often be impossible, thus leading to some "soft-linking noise" (Wene *op. cit.*).

For practical purposes, the set of relevant Common Measuring Points between MESSAGE and 11R was restricted to the following five variables: (1) total primary energy, (2) cumulative consumption of primary fuels, (3) carbon emissions, (4) cumulative carbon emissions, and (5) total electricity demand. In practice, the implementation of the CMP concept means that the total primary energy requirements in scenarios H and R are almost identical in the two energy models. After that, further, less formal iterations are performed to match total electricity consumption, cumulative resource use, and CO_2 emissions in these two cases.

Trajectories of individual primary energy carriers were not included in the set of Common Measuring Points, and since MESSAGE describes the Reference Energy System (RES) in much greater detail than 11R, the resulting primary energy mixes are difficult to match exactly. Those inputs that are identical for both models used the same data, of course, but all that could be done for the remainder of 11R's input data on the energy side was to choose them in a way that made 11R and MESSAGE results similar. As a practical guideline for the degree of similarity to be achieved for the primary energy mixes of 11R and MESSAGE, the goal of achieving a match between the two model outputs that makes them so similar that all conclusions reported here would the same was attempted and achieved. This is the conceptual justification for treating the residual differences as soft-linking noise.

Since the criterion of harmony is not rigorously defined, documented here (in the results section of this paper) are the developments measured at the Common Measuring Points. In the given situation of dependent measuring points, the need to set priorities to reflect the relative importance attributed to the different variables was faced. The highest priority was assigned to harmonizing the results for the world as a whole. Within each region, more weight was put on the agreement of total primary energy than on any other energy measuring point, in particular electricity.

2.4 Iterating 11R

Getting 11R to match the target paths of GDP and total primary energy consumption as set by the *Scenario Generator* is a straightforward task. Growth rates of the SG's target GDP are used as starting points for 11R's reference GDP. The difference between 11R's output on realized GDP and SG's target is then translated into correction terms of the 11R inputs, and the next iteration is started. Typically, two or three iterations were sufficient to bring regional

GDP within 1 percent of the numbers given by the *Scenario Generator.* In a similar way, the 11R inputs describing the reference energy intensity reduction were used to match the two paths of total primary energy. The convergence was as fast as for GDP.

3 Model Input Parameters

One way to look at the functioning of 11R is to regard the annual rates of labor growth as the main driving parameters of economic output during the time period covered by the model. Indeed, in the absence of price changes and changes of energy intensity, GDP increases exactly as prescribed by labor growth, i.e., the product of labor force growth and labor productivity growth. Under the same *ceteris paribus* conditions, energy consumption grows at these rates, too. In actual model applications, the first condition is more relevant, i.e., actual GDP growth rates are close to the labor growth rates defined by the input numbers – at least as long as no drastic energy price changes are introduced. (Scenario L represents such a drastic change by assuming that energy prices are increased by 1.2 percent annually in the developing regions and by 2.4 percent in the industrialized regions.) The second hypothetical condition, constant energy intensity, is purely theoretical, and significant reductions of energy intensity of GDP in our model runs are the consequence of model inputs.

In view of their prime importance, we put labor growth rates and energy intensity changes at the top of the documentation of 11R inputs. As to the remaining inputs, their relative importance is less obvious, and no ranking is implied by the sequence chosen for their presentation here.

For the documentation of the inputs – and of the outputs in the following section – the 11 world regions are usually aggregated into the 3 macro regions defined above, i.e., OECD, the Reforming Economies (REF) and the Developing Countries (DC). A graphic presentation of this quantitative information is provided within the main text. To offer more detailed figures, tables containing the underlying projections have been added in an appendix.

3.1 Economic Development and Other Determinants of Energy Demand

Reference growth rates of GDP[2] for the scenarios H and R were determined so that resulting GDP trajectories match the target GDP given by the *Scenario Generator.* Table 2 summarizes average annual reference growth rates of GDP in the three macro world regions and in the world as a whole for these two scenarios.

Scenario L is much more shaped by 11R than either H or R. It is defined by the same reference economic growth rates as the H scenario, but resulting GDP in this scenario is significantly lower as a consequence of energy price increases due to carbon and energy taxes.

The other parameters determining the model economies are the capital-GDP ratio (KGDP), the annual depreciation of capital (DEPR), the optimal value share of capital (KPVS) in the capital-labor aggregate (in the production function), and the base-year price of non-electric energy (PNREF). Since these parameters cannot easily be aggregated into macro-regional values, Table 3.1 presents them for all 11 regions. The elasticity of substitution (ESUB) determines the response of the optimal allocation of the two aggregated production factors, capital plus labor, and energy, to changes of the relative prices of these factors. Higher values of ESUB correspond to less costly substitution between these aggregated factors. In our scenarios, the production

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[2] All GDP figures – and all monetary units – are expressed in US dollars of 1990 purchasing power. Conversions from other currencies have been made using conventional 1990 market exchange rates.

Table 2: Average annual growth rates of potential GDP, percent

	OECD	REF	DC	World
1990-2020	2.20	1.58	4.67	2.72
2020-2050	1.50	5.18	3.90	2.55
2050-2100	0.74	1.30	1.55	1.25
1990-2020	1.86	0.77	3.72	2.20
2020-2050	1.26	3.71	3.28	2.00
2050-2100	0.63	1.43	1.70	1.24

Table 3: Capital-GDP ratio (KGDP), annual depreciation of capital (DEPR), the optimal value share of capital (KPVS) in the capital-labor aggregate (in the production function), and the base-year price of non-electric energy (PNREF) in the 11 World Regions. Source: Manne and Richels (1995).

	NAM	LAM	WEU	EEU	FSU	AFR	CPA	PAO	PAS	SAS	MEA
KGDP [yr]	2.40	3.00	2.80	3.00	3.00	3.00	3.00	2.80	3.00	3.00	3.00
DEPR [%/yr]	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
KPVS [%/100]	0.24	0.30	0.28	0.30	0.30	0.30	0.30	0.28	0.30	0.30	0.30
PNREF [$/GJ]	2.00	2.00	2.00	2.00	1.00	2.00	2.00	2.00	2.00	2.00	1.00

functions of the OECD subregions have been assumed to be slightly more elastic than those in other world regions.

Table 4 indicates the parameters describing reference energy intensity reduction for scenarios H and R. As with reference GDP, the reference energy intensity changes were chosen so that the resulting total primary energy demand of the two scenarios matches the targets provided by the *Scenario Generator.*

3.2 Primary Energy

World regional primary energy[3] consumption in scenarios H and R is illustrated in Figure 3.

In scenario H, global primary energy is projected to increase from some 9 billion tons of oil equivalent (Gtoe) in 1990 to some 41 Gtoe in 2100. The highest increase – by a factor of 10 – is projected for the Developing Economies. In comparison, primary energy only doubles in the OECD and increases by a factor of 3 in the Reforming Economies. Whereas in 1990, the OECD accounted for almost 50 percent and the Developing Economies accounted for about one-third

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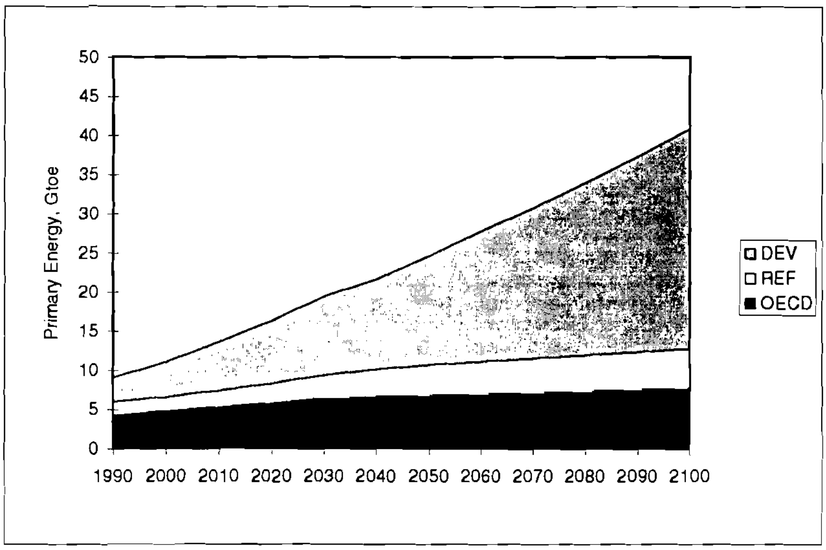
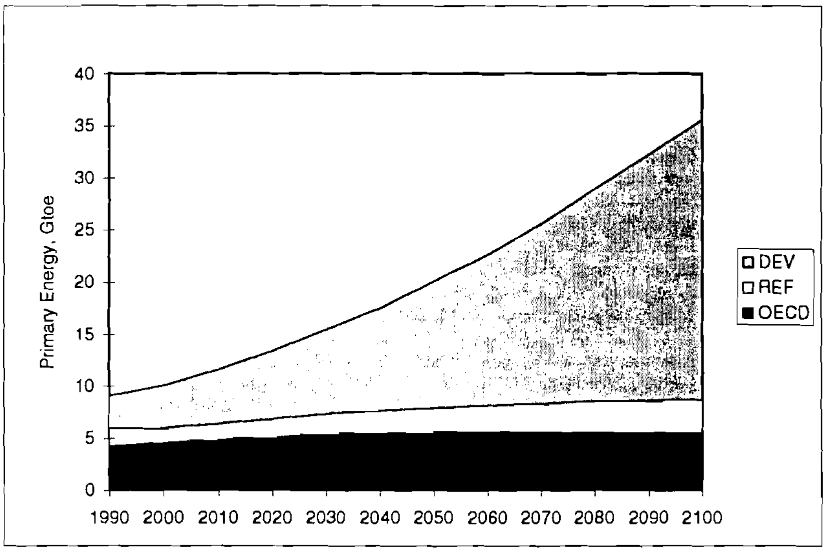
[3] In our scenarios, we model total, i.e., commercial plus non-commercial, primary energy consumption.

Table 4: Average annual rates of potential energy intensity reduction, percent

	OECD	REF	DC	World
1990-2020	1.04	0.90	2.98	1.81
2020-2050	0.52	1.65	2.26	1.61
2050-2100	0.24	0.23	0.83	0.63
1990-2020	0.76	-0.15	2.62	1.38
2020-2050	0.21	1.20	1.95	1.28
2050-2100	0.03	0.31	0.87	0.65



Scenario H



Scenario R

Figure 3: Total primary energy development in scenarios H and R.

of the primary energy, the shares change completely by 2100: the OECD accounts for only 19 percent and the Developing Economies for about 70 percent of total primary energy.

In scenario R, global primary energy consumption increases from almost 9 Gtoe in 1990 to 36 Gtoe in 2100, a factor of almost four. In the same time period, it increases some eightfold in the Developing Countries, doubles in the Reforming Economies, and increases by 30 percent in the OECD. The world regional shares in primary consumption in 2100 are about the same as those in scenario H.

Reference GDP and energy intensity reduction inputs in scenario L are identical to those in scenario H. The purpose of leaving these parameters unchanged was to study the effect of exponentially increasing energy taxes and carbon taxes on general economic development and on primary energy consumption patterns. Total primary energy consumption and GDP development in scenario L is, therefore, a result and not an input as in the case of the other two scenarios.

3.3 Energy Resources

As indicated above, reference growth rates of GDP and reference rates of energy intensity reduction are the most important determinants of total primary energy consumption in 11R. Energy price increases lead to a substitution of capital and labor for energy and therefore reduce reference energy demand. (Price *decreases* have the opposite effect, of course.) Energy prices depend on the costs and the availability of primary energy resources and energy conversion technologies. These inputs will be described below.

The overall occurrence of primary energy resources assumed for the scenarios is documented in Rogner (1996). In accordance with the scenario characteristics described in the introductory section of this paper, different fractions of these total figures have been assumed to be available for conversion to reserves for each of the scenarios.

3.3.1 Oil and Gas

11R inputs for oil and gas are not separated into conventional and unconventional categories. Inputs are just disaggregated into resources and reserves. Each of these is further divided into a high-cost and a low-cost category. To arrive at inputs for these four categories[4], the classification used in WEC and IIASA (1995) was modified for the purpose of better reflecting the costs assumed for the original resource categories. Further, some model iterations were made to determine the most appropriate cutoff point on the original cost curve as reported by Rogner (1996). Cutoff points are different in different regions and in different scenarios. Tables 5 and 6, therefore, show non-uniform cost figures for the high-cost and low-cost categories of oil and gas in the three scenarios. The most important aspect of the scenarios is the cumulative use of natural resources in comparison with the total resource base identified in WEC and IIASA (1995). This comparison is made in Section 4.2.

Production-to-reserves constraints limit the production in each year and each category (high-cost and low-cost) to remain below a given fraction of remaining reserves in that category. This fraction was assumed to be 5 percent for both categories in all regions for all three scenarios. This corresponds to a reserve-to-production ratio of 20 years. The “finding rate”, defined as an upper bound on the fraction of resources of a given category that is converted to reserves in a given time period was also assumed to be 5 percent for all regions in all three scenarios.

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[4] Of these, only three have non-zero amounts as initial quantities because, by definition, low-cost resources in the base year are zero.

Table 5: Availability and cost of oil resource in the three scenarios.

	H				R				L			
Region	OECD	REF	DC	World	OECD	REF	DC	World	OECD	REF	DC	World
Low-Cost												
Reserves, Gtoe	31.9	39.3	165.6	236.8	31.9	39.3	165.6	236.8	17.6	20.6	124.3	162.4
Resources, Gtoe	10.9	20.0	53.5	84.4	10.9	20.0	53.5	84.4	14.3	18.8	41.3	74.4
Cost, $/kgoe	0.11	0.11	0.10	0.10	0.11	0.11	0.10	0.10	0.08	0.08	0.08	0.08
High-Cost												
Resources, Gtoe	399.9	85.4	630.0	1115.3	36.6	30.4	125.7	192.7	10.9	20.0	53.5	84.4
Cost, $/kgoe	0.39	0.32	0.36	0.37	0.25	0.23	0.24	0.24	0.18	0.18	0.18	0.18
Resource Base, Gtoe	442.8	144.6	849.1	1436.5	79.5	89.7	344.8	513.9	42.8	59.3	219.1	321.2

Table 6: Availability and cost of natural gas in the three scenarios.

