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Emulating a Long-Term Energy Scenario with the MERGE2 Model

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About the Author

Paul G.C. Mensink currently is a PhD-student at the Environmental Economics Group, Department of Social Sciences at Wageningen University, in the Netherlands. His thesis aims to contribute to the description and quantitative analyses of efficient decisions with regard to timing of greenhouse gas emission abatement and energy related emission reduction strategies.

Emulating a Long-Term Energy Scenario with the MERGE2 Model

Paul G.C. Mensink (Paul.Mensink@Alg.SHHK.WAU.NL)[*]

Abstract

An attempt is made to mimic a long-term global energy scenario, derived with IIASA's MESSAGE III model, with a version of Manne and Richels' MERGE2 model. If successful this would mean that MERGE2 could be used as an easy-to-handle-substitute for the MESSAGE III model to investigate preliminary research questions, meanwhile taking advantage of its relative consistent description the world's environment-energy-economy interactions.

It is concluded that the MERGE2R4 model, based on the MERGE2 model, could be both suitable and useful for investigating preliminary research questions to reduce time spent in exploring new research fields with the MESSAGE III model. The consistent description of interregional trade and feedback of climate damage and energy costs in the MERGE2R4 ensures that long-term energy and climate change issues in a broader research field can be assessed than with MESSAGE III alone.

This limited mimicking effort can be interpreted as a first stage of structural sensitivity analyses.

1 Introduction

The paper describes the adaptation of the long-term world energy-economy model MERGE2 (Manne and Richels, 1996; Manne and Richels, 1995) with the objective to emulate scenarios generated with the long-term energy model MESSAGE III (Messner and Strubegger, 1994; Messner and Strubegger, 1995). This was done to find out whether an adjusted MERGE2 model could be used as an easy-to-handle substitute for the MESSAGE III model in addressing preliminary research questions.

This report describes the two models in general as well as their differences and similarities (section 2). Section 3 elaborates on the motivation for this effort followed by a description of how MERGE2 model was adapted (Section 4). Section 5 depicts the output of the adapted MERGE2 model and the MESSAGE III model for one scenario. Finally, the conclusions drawn from the observations made are given in section 6.

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2 MERGE2 and MESSAGE III: two long-term energy models

2.1 Context of long-term energy modeling: global warming

When fossil fuels are being combusted, carbon dioxide (CO_2) – among other gases – is emitted. CO_2 remains in the atmosphere for a long time. Excess CO_2 upsets the energy balance of the atmosphere system by absorbing outgoing thermal radiation. Higher concentrations of CO_2 and other radiatively active gases – in the absence of major negative feedbacks and when the energy balance is in equilibrium – lead to a higher mean temperature of the atmosphere. This is called the greenhouse effect.

Previous anthropogenic greenhouse gas emissions are considered to have already influenced the climate system[1] leading to the expectation that the future greenhouse gas emissions will have a significant impact on climate change. This potential man-made climate change could have a large negative impact on human society, for example by causing the sea level to rise or by worsening the weather circumstances for farming.[2]

Most of the anthropogenic CO_2 emissions originate from the combustion of fossil fuels. To assess the issue of climate change originating from the ongoing build up of CO_2 and other greenhouse gases, long-term global energy models have been developed. Some of these models describe the build up of greenhouse gases and resulting climate change on a high aggregation level. Later models are referred to as integrated assessment models (Kelly and Kolstad, 1998; Weyant *et al.* (1996); Parson and Fisher-Vanden, 1997). In order to assess potential responses to climate change, one can refer to Weyant *et al.* (1996, p. 376) who identifies three purposes of integrated assessment.

1. By (i) projecting consequences of particular policy responses, (ii) comparing costs of responses and the severity of impacts they are intended to prevent and (iii) comparing the relative effects and cost of different responses to meet a different target (see for example Hourcade and Richels *et al.*, 1996, and Hourcade and Halsnæs *et al.*, 1996).
2. By promoting a broad view of the issue and providing a representation of uncertainties and a prioritization of those that are most important in practical terms.
3. Addressing the question how important the global warming issue is relative to other matters of human concern.

2.2 Description of the models MERGE2 and MESSAGE III

2.2.1 MERGE 2

The MERGE family of models (Manne, Mendelsohn and Richels, 1995; Manne and Richels, 1995; Manne and Richels, 1999) consists of the most widely used long-term energy-climate models based on an economic methodology that combines the description of international trade, costs of energy conversion and climate change, and an explicit bottom-up description of the energy sector.

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[1] "The balance of evidence suggests a discernible human influence on global climate [via emissions of radiatively active gases] " (IPCC, 1996*b*, p. 5).

[2] For an overview of results from research in the area of climate change see IPCC (1996*b*).

MERGE2, developed by Manne and Richels (1995), is a dynamic general equilibrium model that generates Pareto optimal paths of investment and (energy) production over more than 10 decades, given the following inputs: potential gross domestic product, population, and (energy) production technologies for five world regions. The amount of fossil fuels burned determines emissions of CO_2, CH_4 and N_2O. Prices are determined from the equilibrium between supply and demand in the markets of internationally traded goods: oil, gas, coal, an aggregate non-energy good and emission permits. Two types of final energy are being produced using 20 different technologies and types of primary energy sources. World mean temperature change, a function of the concentrations of CO_2, CH_4 and N_2O in the atmosphere, has a negative impact on GDP.

2.2.2 MESSAGE III

MESSAGE III, a bottom-up energy systems model, is a dynamic linear programming model of the energy system on the technology level that describes cost-efficient energy-related generation and investment decisions in eleven world regions. The technology descriptions consist of the technical parameters (efficiency, plant life), economic parameters (investment, operation and management costs), and environmental effects related to the use of the technology (Messner, 1995, p. 3).