	H				R				L			
Region	OECD	REF	DC	World	OECD	REF	DC	World	OECD	REF	DC	World
Low-Cost												
Reserves, Gtoe	40.9	85.5	114.3	240.7	40.9	85.5	114.3	240.7	21.2	39.8	67.7	128.7
Resources, Gtoe	23.5	66.1	63.7	153.3	23.5	66.1	63.7	153.3	19.7	45.7	46.6	112.0
Cost, $/kgoe	0.09	0.10	0.09	0.09	0.09	0.10	0.09	0.09	0.07	0.07	0.07	0.07
High-Cost												
Resources, Gtoe	337.7	166.0	333.0	836.7	65.4	47.7	78.7	191.8	23.5	66.1	63.7	153.3
Cost, $/kgoe	0.32	0.28	0.31	0.31	0.23	0.21	0.22	0.22	0.18	0.18	0.18	0.18
Resource Base, Gtoe	402.1	317.6	511.1	1230.8	129.8	199.3	256.8	585.9	64.4	151.6	178.0	394.1

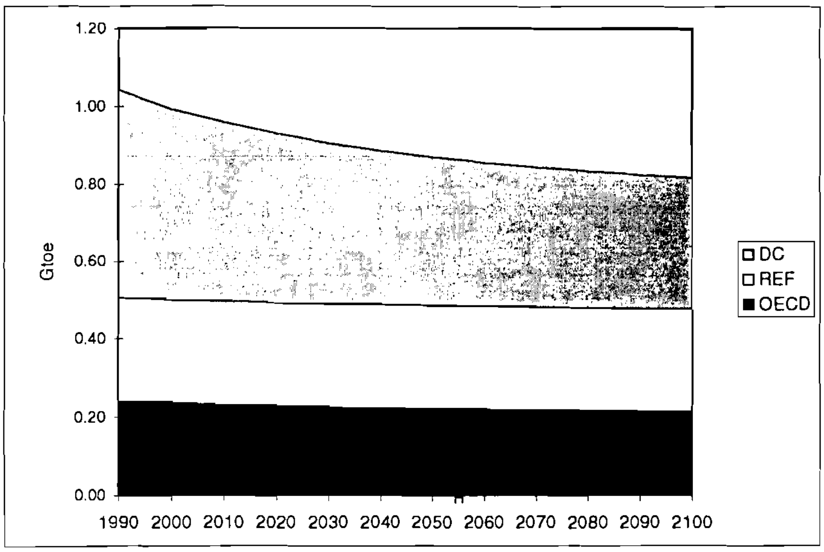
3.3.2 Coal and Natural Uranium

In view of the abundance of global coal resources, no limits on the cumulative availability of coal have been included in 11R. There is, however, a limit on the direct uses of coal (i.e., all uses of coal other than for electricity generation and the production of synthetic fuels). This limit is defined as a negative "income elasticity", i.e., its rate of decline depends on the growth of GDP. This formulation expresses the idea that increased affluence reduces the use of coal for non-electric purposes such as room heating. There are greater efforts involved in using coal for such purposes than using grid-delivered final energy forms ("inconvenience factor"). The resulting upper bounds for the world regions are shown in Figure 4.

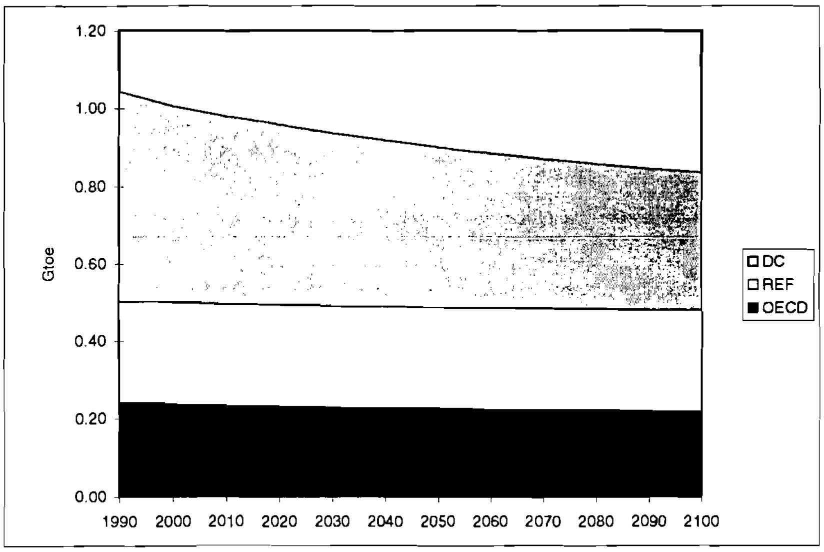
Likewise, but for different reasons, no limits on natural uranium are defined in 11R. In this case, the rationale is that the magnitude of global uranium resources depend so much on the conversion technologies assumed. Since the time horizon of this study reaches more than 100 years into the future, the uncertainties involved are so great that the model alone cannot distinguish between using high-cost uranium in converter reactors or using low-cost reprocessed nuclear fuel in breeder reactors. Therefore only the cumulative amount of primary energy produced by nuclear is reported and these numbers are compared with two different coefficients for converting uranium into energy.

3.3.3 Renewable Energy

The scenarios include three kinds of renewable energy. These are hydroelectricity, other renewable electricity (wind, solar, and electricity from municipal waste), and methanol derived from biomass. All of them are constrained by the limits of their availability in each time period. These availabilities are identical in scenarios H and L, where they reflect the overall optimism of these scenarios. They are lower – and thus probably more realistic – in scenario R. Figure 5



Scenario H



Scenario R

Figure 4: World regional upper limits of direct coal uses in three scenarios.

Table 7: Electricity production technologies in the OECD region.

	th.Eff.,%	¢/kWh		Fuel
	H, R, L	H and L	R	Costs
Coal-R	35.9–38.3	2.50–3.68	2.50–3.68	included
Oil-R	34.5–38.1	0.53	0.53	excluded
Gas-R	37.1–43.7	0.58	0.58	excluded
Nuclear-R	38.5	1.06	1.06	included
Coal-N	43.0	4.47–5.47	4.64–5.64	included
Gas-N	58.0	1.31	1.58	excluded
Nuclear-N	38.5	3.55	4.01	included
Hydro	38.5	1.73–2.73	1.73–2.73	n.a.
Renewables	38.5	2.95–3.80	4.04–5.22	n.a.

Table 8: Non-electric fuels (other than oil and gas) in the OECD region.

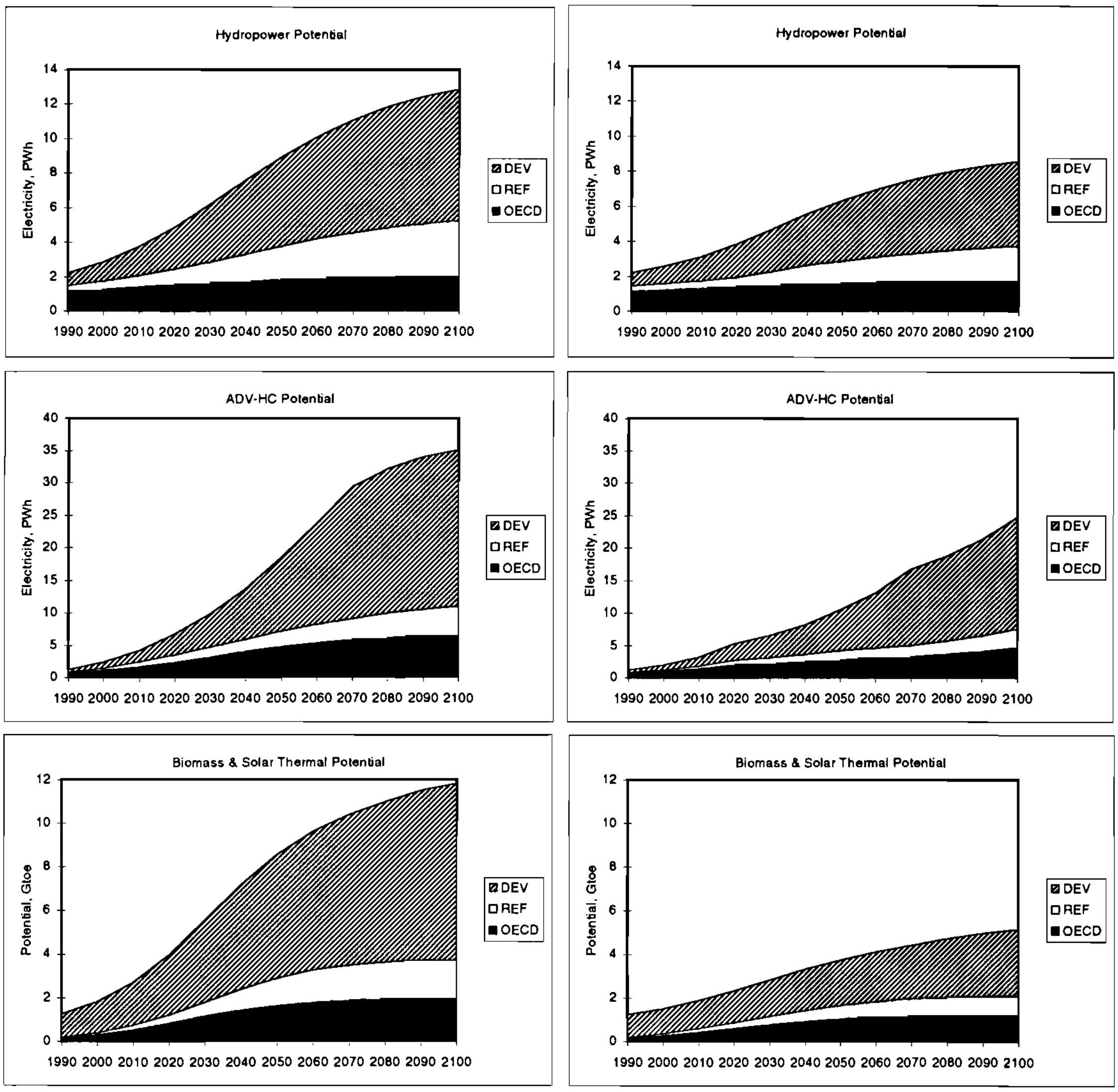
	$/kgoe	
	H and L	R
Coal, direct uses	0.07–0.12	0.07–0.12
Synthetic fuels	0.36–0.44	0.39–0.48
Methanol from biomass	0.33	0.34
Nuclear hydrogen	0.59	0.65

shows the limits assumed for renewable energy for the three macro world regions and for the world as a whole.

3.4 Conversion Technologies

The source of data describing the energy conversion technologies of 11R is the same as for the corresponding MESSAGE data. Since 11R does not distinguish between capacities of technologies and their utilization, it assumes predetermined utilization factors for the calculation of annualized capital costs. For all technologies other than those electric power plants that consume oil or natural gas, fuel costs are added to the technology costs. The resulting cost figures are shown in Tables 7 through 12, which also contain the conversion efficiencies and three macro regions OECD, REF, and DC. In these tables technology names ending in "-R" describe capacities that exist in the base year and that are phased out. For these, no investment costs are included in the model because they are assumed to be sunk costs. In contrast, the "-N" technologies are assumed to be available from the year 2000 onwards.

The "Renewables" category includes power generation from photovoltaic, wind, and municipal waste. The original cost projections, in particular for technologies converting renewable energy, are time series (a cost-reducing effect of learning was assumed that lowers technology costs in the course of time). The year 2020 was chosen for which the original cost data were taken into 11R.



Scenario H, L

Scenario R

Fig. 5

Figure 5: World regional limits of three categories of renewable energy in three scenarios.

Table 9: Electricity production technologies in the Reforming Economies.

	th.Eff.,% H, R, L	¢/kWh H and L	 R	Fuel Costs
Coal-R	31.5–32.7	2.28–2.90	2.28–2.90	included
Oil-R	18.3–29.5	0.53	0.53	excluded
Gas-R	20.3–34.4	0.58	0.58	excluded
Nuclear-R	38.5	1.06	1.06	included
Coal-N	43.0	4.14–4.55	4.30–4.72	included
Gas-N	58.0	1.31	1.58	excluded
Nuclear-N	38.5	3.55	4.01	included
Hydro	38.5	1.66–2.15	1.66–2.15	n.a.
Renewables	38.5	3.65–3.80	5.01–5.22	n.a.

Table 10: Non-electric fuels (other than oil and gas) in the Reforming Economies.

	$/kgoe	
	H and L	R
Coal, direct uses	0.05–0.08	0.05–0.08
Synthetic fuels	0.33–0.37	0.36–0.40
Methanol from biomass	0.33	0.34
Nuclear hydrogen	0.59	0.65

Table 11: Electricity production technologies in the Developing Countries.

	th.Eff.,%	¢/kWh		Fuel
	H, R, L	H and L	R	Costs
Coal-R	28.6–35.6	1.92–2.40	1.92–2.40	included
Oil-R	22.0–37.2	0.32	0.32	excluded
Gas-R	17.3–37.1	0.35	0.35	excluded
Nuclear-R	38.5	0.64	0.64	included
Coal-N	43.0	4.30–4.72	4.47–4.89	included
Gas-N	58.0	1.05	1.24	excluded
Nuclear-N	38.5	3.55	4.01	included
Hydro	38.5	0.94–1.48	0.94–1.48	n.a.
Renewables	38.5	2.54–3.51	3.48–4.89	n.a.

Table 12: Non-electric fuels (other than oil and gas) in the Developing Countries.

	$/kgoe	
	H and L	R
Coal, direct uses	0.06–0.08	0.06–0.08
Synthetic fuels	0.35–0.38	0.38–0.41
Methanol from biomass	0.28	0.27–0.30
Nuclear hydrogen	0.59	0.65

3.5 Other Input Data

11R uses a path of the price development of internationally traded crude oil as input, which is identical in all three scenarios. It is shown in Figure 6. The curve shown is logistic with three defining parameters, i.e., US$15 per barrel (bbl) in the year 2000, US$22/bbl in 2020, and an asymptotic value of US$45/bbl. The basis for this curve is basically judgmental, influenced by 1995 IEW poll results (Manne and Schrattenholzer, 1995).

In scenario L, carbon emissions and energy use are taxed. The carbon tax increases along a logistic curve (with an asymptotic value of 500) from $20 in 1990 to $400 per ton of carbon in 2100 in all regions. The energy tax increases by 1.2 percent per year in the DC region and by 2.4 percent per year in the REF and OECD regions.

There are two more sets of constraints that play an important role in the scenarios. One of them limits the share of nuclear in total electricity to a maximum of 45 percent. In scenario L, there is an additional constraint leading to the gradual phaseout of nuclear energy so that at the end of the time horizon, its global contribution is approaching zero.[5] The second set of constraints defines a lower limit of 67 percent for the share of liquid fuels in total non-electric energy.

4 Model Outputs

In this section, all scenarios are described by group of outputs (i.e., GDP for all three scenarios, followed by primary energy for all scenarios, etc.) rather than describing each scenario separately. This avoids duplications where the descriptions are independent of the scenario or relating to all scenarios simultaneously.

4.1 Economic Development

In this subsection, the economic development in the scenarios H and R are described. Since scenario L is conceived very differently from H and R, its economic development is described in a separate subsection below.

Figure 7 shows global GDP development in scenarios H and R for 11R and, for comparison, the GDP as defined by the *Scenario Generator*. In scenario H, global output increases almost 15 fold i.e., from 21 T$ (trillion - 10^{12} - US dollars of 1990, measured at market exchange rates) in 1990 to 308 T$ in 2100. In scenario R, Global GDP increases 10-fold between 1990 and 2100. This is the lowest overall growth of all three scenarios.

The distribution of this global output over the three macro world regions is shown in Figure 8. In both H and R, it changes drastically during the time horizon considered. In scenario H, the share of the OECD region drops from almost 80 percent in 1990 to 33 percent in 2100, Developing Countries (DC) increase their share from 16 to 58 percent, and reforming economies are projected to almost double their 1990 share of 5 percent.

In scenario R, the highest increase of macro-regional GDP occurs in the Developing Countries with a factor of 35 based on the 1990 level. While GDP increases 14 fold in the REF region, it only grows by a factor of 4.4 in the OECD. Similar to scenario H, the DC region accounts for almost 60 percent of world GDP in 2100. While the Reforming Economies increase their share

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[5] This constraint reflects a "mainstream" green philosophy. Other members of the "Low" family of scenarios include inherently safe and decentralized nuclear energy generation, reflecting the assumption that a new nuclear technology will be developed that responds to today's concerns about its risks and, therefore, becomes universally accepted.

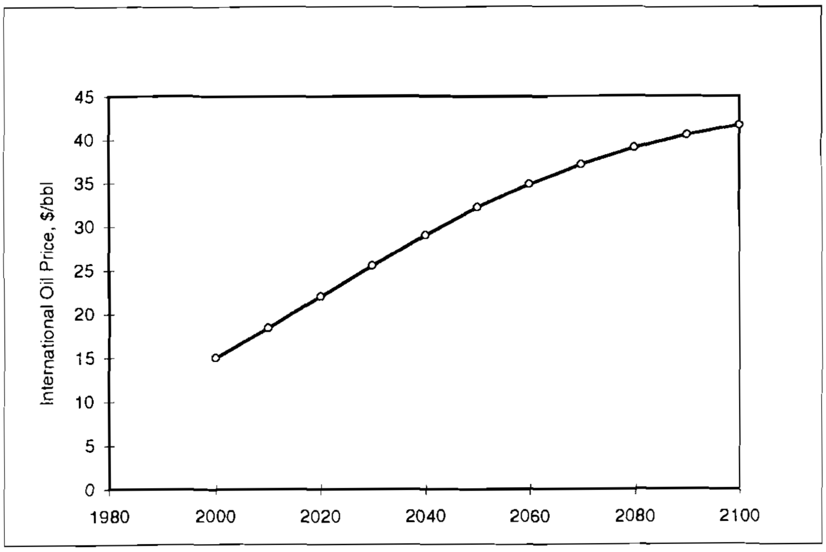
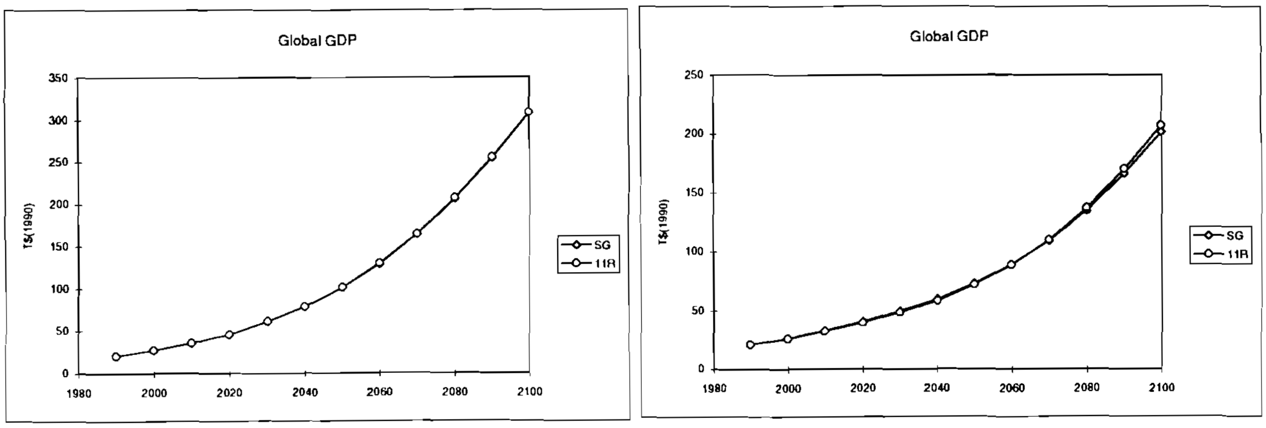


Figure 6: Development of the international oil price assumed for the three scenarios.

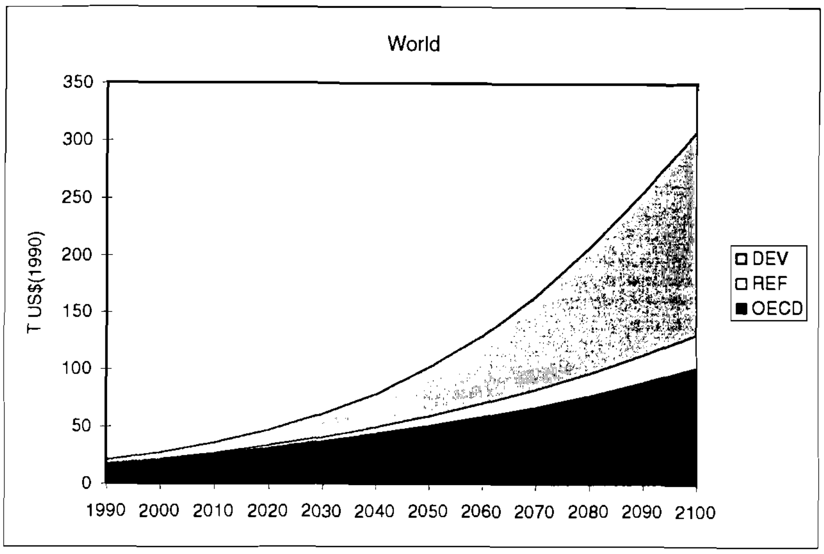


Scenario H

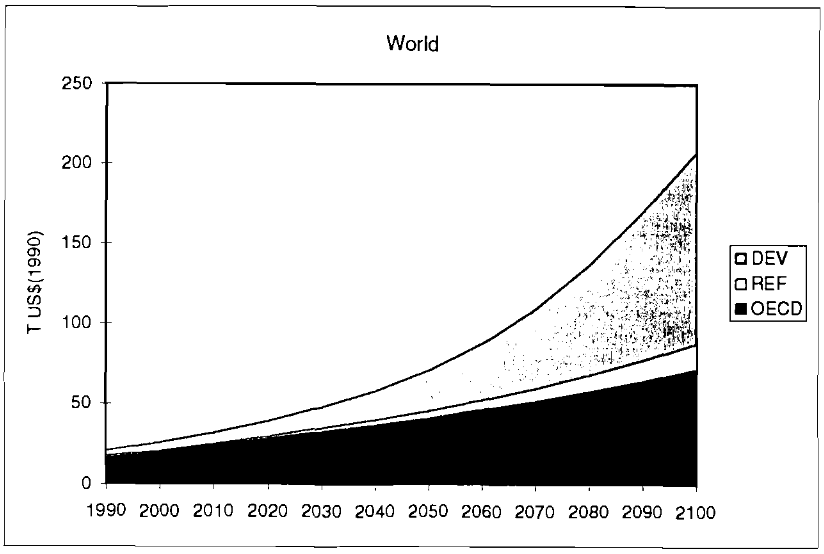
Scenario R

F7

Figure 7: Global GDP development in scenarios H and R, 11R and *Scenario Generator*.



Scenario H



Scenario R

Figure 8: World regional GDP development in scenarios H and R.

in global GDP from 5 to 8 percent, the share of the OECD in the production of the world's economic output decreases from almost 80 to 35 percent.

An important characteristic of long-term scenarios of economic development is how much the income gap between the industrialized and the developing countries changes over time. In 1990, average per capita income in the OECD region was higher than that in the developing countries by a factor of 22. This gap narrows in both the H and R scenarios to 6 by the year 2100. This flattening of the global income distribution may seem optimistic. It is the consequence of the assumption that, eventually, all world regions will successfully industrialize within the time horizon of our scenarios, following a dynamic pattern similar to those of the industrialized countries of today. At the same time, the high-income countries' growth is assumed to slow down with higher per capita income. (For more details, see WEC-IIASA, 1995.)

The comparison between the OECD and the Reforming Economies shows that this ratio drops from approximately 7 in 1990 to 2.0 in 2100 in scenario H and to 2.6 in scenario R.

Thus far, 11R results mainly mirror the *Scenario Generator*. An endogenous model result is the allocation of total economic output to energy costs, macroeconomic consumption, and investment.[6] Figure 9 shows the development over time of these three variables, expressed as shares of total economic output for the scenarios H and R for the world as a whole. On the global average, the ever decreasing energy intensity of GDP means a slight decrease of the share of energy costs. This moves from 5.7 percent in 1990 to approximately 3 percent in 2100 (3.5 in R and 2.3 in H). Macroeconomic investment remains between 17 and 20 percent of the total output for the whole time horizon. Consumption keeps increasing slightly to stabilize at almost 80 percent of global output towards the end of the century.

Two kinds of problems are hidden behind this undramatic picture of the future. One is the structure of output distribution in the Reforming Economies in the near future. In that region, energy costs peak at 17 percent of total economic output in the year 2000, and macroeconomic investment at 26 percent in 2030. These rates might seem realistic in the light of high saving rates in this region during planning times. Much of those savings were "forced savings", however. That is, they reflected controlled prices (Centre for Economic Policy Research, 1990), and "new" savings are at a much lower level. Therefore, the present situation is one of increased investment needs to finance the transition and the "catching up" of the Reforming Economies. In view of the presently low savings rates, this means that the lion's share of this region's investment will have to be financed from foreign sources (*ibid.*). Even if foreign investment capital can be attracted in the desired quantities, e.g., from Western Europe, the consequences of diverting savings from that region might lead to world-wide repercussions. See, e.g., Collins and Rodrik (1991) or Holzmann *et al.* (1993). In other words, even if the Reforming Economies' problem of investments can be solved, other problems can be expected to arise elsewhere on the globe. Clearly, this situation is far from "business as usual", and only the future will show how well 11R describes the Reforming Economies' development in the years to come. Presumably, it could be described closely if only the macroeconomic parameters were known, but a realistic modeling strategy should expect the model to require regular updates of its inputs.

Total consumption in the Reforming Economies moves from 80 percent in 1990 to 77 percent in 2100, there is a period between 2010 and 2030 where only around 60 percent of total economic output is available for consumption.

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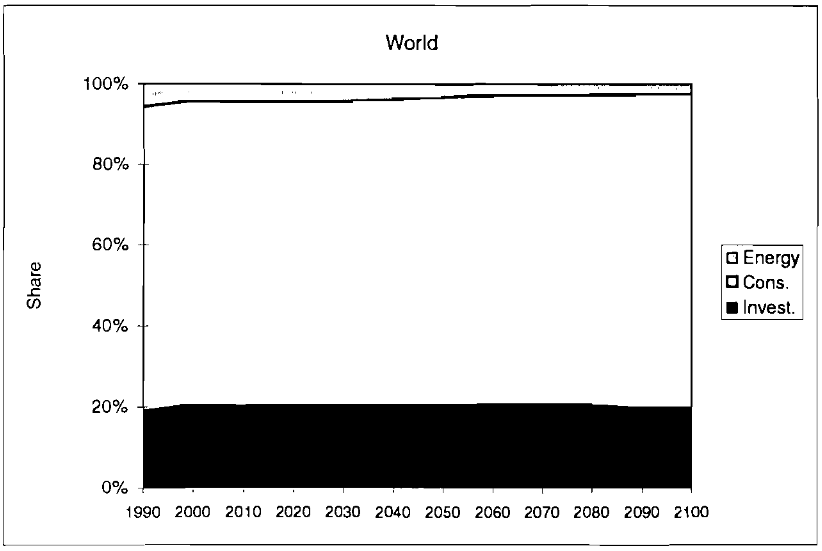
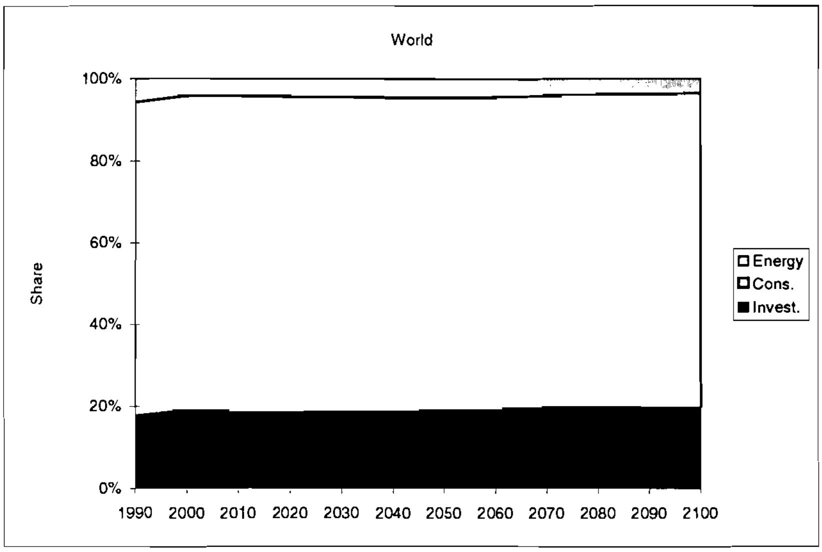
[6] According to the model formulation, costs of secondary energy are considered "interindustry payments" and therefore part of economic output, but not counted towards GDP. GDP in 11R is defined as the sum of consumption and investment, and the initial conditions are calibrated accordingly. Energy costs are singled out, because energy is in the focus of the model. Since 11R does not distinguish between capacities and production, i.e., a fixed capacity utilization is assumed, resulting energy costs are not disaggregated into capital costs, fuel costs, and O&M costs.



Scenario H



Scenario R

Figure 9: Allocation of economic output to consumption, investment, and energy costs for the world, scenarios H and R.

The second problem is hidden behind the superficially favorable development of the share of energy costs in Developing Countries. Although in both scenarios this share decreases by 2100 to between 3 and 5 percent, the present trend of difficulties in financing investments (in particular in the energy sector) suggests that the absolute numbers must also be analyzed. Doing this results in seeing that annual energy costs go from 420 billion (10^9) US dollars (1990) in the base year to 1.1 trillion dollars in 2020 in scenario H. This increase must be seen in the light of the fact that governments and international development agencies, the traditional financing sources, are increasingly constrained. For example, official development finance commitments in the energy sector practically stagnated between 1984 and 1991 even in *current* money! (Pachauri *et al.*, 1995) This means that the private sector is increasingly called upon for providing the required investment funds. But private-sector money is likely to be attracted only if rates of return are competitive. A summary of rates of return for World Bank projects between 1974 and 1992 finds the returns in the power sector less than 50 percent of peak rates in urban development and ranking behind transport, telecommunications, and other sectors (Hyman, 1994). Over the period 1966 to 1987, the performance of utilities in developing countries deteriorated markedly. The rate of return on assests fell from 9.2 percent to 4.4 percent (Jhirad, 1991).

Attractive return rates require adequate pricing of energy, especially of electricity. However, prospects for increasing prices seem poor in the light of the downward drift of average tariffs from US¢ 5.21 in 1979 to US¢ 3.79 per kilowatthour in 1988, a decrease of more than 30 percent in less than 10 years (Schramm, 1991).

4.1.1 Global Cooperation, the Special Case of Scenario L

Taking scenario H's assumptions about reference GDP and energy intensity reductions as a basis, scenario L assumes that the world regions will undertake major efforts within their countries and, moreover, that they will cooperate with each other at an unprecedented level. The aim of this hypothetical endeavor is to reduce the risks of the adverse effects of global climate change by cutting global carbon emissions in a way that atmospheric CO_2 concentrations will remain well below twice the preindustrial level. In 11R, this goal is achieved by two means. One is a carbon tax that gradually increases from \$ 20 US('90) per ton of carbon (\$/tC) in 2000 to 400 \$/tC in 2100. The other way is an energy tax that, over and above the carbon tax, increases energy costs by 1.2 percent per year in developing countries and by 2.4 percent by year in the industrialized world regions, i.e., in the Reforming Economies and the OECD (see the description in Section 3.5). At 1.2 percent per year, such an energy tax doubles energy prices by the year 2050 relative to what they would be without the tax, the higher rate more than quadruples them in the same time period. These taxes reflect the domestic efforts to reduce carbon emissions. International cooperation is included in scenario L by assuming that the revenues of the energy tax collected in the OECD region are transferred to the developing countries. The energy taxes collected in the DC and REF regions are assumed to be recycled into the respective economies.

The effect of these normative assumptions is illustrated in Figure 10, showing GDP development in the three macro world regions in scenarios H and L. Global GDP increases from 21 T\$ in 1990 to 277 T\$ instead of 308 T\$ in the year 2100. This means that the costs, expressed as the difference between annual GDP in scenarios H and L, of introducing energy and carbon taxes is 31 T\$ or a 10 percent reduction by 2100. The reduction is the highest, 23 percent, in the Reforming Economies, 15 percent in the OECD and 6 percent in the Developing Countries. GDP losses in the Developing Countries remain under 5 percent until 2050. During the second half of next century they are around 5.5 percent. This comparatively favorable picture is the consequence of the transfer payments from the OECD into the DC region. These transfers are 130 billion dollars - 0.6 percent of OECD's GDP - in the year 2000, 1.7 trillion (3.4 percent) in

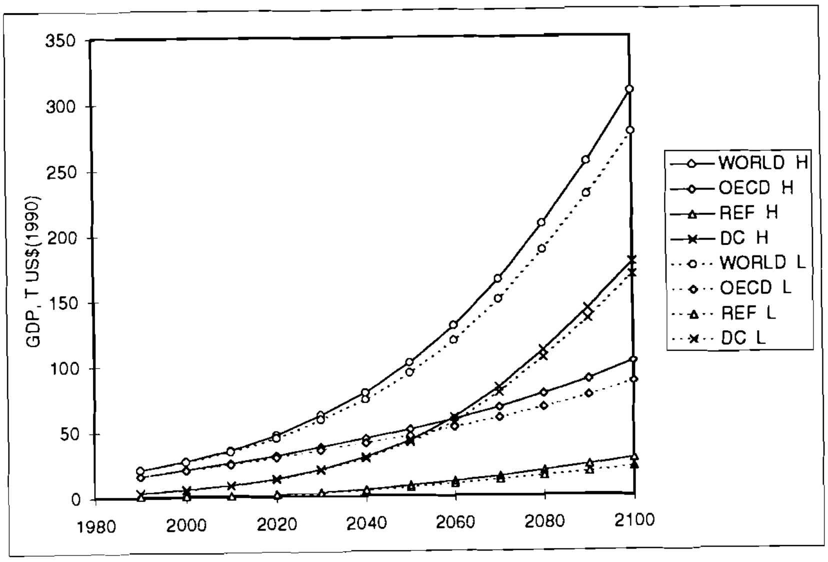


Figure 10: GDP development in the three macro world regions; comparison between scenarios H and L.

2050, and 4.9 trillion (4.9 percent) in 2100. For comparison, the present guideline number for official development aid is 0.7 percent of the industrialized countries' GDP.

As huge as the reductions in the OECD and in the Reforming Economies may seem, their economic output still grows at average annual rates of 1.5 and 2.8 percent, respectively, between 1990 and 2100. Between 1990 and 2050 the difference between the rates of average annual GDP growth in the OECD is a mere 0.2 percentage points, i.e., 2.7 percent in scenario H and 2.5 percent in scenario L.

Accordingly, the disaggregation of the total economic output into overall consumption, macroeconomic investment, and energy costs shown in Figure 11 reflects a significantly different situation than in the other two scenarios. In contrast to an ever decreasing share of energy costs there, scenario L exhibits a steady increase of energy costs to reach 6.9 percent of global output in the year 2100. Comparing these global shares with those of the other two scenarios, overall consumption in scenario L decreases slightly to 74 percent of total output through the year 2100. Investments slightly decrease, but remain approximately close to 19 percent of total output between 1990 and 2100.

The ratio between the average per capita income in the OECD region and the Developing Countries moves from 22 in 1990 to 5.8 in the year 2100. This "income gap" of scenario L is practically the same as in scenario H and less than that of scenario R (with a factor of 6).

4.2 Primary Energy

Like GDP, total primary energy consumption of scenarios H and R has been arrived at with 11R by following the target given by the outputs of the *Scenario Generator*. The model outputs were steered to this target by adjusting the model inputs on reference energy intensity reduction. In contrast, scenario L is mainly the product of 11R where taxes on carbon and total energy

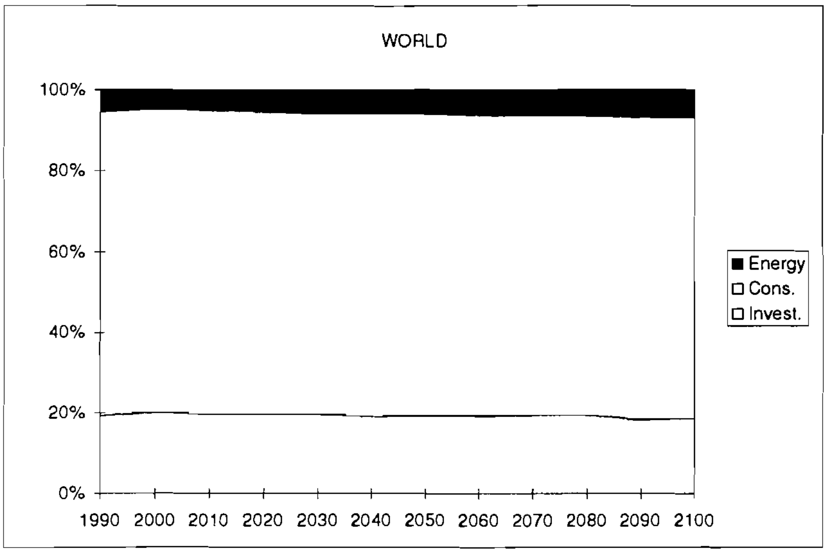


Figure 11: Allocation of economic output to consumption, investment, and energy costs, world, scenario L.

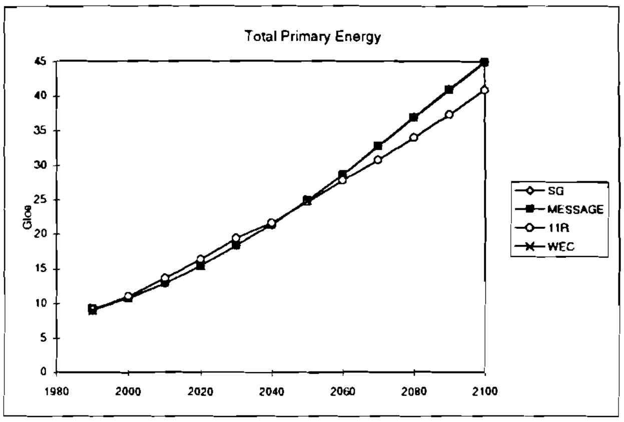
consumption and their redistribution determine the development of GDP and primary energy consumption in the world regions.

Total primary energy grows from 9 Gtoe in 1990 to 41, 36, and 19 Gtoe in 2100 in scenarios H, R, and L respectively as reported in Figure 12. The match between the trajectories describing total primary energy is less precise than for GDP, however because adjusting 11R to match the target electricity consumption (see below) changed the total primary energy consumption trajectory, thereby undoing some of the harmonization that was achieved before.

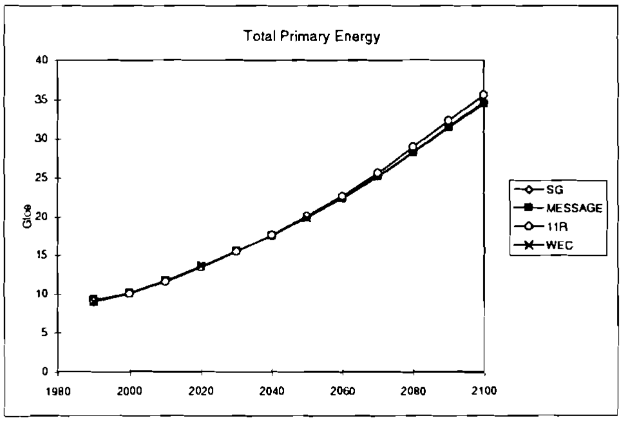
The primary energy mix in the three scenarios is shown in Figure 13 for 11R and, for comparison, for MESSAGE. Since the outputs of the two models were harmonized, the conclusions reported here are the same unless in special cases (mainly for scenario L) in which the reasons for discrepancies will be explained.

In all three scenarios, the share of carbon emitting fuels decreases significantly, albeit to very different values by the year 2100. Fossil fuels account for approximately one-half of total primary energy supply in scenario H and R. In scenario L, energy prices increase as a consequence of high carbon taxes lead to a reduction of the share of fossil fuels to less than 10 percent in 2100. Together with the decrease of total energy consumption in this highly cooperative scenario, the global energy system will have decarbonized considerably, emitting just 20 percent of carbon in comparison with 1990.

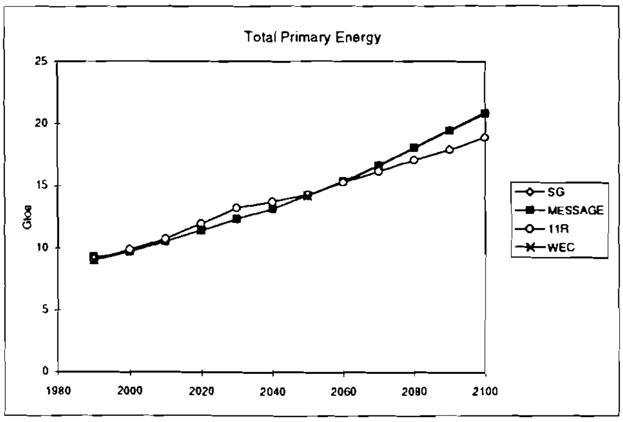
As already mentioned, scenario L was run virtually independently from the scenario generator and the MESSAGE model, due to 11R's inherent characteristics of dealing with economic constraints. Given this prerequisite, deviations between the development of primary energy between 11R and the MESSAGE model are relatively modest in 2100 and even zero in 2050.



Scenario H



Scenario R



Scenario L

Figure 12: Total primary energy use in the world. 11R results are compared with *Scenario Generator* targets and MESSAGE results.

Table 13: Cumulative consumption (in Gtoe) of fossil energy and uranium in selected time periods and consumption through 2100 shown as percent of the total resource base.

	Coal			Oil			Gas			Uranium		
	H	R	L	H	R	L	H	R	L	H	R	L
1990–2020	61.5	56.4	55.3	128.6	103.9	98.5	115.7	108.3	84.6	25.2	21.3	25.4
1990–2050	113.3	144.9	108.3	337.1	230.5	174.1	305.8	255.1	181.1	90.4	76.8	73.1
1990–2100	249.4	528.3	138.3	697.2	419.1	219.6	766.0	485.0	267.9	316.5	316.2	160.9
% of Resource Base	n.a.	n.a.	n.a.	48.5	81.6	68.4	62.2	82.8	68.0	n.a.	n.a.	n.a.

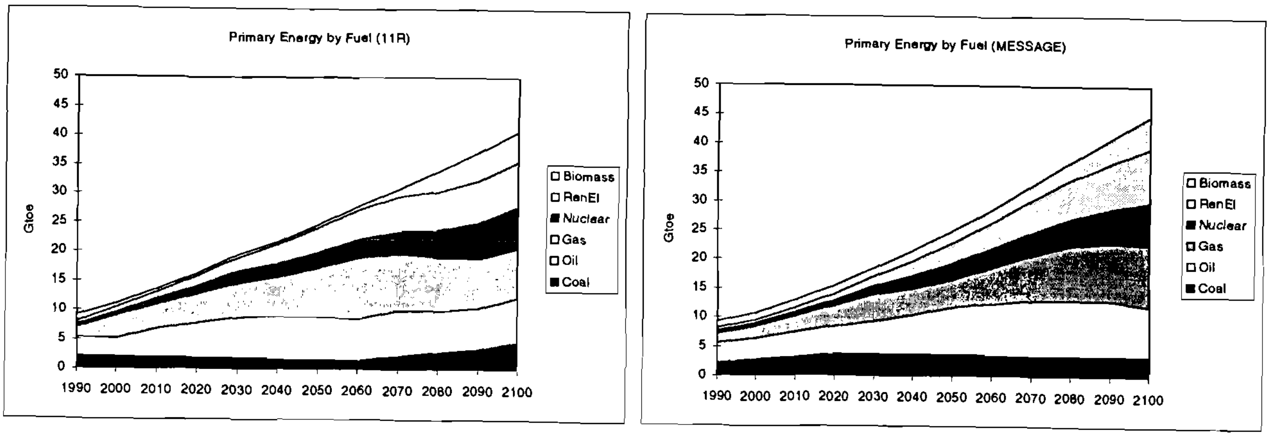
Decarbonization in scenarios H and R is driven by the gradual phase-out of oil and gas which become increasingly expensive as the conventional part of their resources becomes scarcer and scarcer. Direct uses of coal are limited not by resource constraints but rather through the "inconvenience constraints" described in the section on model input parameters (Section 3.3.2). As a result, on a global scale, 1000 Mtoe of coal used outside the power sector in 1990 are restricted to approximately 820 Mtoe in the year 2100 in scenarios H and L. Since this phase-out depends on the model inputs on reference economic growth, scenario R allows a slightly higher limit, i.e., 840 Mtoe in 2100. In that year, coal increases its share in total primary energy supply, however, because it competes successfully with increasingly expensive natural gas in the power sector in scenarios H and R. Cumulative production of the three fossil fuels and of natural uranium between 1990 and selected years of the model's time horizon is shown in Table 13.

In all three scenarios, the total consumption of fossil fuels over the entire time horizon remains below the resource base limits as identified by WEC and IIASA (1995). For oil, the relative consumption figures are 49, 82, and 68 percent of total (conventional and unconventional) reserves and resources consumed in the scenarios H, R, and L respectively. For natural gas, the corresponding numbers are 62, 83, and 68 percent. Coal consumption remains well below total reserves in all three scenarios.

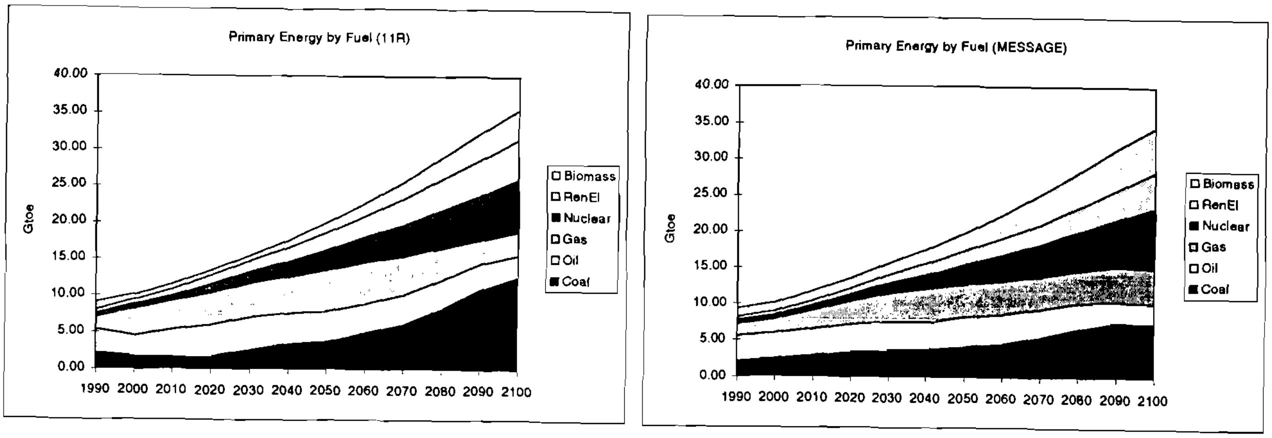
The results for natural uranium are more difficult to report because the energy content of uranium depends on the conversion technology used for power generation. 11R does not distinguish between converter and breeder reactors. Therefore primary energy equivalents of nuclear power were calculated in our scenarios assuming a conversion efficiency of 38.5 between primary energy and secondary electricity. Comparing these primary energy equivalents with the resource base (WEC and IIASA, 1995), it can be seen that converter reactors would not find enough uranium for generating the electricity of scenarios H and R. This means that in these two scenarios, either breeder reactors must be used to generate the same amount of electricity with less inputs of natural uranium or that low-grade (and expensive) resources of uranium (such as uranium from sea water) must be tapped to increase the resource base.

Renewables are assumed to become less expensive in the future, due to the favorable effect of "learning curves". (See the description of technology costs in Section 3.4 on model inputs.) In addition, they become relatively less costly than oil and gas over time as the model exhausts the fossil fuels' low-cost and begins to tap the respective high-cost categories. Biomass during the first decades of the time horizon chosen is mostly non-commercial energy and, therefore, declining in the early time periods. Later, when oil and gas become increasingly expensive, commercial biomass takes an increasing share of its assumed potential, reaching a maximum of 5.1 Gtoe in the year 2100 in scenario H. All renewables together (biomass, hydro, solar, wind, and municipal waste) contribute 32 percent to global primary energy supply in scenario H in the year 2100, 27 percent in scenario R, and 79 percent in scenario L.

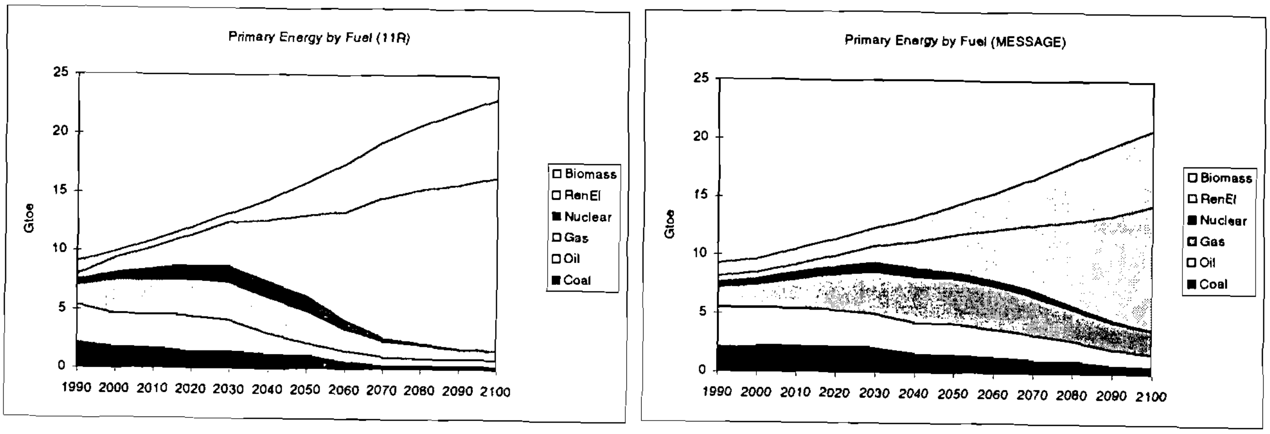
The comparison of the cumulative consumption of primary fuels is shown in Figure 14. The comparison shows that global consumption of coal in 11R is slightly lower than in MESSAGE, but that oil, gas, and nuclear are higher in 11R. Thus, the numerical results are not identical in



Scenario H



Scenario R



Scenario L

Figure 13: Total primary energy in Scenario H, R, L for the world; comparison of MESSAGE and 11R results.

the two models, but they do not have any importance in the conclusions, in particular, because there is very good harmony of the model results on carbon emissions. Differences between the two models are largest in Scenario L. This is primarily because of the significantly higher production of the absolute amount of electricity and its renewable share, which permanently results in lower levels of all fossil fuels through 2100 (see below).

The consumption profiles of the fossil fuels could be made to agree better. However, the degree of harmony displayed in the comparison is as high should be expected. Going much further would, with great efforts, reduce 11R to a mere emulator of MESSAGE without providing any further insights.

4.3 Electricity Generation

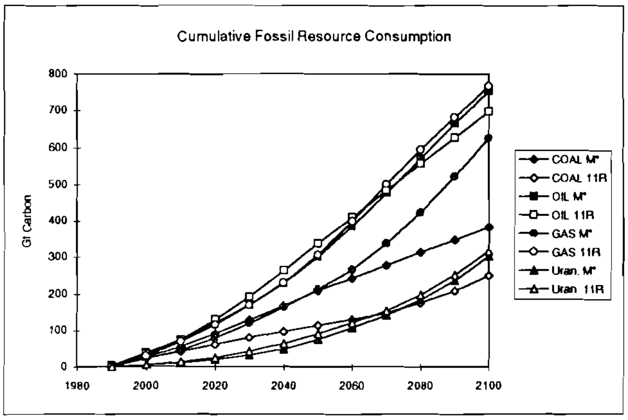
Global electricity generation is projected to increase from almost 12 PWh (10^{15} watt hours) in 1990 to 84, 71, and 44 PWh in 2100 in scenarios H, R, and L respectively. (See Figure 15 for 11R, MESSAGE, and *Scenario Generator* results.) In scenario H, the sevenfold increase compares with an increase of total primary energy by a factor of 4.5 only. This overproportional growth in all three scenarios is a basic scenario characteristic, reflecting the trend to an increasing convenience of final energy use.

Figure 16 reports the electricity generation mix for 11R and MESSAGE. In the world as whole, carbon-free electricity generation increases from 37 percent of total electricity generation in 1990 to 80 percent in scenario H and R and 96 percent in scenario L in 2100. In scenario H, 48 percent of the non-fossil power is generated by nuclear, the rest by renewable energy. In scenario R, this share of nuclear is 56 percent. Worldwide, solar electricity (including wind and municipal waste) exhausts 62 percent (21.8 PWh) of its potential, 35 PWh, assumed for scenarios H and L in 2100. In scenario R, the potential is lower (24.7 PWh), and 66 percent of it (16.4 PWh) is used in the year 2100. Approximately two-thirds of fossil electricity in scenarios H and R in 2100 is produced from coal, a consequence of coal's relative abundance, which lets it compete successfully against natural gas.

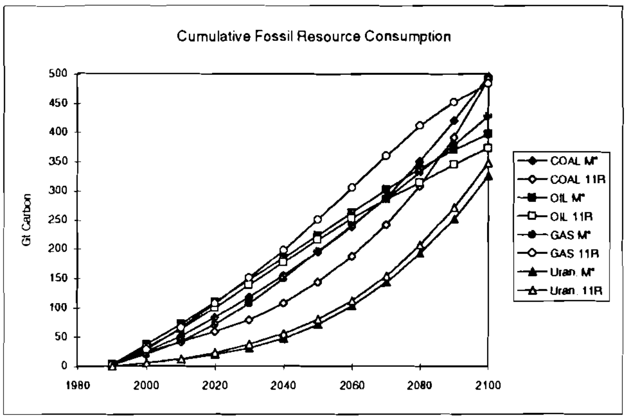
While electricity production is iterated with that in MESSAGE for scenario H and R, the share of electricity in total energy demand in scenario L uses the ELVS parameters used for scenario H, which results in a more than 60 percent higher production compared to the MESSAGE result.

Nuclear power is constrained to supply a maximum of 45 percent of total electricity in each of the 11 world regions. In scenarios H and R, this is a binding constraint in most regions, in particular in the OECD where it is binding from the year 2030 onwards in most cases. In the Reforming Economies, Eastern Europe shows a slower penetration of nuclear power in both H and R. There the constraints become binding in 2040 (scenario H) and 2050 (scenario R). In the FSU fossil fuels are more abundant and the nuclear constraint becomes binding only late in the next century (2100 in scenario H and R). In CPA it is only binding from 2050 in scenario R. In all other developing regions it only becomes binding in the second half of the next century – if at all.

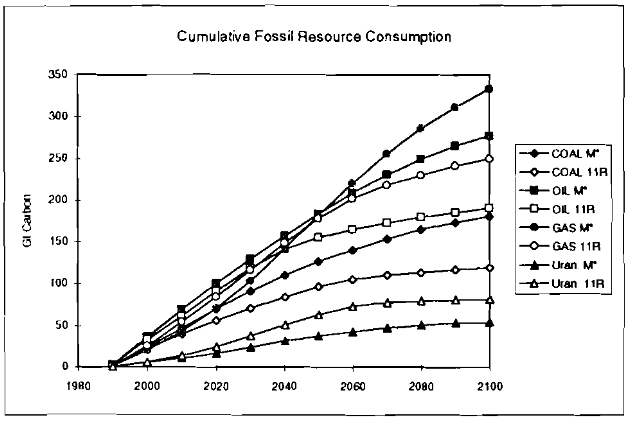
Of the aggregate indicators, electricity consumption shows the least congruence between *Scenario Generator*, MESSAGE, and 11R. In both energy models, the control of electricity consumption can be elusive. In MESSAGE, electricity can substitute for other final energy carriers, e.g., in the space heating category. In 11R, substitution between electric and non-electric energy is governed by the electricity value share. In theory, this parameter can be changed from period to period to finetune total electricity consumption, but proceeding in this way results in implausible movements of this parameter, sometimes increasing and sometimes decreasing. Worse, it has a similarly erratic effect on total primary energy consumption. In practice, therefore, the decision



Scenario H



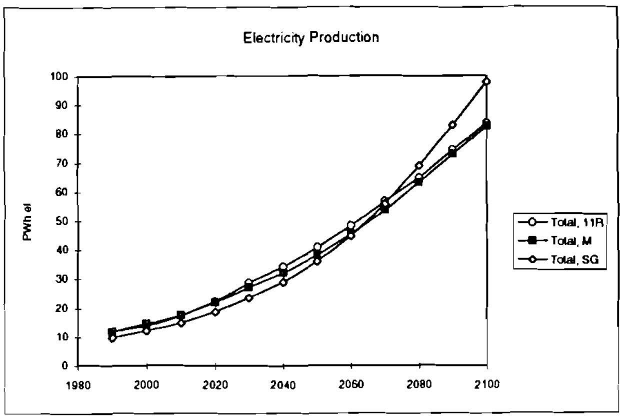
Scenario R



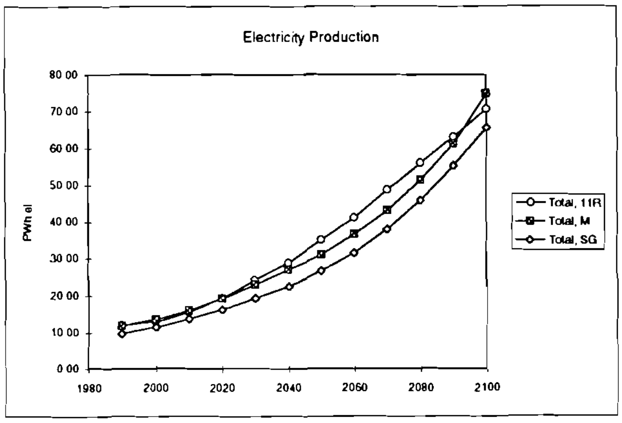
Scenario L

Fig. 14

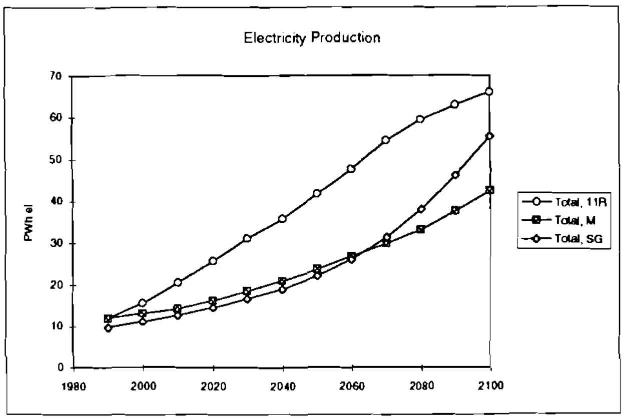
Figure 14: Cumulative consumption of primary fuels in scenarios H, R, L for the world; comparison of MESSAGE and 11R results.



Scenario H

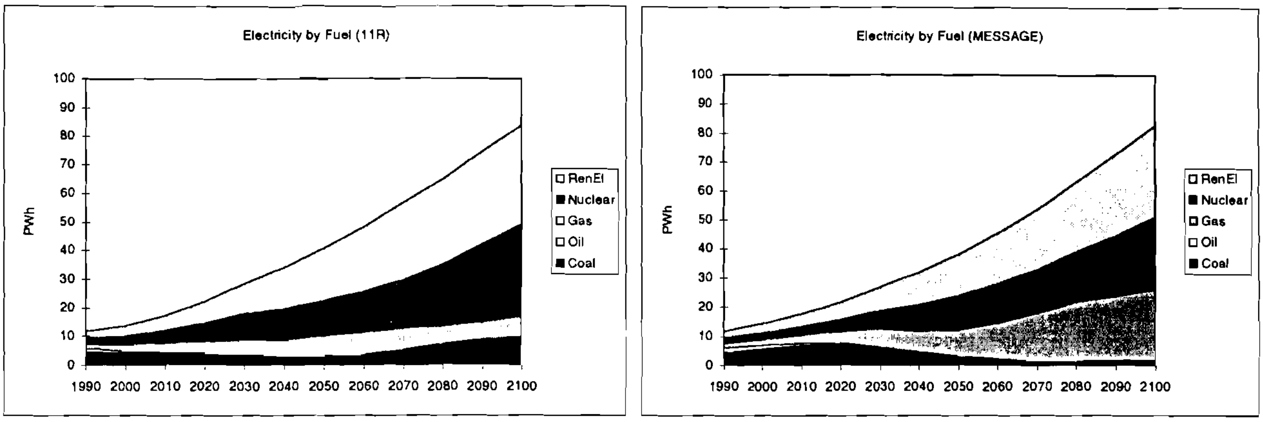


Scenario R

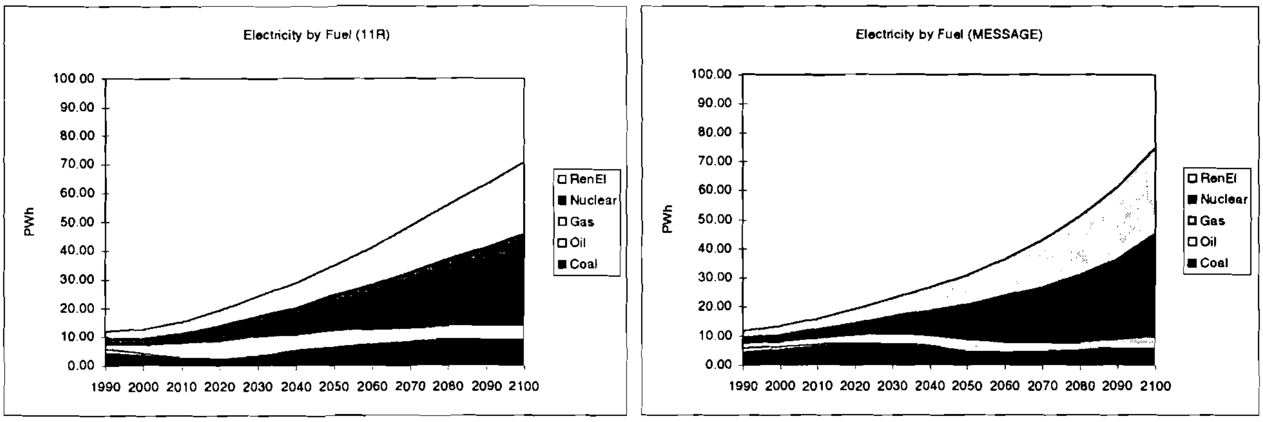


Scenario L

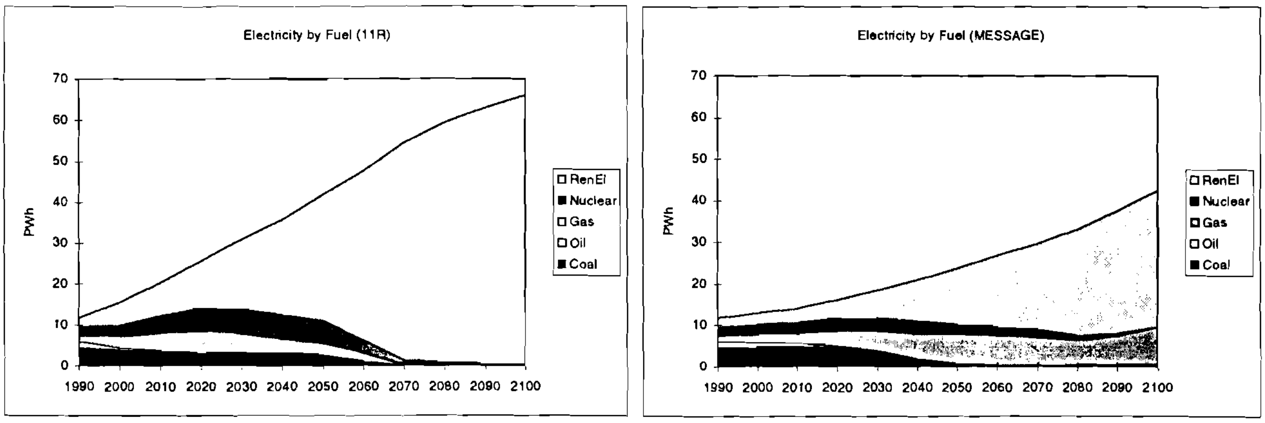
Figure 15: Total electricity generation in the three scenarios. 11R results are compared with *Scenario Generator* targets and MESSAGE results.



Scenario H



Scenario R



Scenario L

Figure 16: Electricity generation by fuel in the world in Scenario H, R, and L; comparison of MESSAGE and 11R results.

was taken to restrict the movements of the electricity value share to monotonously increasing trajectories only, and not to aim at complete congruence of the resulting electricity generation paths.

4.4 Carbon Emissions

Global carbon emissions in the three scenarios are shown in Figure 17 for 11R and MESSAGE. Emissions in scenario H are slightly lower than those of scenario R. (16.9 GtC in comparison to 18.1 GtC in the year 2100.) Higher energy consumption in H is compensated by higher decarbonization rates. Carbon emissions in the normative scenario L from 2030 onwards stay well below the trajectory that leads to a stabilization of atmospheric concentrations of CO_2 at twice its pre-industrial level. (This trajectory is denoted by the dashed line in Figure 17.)

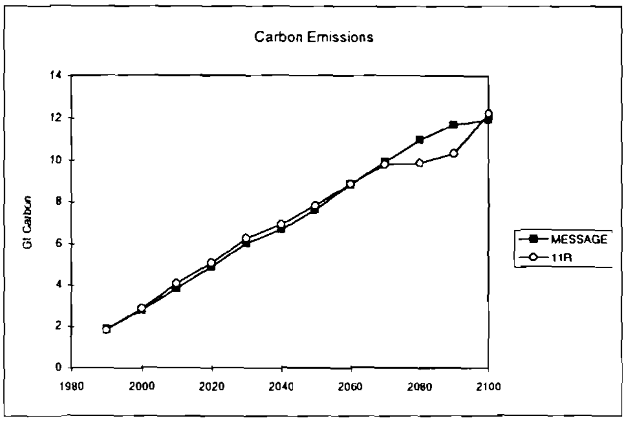
Figure 18 shows the carbon intensity of total primary energy consumption in the three scenarios. These developments are compared with a global scenario in which global decarbonization is assumed to follow historical trends of approximately 0.3 percent per year (Nakićenović *et al.*, 1993). This trend extrapolation almost coincides with the development of carbon intensity in our scenario H. In comparison, scenario R looks pessimistic, although here also, there is an overall decrease of carbon intensity over the time horizon. Scenario L, of course, reduces carbon emissions to almost zero by the end of next century.

Figure 19 shows cumulative emissions for the scenarios H, R, L in comparison to the MESSAGE results for the world. Cumulative carbon emissions result in 1400 and 1200 GtC for scenarios H and R, respectively. Since cumulative carbon emissions was one of the common measuring points (see Section 2.3) for these two scenarios, the fit between the two model outputs is very good. In contrast, scenario L, which was run independently from MESSAGE and exclusively builds on scenario H, results in 500 GtC only, about 100 GtC less compared to the MESSAGE result. Again, this is primarily a consequence of the large amount of (zero-carbon) electricity produced.

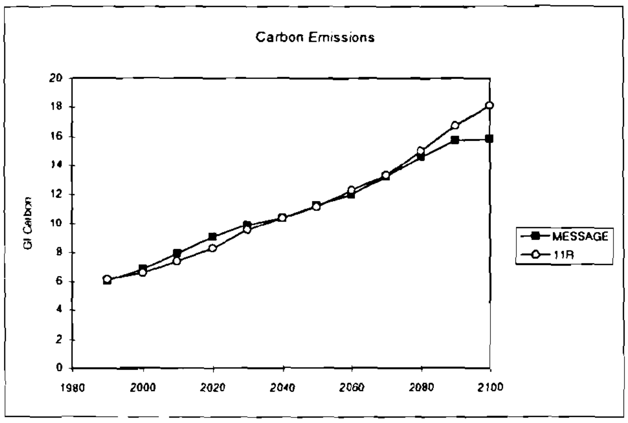
5 Outlook

This paper reports on work in progress. Therefore, the scenarios will receive further attention concerning their 11-regional detail. Refining the scenarios and peer review comments on the scenarios will surely lead to some modifications of the results presented here. As to methodology, one important experience made during working with MESSAGE and 11R at the same time was the problem of double coverage of primary energy supply, once in each model. On the positive side, different kinds of insights can be gained from different results of different model formulations. It is also useful to be constantly made aware of the uncertainties surrounding the distant future that make one primary energy mix as plausible as many similar scenarios. At the same time, inconsistencies between two models seem like an unnecessary aesthetic nuisance, in particular when results of one model cannot easily be emulated in the other due to differences in their scope. Work has therefore begun to replace the entire energy module of 11R by simple cost curves derived from MESSAGE runs. By doing this, the overlap between the two models is eliminated, and consistency between the macroeconomic and the energy system can be achieved through iterations. First experiences with this coupling and the results by Manne and Wene (1994) with MARKAL-MACRO raises expectations that such an iteration will converge in very few iterations.

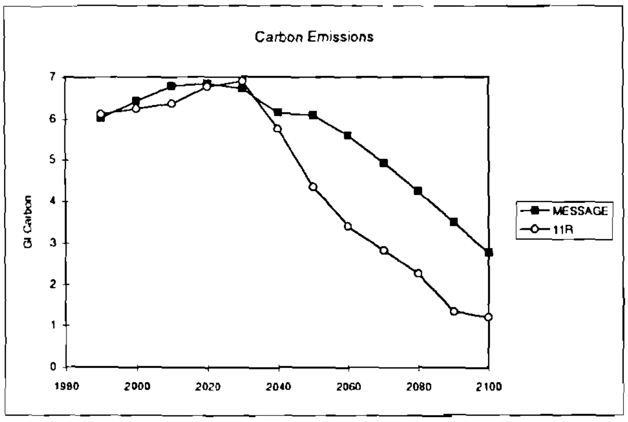
At present, 11R uses secondary energy as a production factor. It would seem that from an economic point of view, final energy – the energy form that is actually bought by the final consumer – is a more appropriate descriptor of the interaction between the economic and energy



Scenario H



Scenario R



Scenario L

Fig. 17

Figure 17: Global energy-related carbon emissions in three scenarios and a trajectory leading to an atmospheric concentration of 550 ppm for comparison; 11R and MESSAGE results.

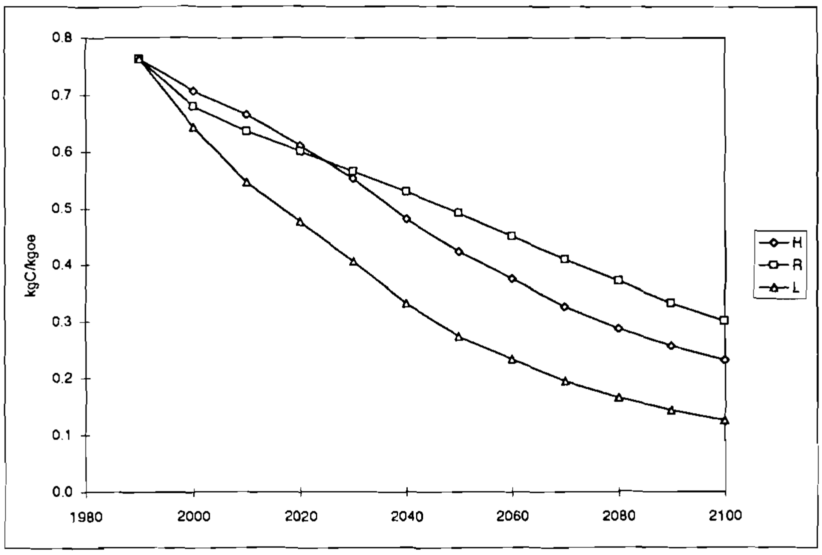
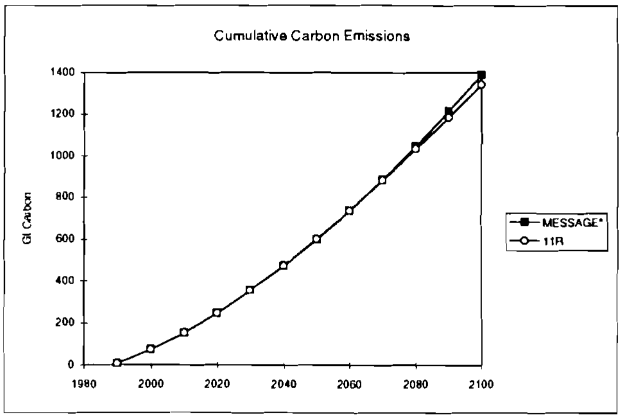


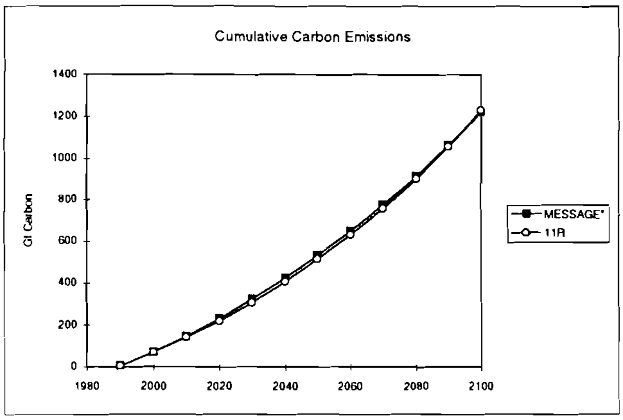
Fig. 18

Figure 18: Carbon intensity of total primary energy consumption in three scenarios.

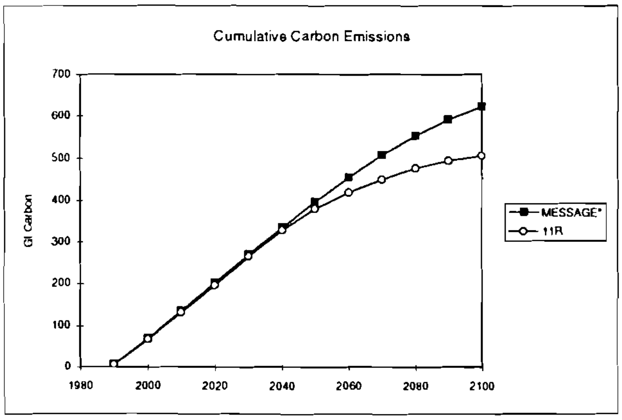
system. It is therefore planned to replace the two energy-related production factors of 11R (electric and non-electric energy) by final energy carriers. This requires an extension of the present production function to more than two kinds of energy, but in a later version of the model, one that is stripped of its reference energy system, the net effect of implementing both changes should result in a significant reduction rather than an increase of the computational task of model solution.



Scenario H



Scenario R



Scenario L

Figure 19: Cumulative carbon emissions in Scenarios H, R, L for the world in 11R and MESSAGE.

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APPENDICES

Tables with numbers quantifying the informations in the figures of the main text.

Table A.1.

Figure 3: Primary Energy by Region.

Scenario H	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
OECD	4.2	4.8	5.4	5.9	6.4	6.6	6.8	6.9	7.1	7.3	7.5	7.8
REF	1.7	1.7	2.0	2.5	3.0	3.4	3.9	4.1	4.4	4.6	4.8	4.9
LDC	3.1	4.5	6.3	8.0	10.0	11.6	13.9	16.7	19.3	22.1	25.0	28.0
Total	9.1	11.1	13.6	16.3	19.4	21.7	24.6	27.8	30.7	33.9	37.3	40.8
Scenario R	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
OECD	4.2	4.6	4.9	5.1	5.4	5.5	5.6	5.6	5.6	5.6	5.5	5.5
REF	1.7	1.3	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.9	3.1	3.2
LDC	3.1	4.1	5.3	6.6	8.2	10.0	12.2	14.5	17.3	20.4	23.7	26.8
Total	9.1	10.1	11.6	13.4	15.4	17.6	20.0	22.6	25.5	28.9	32.3	35.5

Table A.2.

Figure 4: CLDU Limits.

	Scenario H				Scenario R			
	OECD	REF	LDC	WORLD	OECD	REF	LDC	WORLD
1990	0.24	0.26	0.54	1.04	0.24	0.26	0.54	1.04
2000	0.24	0.26	0.49	0.99	0.24	0.26	0.51	1.01
2010	0.23	0.26	0.47	0.96	0.24	0.26	0.48	0.98
2020	0.23	0.26	0.44	0.93	0.23	0.26	0.46	0.96
2030	0.23	0.26	0.42	0.91	0.23	0.26	0.45	0.94
2040	0.22	0.26	0.40	0.89	0.23	0.26	0.43	0.92
2050	0.22	0.26	0.39	0.87	0.23	0.26	0.41	0.90
2060	0.22	0.26	0.37	0.86	0.23	0.26	0.40	0.89
2070	0.22	0.26	0.36	0.84	0.22	0.26	0.39	0.87
2080	0.22	0.26	0.35	0.83	0.22	0.26	0.37	0.86
2090	0.22	0.26	0.35	0.82	0.22	0.26	0.36	0.85
2100	0.21	0.26	0.34	0.82	0.22	0.26	0.36	0.84

Table A.3.

Figure 5: Renewable Energy Resources.

Hydropower Potential, PWh

Scenario H, L	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
OECD	1.1	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.9	2.0	2.0	2.0
REF	0.3	0.4	0.6	0.9	1.2	1.5	1.9	2.3	2.6	2.9	3.1	3.2
DEV	0.8	1.1	1.7	2.5	3.4	4.3	5.2	5.9	6.5	7.0	7.4	7.7
World	2.2	2.9	3.7	4.9	6.2	7.6	8.9	10.1	11.1	11.9	12.5	12.9

Scenario R	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
OECD	1.1	1.2	1.3	1.4	1.5	1.5	1.6	1.6	1.7	1.7	1.7	1.7
REF	0.3	0.3	0.4	0.5	0.8	1.1	1.3	1.4	1.6	1.7	1.9	1.9
DEV	0.8	1.0	1.4	1.9	2.4	3.0	3.5	3.9	4.2	4.5	4.7	4.9
World	2.2	2.6	3.1	3.8	4.7	5.6	6.3	6.9	7.5	7.9	8.3	8.6

ADV-HC Potential, PWh

Scenario H, L	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
OECD	0.7	1.1	1.7	2.4	3.2	4.0	4.8	5.3	5.8	6.2	6.4	6.6
REF	0.1	0.3	0.6	1.1	1.5	1.8	2.3	2.7	3.2	3.7	4.1	4.4
DEV	0.4	0.9	1.8	3.2	5.2	7.8	11.4	15.6	20.3	22.2	23.4	24.1
World	1.2	2.4	4.2	6.7	9.8	13.6	18.5	23.7	29.3	32.1	33.9	35.0

Scenario R	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
OECD	0.7	1.0	1.4	1.9	2.2	2.5	2.8	3.0	3.3	3.7	4.1	4.7
REF	0.1	0.2	0.4	0.8	0.9	1.1	1.3	1.5	1.7	2.0	2.3	2.9
DEV	0.4	0.8	1.4	2.6	3.4	4.6	6.4	8.6	11.7	13.1	14.9	17.2

Biomass & Solar Thermal Potential, Gtoe

Scenario H, L	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
OECD	0.1	0.3	0.5	0.8	1.2	1.4	1.6	1.8	1.9	1.9	2.0	2.0
REF	0.0	0.1	0.2	0.4	0.6	0.9	1.2	1.5	1.6	1.7	1.7	1.8
DEV	1.1	1.4	2.0	2.8	3.8	4.8	5.7	6.4	6.9	7.4	7.8	8.1

Scenario R	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
OECD	0.1	0.3	0.4	0.6	0.8	0.9	1.1	1.1	1.2	1.2	1.2	1.2
REF	0.0	0.1	0.1	0.2	0.3	0.5	0.6	0.7	0.8	0.8	0.9	0.9
DEV	1.1	1.2	1.3	1.5	1.7	1.9	2.1	2.3	2.4	2.7	2.9	3.0

Table A.4.

Figure 6: International Oil Price, $/Bbl.

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
$/GJ		15.0	18.4	22.0	25.6	29.1	32.2	35.0	37.2	39.1	40.6	41.7

Table A.5.

Figure 7: World GDP Development in Scenario H and R, SG and 11R, TUS$(1990).

Scenario H, L	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
SG	20.9	27.4	36.0	46.9	61.6	78.8	101.5	129.2	164.7	207.0	254.8	308.0
11R	20.9	27.4	36.0	46.9	61.6	78.9	101.6	129.4	164.8	207.1	255.1	308.3

Scenario R	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
SG	20.9	26.2	32.6	40.2	49.3	59.7	72.8	88.6	108.9	134.7	166.4	201.6
11R	20.9	26.0	32.0	39.2	48.0	58.2	71.5	87.9	109.3	136.5	170.0	207.4

Table A.6.

Figure 8: GDP Development by Region, TUS$(1990).

Scenario H	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
OECD	16.4	20.9	26.0	31.6	37.8	44.1	51.1	58.5	67.3	77.3	88.8	101.9
REF	1.1	0.8	1.1	1.7	3.0	4.9	7.9	11.2	14.9	19.0	23.5	28.4
DEV	3.4	5.7	8.8	13.5	20.8	29.8	42.7	59.7	82.5	110.8	142.8	178.0
World	20.9	27.4	36.0	46.9	61.6	78.9	101.6	129.4	164.8	207.1	255.1	308.3
Scenario R	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
OECD	16.4	20.2	24.3	28.6	33.0	37.2	41.8	46.4	51.8	57.7	64.3	71.6
REF	1.1	0.8	0.9	1.2	1.8	2.7	3.9	5.5	7.5	9.9	12.6	15.8
DEV	3.4	5.0	6.8	9.3	13.1	18.3	25.8	36.0	50.0	69.0	93.1	120.0
World	20.9	26.0	32.0	39.2	48.0	58.2	71.5	87.9	109.3	136.5	170.0	207.4

Table A.7.

Figure 9: Allocation of Economic output, %.

Scenario H	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Invest.	19.2	20.7	20.3	20.4	20.6	20.2	20.8	20.7	20.9	20.6	19.8	20.2
Cons.	75.2	75.0	75.1	75.1	75.1	75.9	75.8	76.3	76.3	76.7	77.7	77.5
Energy	5.7	4.3	4.6	4.5	4.3	3.8	3.4	3.1	2.9	2.7	2.5	2.3
Scenario R	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Invest.	17.8	19.3	18.8	18.7	18.7	18.6	19.1	19.3	19.8	20.2	19.7	19.9
Cons.	76.5	76.5	77.0	77.0	76.8	76.8	76.3	76.3	75.9	75.8	76.4	76.6
Energy	5.7	4.2	4.2	4.4	4.5	4.6	4.6	4.5	4.2	4.0	3.9	3.5

Table A.8.

Figure 10: GDP Development in Scenarios H and L, TUS$(1990).

Scenario H	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
OECD	16.4	20.9	26.0	31.6	37.8	44.1	51.1	58.5	67.3	77.3	88.8	101.9
REF	1.1	0.8	1.1	1.7	3.0	4.9	7.9	11.2	14.9	19.0	23.5	28.4
DEV	3.4	5.7	8.8	13.5	20.8	29.8	42.7	59.7	82.5	110.8	142.8	178.0
World	20.9	27.4	36.0	46.9	61.6	78.9	101.6	129.4	164.8	207.1	255.1	308.3
Scenario L	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
OECD	16.4	20.6	25.1	29.9	35.2	40.5	46.2	52.3	59.2	67.1	76.3	86.7
REF	1.1	0.8	1.1	1.6	2.6	4.2	6.5	9.3	12.2	15.0	18.3	21.9
DEV	3.4	5.6	8.6	13.2	20.3	29.0	41.0	56.6	78.3	105.3	135.0	168.2
World	20.9	27.0	34.8	44.7	58.2	73.7	93.7	118.1	149.7	187.5	229.6	276.8

Table A.9.

Figure 11: Allocation of Economic output, %.

Scenario L	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Invest.	19.2	20.1	19.4	19.5	19.4	19.0	19.3	19.1	19.4	19.2	18.2	18.7
Cons.	75.2	75.1	75.5	75.0	74.6	75.0	74.6	74.5	74.1	74.2	74.9	74.4
Energy	5.7	4.9	5.2	5.5	6.0	6.0	6.1	6.4	6.5	6.6	6.9	6.9

Table A.10.

Figure 12: Total Primairy Energy Use: 11R, SG, MESSAGE, Gtoe.

Scenario H	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
11R	9.1	11.1	13.6	16.3	19.4	21.7	24.6	27.8	30.7	33.9	37.3	40.8
SG	9.0	10.8	12.9	15.4	18.4	21.3	24.8	28.6	32.7	36.9	41.0	44.9
MESSAGE	9.3	10.7	12.9	15.4	18.4	21.3	24.8	28.5	32.7	36.9	40.9	44.8
Scenario R	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
11R	9.1	10.1	11.6	13.4	15.4	17.6	20.0	22.6	25.5	28.9	32.3	35.5
SG	9.0	10.1	11.8	13.6	15.5	17.5	19.8	22.3	25.1	28.3	31.6	34.7
MESSAGE	9.2	10.1	11.8	13.6	15.5	17.5	19.8	22.2	25.0	28.2	31.4	34.4

Table A.11.

Figure 13: Primairy Energy Use by Fuel: 11R, MESSAGE, Gtoe.

Scenario H												
11R	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Coal	2.2	1.9	2.0	1.8	1.9	1.7	1.4	1.7	2.3	3.0	3.5	4.8
Oil	3.2	3.1	4.8	6.0	6.8	7.3	7.5	6.9	7.7	6.9	7.0	7.6
Gas	1.7	3.9	4.2	4.8	5.9	6.6	8.3	10.4	9.7	9.1	8.5	8.4
Nuclear	0.4	0.6	0.9	1.4	2.1	2.4	2.7	3.2	3.8	4.8	6.0	7.2
RenEl	0.5	0.8	1.2	1.7	2.4	3.2	4.1	5.1	6.0	6.6	7.3	7.8
Biomass	1.1	0.6	0.5	0.5	0.5	0.5	0.5	0.6	1.3	3.5	5.0	5.1
Total	9.1	11.1	13.6	16.3	19.4	21.7	24.6	27.8	30.7	33.9	37.3	40.8
MESSAGE												
Coal	2.2	2.7	3.2	3.7	3.9	4.0	3.8	3.5	3.5	3.5	3.5	3.5
Oil	3.3	3.5	4.1	4.7	5.4	6.4	7.9	8.8	9.4	9.5	9.4	8.5
Gas	1.7	2.1	2.8	3.6	4.6	4.6	4.7	6.3	7.9	9.4	10.0	10.8
Nuclear	0.4	0.5	0.7	0.9	1.4	2.2	2.9	3.3	3.8	4.6	5.9	7.3
RenEl	0.5	0.6	0.7	1.1	1.6	2.5	3.6	4.5	5.7	6.7	7.9	9.3
Biomass	1.1	1.2	1.3	1.4	1.5	1.7	2.0	2.2	2.5	3.1	4.2	5.5
Total	9.3	10.7	12.9	15.4	18.4	21.3	24.8	28.5	32.7	36.9	40.9	44.8
Scenario R												
11R	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Coal	2.2	1.8	1.7	1.8	2.6	3.5	3.8	5.0	6.2	8.2	10.8	12.5
Oil	3.2	2.7	3.7	4.2	4.4	4.1	4.1	3.9	3.9	3.9	3.5	3.1
Gas	1.7	3.7	3.9	4.4	4.6	5.0	5.6	5.6	5.2	4.4	3.3	3.2
Nuclear	0.4	0.5	0.7	1.2	1.5	2.1	2.7	3.5	4.3	5.2	6.0	7.1
RenEl	0.5	0.7	0.9	1.2	1.6	1.9	2.3	2.9	3.6	4.2	4.9	5.6
Biomass	1.1	0.6	0.7	0.7	0.7	1.0	1.5	1.7	2.3	2.9	3.7	4.1
Total	9.1	10.1	11.6	13.4	15.4	17.6	20.0	22.6	25.5	28.9	32.3	35.5
MESSAGE												
Coal	2.1	2.4	2.9	3.4	3.6	3.8	4.1	4.6	5.5	6.6	7.5	7.5
Oil	3.3	3.5	3.6	3.8	3.8	3.6	4.0	4.0	3.8	3.4	2.9	2.6
Gas	1.7	1.9	2.6	3.2	4.0	4.6	4.5	4.6	4.5	4.5	4.9	4.9
Nuclear	0.4	0.5	0.7	0.9	1.4	2.0	2.7	3.7	4.4	5.4	6.4	8.3
RenEl	0.5	0.6	0.7	0.9	1.2	1.6	1.9	2.3	2.8	3.4	4.1	4.9
Biomass	1.1	1.2	1.3	1.4	1.6	2.0	2.5	3.2	4.1	4.8	5.6	6.3
Total	9.2	10.1	11.8	13.6	15.5	17.5	19.8	22.3	25.0	28.2	31.4	34.5
Scenario L												
11R	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Coal	2.2	1.8	1.7	1.5	1.5	1.3	1.1	0.7	0.3	0.3	0.3	0.3
Oil	3.2	2.8	2.9	3.0	2.6	1.7	1.1	0.9	0.7	0.6	0.5	0.5
Gas	1.7	3.0	2.9	3.2	3.3	3.1	2.8	1.9	1.4	1.2	0.8	0.8
Nuclear	0.4	0.6	0.9	1.2	1.3	1.3	1.2	0.7	0.3	0.1	0.0	0.0
RenEl	0.5	1.2	1.8	2.6	3.8	5.2	6.9	9.2	11.9	13.1	14.0	14.7
Biomass	1.1	0.6	0.6	0.6	0.8	1.8	2.8	4.0	4.8	5.5	6.2	6.7
Total	9.1	10.0	10.9	12.0	13.3	14.4	15.9	17.4	19.4	20.7	21.9	23.0
MESSAGE												
Coal	2.1	2.2	2.3	2.3	2.1	1.7	1.5	1.4	1.2	1.0	0.7	0.6
Oil	3.3	3.3	3.2	3.0	2.9	2.6	2.7	2.3	2.1	1.7	1.3	1.0
Gas	1.7	2.0	2.5	3.1	3.6	4.0	3.9	3.8	3.3	2.7	2.4	2.1
Nuclear	0.4	0.5	0.6	0.7	0.7	0.7	0.5	0.5	0.4	0.3	0.1	0.0
RenEl	0.5	0.6	0.7	1.0	1.4	2.2	3.2	4.3	5.6	7.2	8.9	10.6
Biomass	1.1	1.2	1.3	1.4	1.6	2.0	2.5	3.1	4.0	5.0	6.0	6.5
Total	9.2	9.7	10.5	11.4	12.4	13.2	14.2	15.4	16.6	18.1	19.5	20.8

Table A.12.

Figure 14: Cumulative Fuel Consumption, 11R and MESSAGE, Gtoe.

Scenario H	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
COAL M	2.2	26.5	56.3	91.0	129.0	168.4	207.2	243.5	278.1	312.7	347.4	382.0
COAL 11R	2.2	22.7	42.4	61.5	80.0	97.6	113.3	128.8	148.7	175.4	208.0	249.4
OIL M	3.3	37.7	76.0	119.8	170.1	228.9	300.2	383.9	475.1	569.7	664.2	753.5
OIL 11R	3.2	34.7	74.4	128.6	192.8	263.3	337.1	409.1	482.2	555.1	624.5	697.2
GAS M	1.7	21.0	45.8	77.9	118.9	164.6	211.0	265.8	336.6	423.0	520.4	624.6
GAS 11R	1.7	29.8	70.5	115.7	169.2	231.4	305.8	399.1	499.2	593.2	681.5	766.0
Uran. M	0.4	5.3	11.3	19.2	31.0	49.2	74.7	105.8	141.5	183.6	236.1	301.9
Uran. 11R	0.4	5.8	13.5	25.2	42.6	64.9	90.5	119.8	154.4	197.0	250.8	316.8
Scenario R	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
COAL M	2.1	25.1	51.7	83.0	118.1	155.4	195.3	238.7	289.0	349.6	420.2	495.1
COAL 11R	2.2	22.6	41.1	58.6	79.3	107.9	143.8	187.8	241.9	308.6	392.0	491.3
OIL M	3.3	37.2	72.6	109.7	147.7	184.8	223.0	263.0	301.7	337.7	369.4	397.1
OIL 11R	3.2	32.2	62.9	100.0	139.2	177.7	215.2	252.6	285.7	314.4	344.4	373.5
GAS M	1.7	20.0	42.7	71.6	107.4	150.2	195.6	241.1	286.5	331.5	378.7	427.6
GAS 11R	1.7	28.2	65.8	106.7	151.0	198.3	250.4	305.1	359.9	411.0	451.5	484.0
Uran. M	0.4	5.3	11.4	19.3	30.7	47.5	71.0	103.0	143.5	192.7	251.8	325.3
Uran. 11R	0.4	5.5	12.5	23.1	37.6	55.9	79.6	111.4	153.9	207.3	271.5	346.5
Scenario L	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
COAL M	2.1	23.9	46.5	69.5	91.3	110.1	126.1	140.5	153.4	164.5	173.3	180.2
COAL 11R	2.2	22.2	39.9	55.8	70.5	84.2	96.1	105.1	110.1	113.2	116.2	119.1
OIL M	3.3	36.3	68.8	100.0	129.6	156.9	183.0	208.0	230.0	249.0	264.3	276.1
OIL 11R	3.2	32.9	61.4	91.1	119.0	140.6	154.6	164.4	172.4	179.0	184.7	190.0
GAS M	1.7	20.3	42.6	70.3	103.7	141.8	181.2	219.6	255.1	285.3	310.7	333.2
GAS 11R	1.7	24.9	54.2	84.5	116.5	148.3	177.7	201.2	217.5	230.1	240.2	248.6
Uran. M	0.4	5.3	10.7	16.9	23.9	31.2	37.4	42.3	47.0	50.7	52.8	53.5
Uran. 11R	0.4	5.8	13.6	24.5	37.2	50.3	63.0	72.6	77.6	79.7	80.5	80.8

Table A.13.

Figure 15: Total Electricity Generation: 11R, SG, MESSAGE.

Scenario H	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
11R	11.8	13.6	17.2	22.2	28.5	34.0	40.8	48.1	56.5	64.6	74.4	83.6
SG	9.7	12.0	14.9	18.5	23.4	28.8	35.9	44.6	55.7	68.7	82.9	98.1
MESSAGE	11.8	14.3	17.6	21.6	26.9	31.8	38.0	45.3	53.6	63.0	72.7	82.6
Scenario R	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
11R	11.8	12.7	15.3	19.2	24.1	28.8	34.9	41.1	48.5	55.9	63.1	70.6
SG	9.7	11.4	13.6	16.1	19.2	22.4	26.6	31.5	37.9	45.8	55.2	65.5
MESSAGE	11.8	13.5	15.9	19.1	22.9	26.8	31.0	36.5	43.0	51.3	61.1	74.8
Scenario L	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
11R	11.8	15.5	20.4	25.7	31.0	35.8	41.8	47.6	54.5	59.4	63.0	66.0
SG	9.7	11.0	12.6	14.4	16.5	18.9	22.0	26.0	31.3	38.0	46.2	55.3
MESSAGE	11.8	13.0	14.1	16.1	18.4	20.9	23.6	26.7	29.7	33.1	37.6	42.6

Table A.14.

Figure 16: Electricity Generation by Fuel in Scenario: 11R, MESSAGE.

Scenario H												
11R	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Coal	4.5	4.4	4.7	4.1	3.4	2.6	2.8	3.6	5.5	7.4	9.0	9.9
Oil	1.4	0.5	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gas	1.6	2.3	3.1	4.2	5.2	6.1	7.4	7.8	7.2	6.3	6.1	6.9
Nuclear	2.0	2.8	4.2	6.4	9.2	10.7	12.1	14.1	16.8	21.3	26.9	32.1
RenEl	2.3	3.6	5.2	7.6	10.6	14.5	18.5	22.7	27.0	29.7	32.5	34.7
Total	11.8	13.6	17.2	22.2	28.5	34.0	40.8	48.1	56.5	64.6	74.4	83.6
MESSAGE												
Coal	4.5	5.7	6.9	7.4	6.0	4.6	3.0	2.1	1.1	1.3	1.8	1.9
Oil	1.3	1.0	0.6	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Gas	1.6	2.0	2.8	4.1	6.4	7.0	9.1	12.3	16.7	20.6	21.9	24.1
Nuclear	2.0	2.3	3.0	4.0	6.2	9.0	11.7	13.5	14.9	17.1	20.7	24.9
RenEl	2.3	3.3	4.2	5.9	8.2	11.2	14.2	17.4	20.9	24.1	28.2	31.7
Total	11.8	14.3	17.6	21.6	26.9	31.8	38.0	45.3	53.6	63.0	72.7	82.6
Scenario R												
11R	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Coal	4.5	3.7	2.9	2.2	3.4	5.3	6.5	7.5	8.3	9.4	9.0	9.0
Oil	1.4	0.5	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gas	1.6	3.1	5.1	6.5	6.9	5.5	5.8	5.2	4.8	4.5	5.2	4.9
Nuclear	2.0	2.4	3.3	5.2	6.8	9.3	12.2	15.5	19.4	23.2	27.0	31.8
RenEl	2.3	3.0	4.0	5.4	7.0	8.7	10.4	12.9	16.0	18.8	21.9	25.0
Total	11.8	12.7	15.3	19.2	24.1	28.8	34.9	41.1	48.5	55.9	63.1	70.6
MESSAGE												
Coal	4.5	5.4	6.5	7.4	7.4	6.6	4.6	4.1	4.7	5.3	5.7	5.9
Oil	1.3	1.0	0.6	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.1
Gas	1.6	1.7	2.2	2.7	3.3	3.6	4.2	3.9	3.0	2.7	3.3	3.9
Nuclear	2.0	2.3	3.0	4.0	6.0	8.5	11.8	15.7	18.9	23.1	27.3	35.3
RenEl	2.3	3.1	3.7	4.7	6.1	8.1	10.3	12.8	16.4	20.2	24.8	29.5
Total	11.8	13.5	15.9	19.1	22.9	26.8	31.0	36.5	43.0	51.3	61.1	74.8
Scenario L												
11R	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Coal	4.5	3.9	3.7	3.0	3.6	3.4	2.7	1.2	0.0	0.0	0.0	0.0
Oil	1.4	0.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gas	1.6	2.7	4.1	5.6	4.4	3.1	2.9	2.1	0.1	0.4	0.2	0.4
Nuclear	2.0	2.8	4.2	5.5	5.8	6.0	5.5	3.1	1.4	0.5	0.2	0.1
RenEl	2.3	5.5	8.2	11.5	17.2	23.3	30.8	41.2	53.1	58.5	62.6	65.5
Total	11.8	15.5	20.4	25.7	31.0	35.8	41.8	47.6	54.5	59.4	63.0	66.0
MESSAGE												
Coal	4.5	4.9	5.1	4.6	3.6	1.8	0.7	0.2	0.2	0.4	0.5	0.4
Oil	1.3	1.0	0.6	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Gas	1.6	1.9	2.5	3.7	4.8	6.1	7.2	7.4	6.9	5.9	6.9	9.2
Nuclear	2.0	2.3	2.5	2.9	3.2	3.1	2.2	2.0	1.8	1.3	0.5	0.0
RenEl	2.3	2.9	3.4	4.5	6.6	9.9	13.4	17.2	20.8	25.5	29.6	32.9
Total, M	11.8	13.0	14.1	16.1	18.4	20.9	23.6	26.7	29.7	33.1	37.6	42.6

Table A.15.

Figure 17: Global energy related C-Emissions, GtC.

Scenario H	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
11R	6.1	6.6	7.4	8.3	9.5	10.4	11.1	12.3	13.3	15.0	16.8	18.1
MESSAGE	6.0	6.8	7.9	9.0	9.9	10.4	11.2	12.0	13.2	14.6	15.7	15.8
Scenario R	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
11R	6.1	6.6	7.4	8.3	9.5	10.4	11.1	12.3	13.3	15.0	16.8	18.1
MESSAGE	6.0	6.8	7.9	9.0	9.9	10.4	11.2	12.0	13.2	14.6	15.7	15.8
Scenario L	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
11R	6.1	6.3	6.4	6.8	6.9	5.8	4.4	3.4	2.8	2.3	1.3	1.2
MESSAGE	6.0	6.4	6.8	6.8	6.7	6.1	6.1	5.6	4.9	4.3	3.5	2.8

Table A.16.

Figure 18: Carbon intensity of primary energy, kgC/kgoe.

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
H	0.8	0.7	0.7	0.6	0.6	0.5	0.4	0.4	0.3	0.3	0.3	0.2
R	0.8	0.7	0.6	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.3	0.3
L	0.8	0.6	0.5	0.5	0.4	0.3	0.3	0.2	0.2	0.2	0.1	0.1

Table A.17.

Figure 19: Cumulative carbon emissions, GtC.

Scenario H	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
11R	6.1	72.9	153.6	248.7	356.6	474.5	600.9	737.8	884.6	1034.7	1184.7	1344.4
MESSAGE	6.0	72.9	153.5	248.2	356.4	474.5	600.5	737.3	886.2	1047.1	1217.6	1392.0
Scenario R	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
11R	6.1	69.6	139.5	217.7	306.6	406.0	513.4	630.2	758.0	899.6	1058.4	1232.7
MESSAGE	6.0	70.3	144.1	228.8	323.5	424.9	532.6	648.4	774.2	913.1	1064.4	1221.9
Scenario L	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
11R	6.1	68.0	131.0	196.7	265.1	328.5	379.1	417.9	449.0	474.5	492.5	505.3
MESSAGE	6.0	68.3	134.3	202.4	270.2	334.6	395.8	454.1	506.7	552.6	591.4	622.7