2.3 Similarities between MERGE2 and MESSAGE III

Due to the main characteristics of the global warming issue, long-term energy models have a number of characteristics in common. This also holds for the MERGE2 and MESSAGE III models. The most important similarities between the two models are:

Time horizon: Due to the long lifetime of greenhouse gases in the atmosphere and inertia of the climate system, energy models used for climate change assessments in general describe energy production and consumption for a very long time period. A reasonable minimum for the time horizon of such models is 100 years.

Regionalized world: The effect of greenhouse gases on the climate system is, in the long run, independent of the region where they are emitted, i.e., greenhouse gases are perfect mixing pollutants. Therefore, analysis of the climate change issue usually takes a global perspective. Both models thus describe the *global* energy system.

They also disaggregate the globe into a number of world regions because the economies and so the energy systems of different regions in the world tend to have different characteristics. Modeling results describing several world regions also appeal better to potential decision makers.

Rational behavior: Usually actors such as world regions show cost minimizing and clairvoyant behavior. This means that it is assumed that the peoples of the world are clairvoyant with regard to future options to choose from with respect to energy technology options and tend to act in a cost efficient and therefore rational – from an economic perspective – way.

2.4 Differences between MERGE2 and MESSAGE III

The most relevant differences between MERGE2 and MESSAGE III are:

Detail of energy conversion technologies: Where MERGE2 allows for 20 different energy conversion technologies to generate two final-energy forms, i.e., electric and non-electric energy, MESSAGE III describes over 300 energy conversion technologies and includes primary energy, final energy and useful energy. Also investments in technology infrastructure are implicitly modeled in MESSAGE III.

Climate system: The MERGE2, in contrast to the MESSAGE III model, includes a simple global climate module and a climate change damage function.

Economic feedbacks: In the MESSAGE III model, useful energy demand is exogenous whereas in the MERGE2 model, energy demand is endogenous: in MERGE2 energy demand is influenced by GDP that in turn is determined endogenously, among other factors, by the costs of energy conversion and the costs caused by damages from climate change.

Regional dimension: The MERGE2 model describes energy-related variables in five world regions whereas the MESSAGE III model describes energy-related variables for eleven world regions. MERGE2's successor, MERGE3, includes nine world regions (Manne and Richels, 1999, p. 2).

Trade: The MERGE2 model is a dynamic general equilibrium model where each of the five geographical regions corresponds with one actor in the general equilibrium framework. Therefore interregional trade flows and prices of oil, gas, coal, the consumption good and carbon emission permits are endogenous and are determined by demand and supply of the different regions.

Size and running time: Due to the difference in level of detail of the description of the energy sector, the running times and the time to construct new scenarios differ in favor of the MERGE2 model. To solve MERGE2 takes approximately 1 hour on a PC with a Pentium 90 processor (DOS) and 12 minutes on a typical IIASA UNIX machine.

Due to these different characteristics each of these two models models has its advantages: MERGE2 is more suitable when questions related to the overall economy are to be addressed and MESSAGE III is more suitable for detailed analyses of the developments of the energy conversion sectors.

3 Motivation for emulating MESSAGE III scenarios

As outlined in sections 2.3 and 2.4 the similarities and differences of the MERGE2 and MESSAGE III models give rise to their comparative advantages. To make the best use of the advantages was the motivation to attempt to make the results of the two comparable: If one succeeds in generating the same kind of energy conversion scenarios with the MERGE2 model as with the MESSAGE III model one can:

1. Use the MERGE2 model as a relatively small substitute for the MESSAGE III model and thereby reduce the efforts needed to accomplish preliminary analyses before, more time is invested in assessing more detailed research questions with the MESSAGE III model.
2. Assess, with MERGE2, the effects of costs of different energy strategies, as determined by MESSAGE III, and costs of climate change on economic growth and energy demand in a relatively consistent way.

4 Adapting the MERGE 2 model: MERGE2r4

4.1 Standardizing the inputs: the A1B scenario

To find out whether it is possible to emulate MESSAGE III scenarios with the MERGE2 model the decision was made to emulate the MESSAGE III-A1B scenario. The A1B scenario is one of the scenarios contributed by IIASA to the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (Working Group III of the IPCC, 2000).

In the A1B scenario world primary energy production between 1990 and 2050 quadruples and and annual world CO_2 emissions triple between 1990 and 2050. These trends are driven by a 60% rise in world population and a five-fold increase in per capita GDP in that same period. Between 1990 and 2050 energy intensity drops approximately 45% and carbon intensity 30%.

It was assumed that this scenario would be a good indicator for testing the hypothesis whether the MERGE2 model is well-suited for emulating MESSAGE III scenarios. The A1B input assumptions are rather extreme with respect to (energy) consumption growth. It was assumed that if A1B scenario could be emulated, relatively middle-of-the-road scenarios could be emulated as well.[3]

The general strategy to tackle the task was to first emulate with MERGE2 the development over time of world final energy shares for electricity, natural gas, liquid fuels and solid fuels in the MESSAGE III-A1B scenario. After mimicking the development of final energy shares as well as possible we compared the output of both models with respect to CO_2 emissions and primary energy production. The results of these steps are described in the following subsection.

4.2 Steps taken to emulate the MESSAGE III – A1B scenario

As a result of the many changes the resulting model was labeled with a new name-MERGE2R4. The MERGE2R4 model has been made available both in DOS format as well as in Unix format. An Excel interface was programmed to ease interpretation and comparison of the output.

In order to emulate the shares of final energy in particular and the MESSAGE III-A1B scenario. The following steps were taken:

1. Dimension:
   The MERGE2 model was re-regionalized from five world regions (USA, OtherOECD,

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[3] The assumptions with regard to the main driving forces of the A1B scenario are summarized in appendix A.

former Soviet Union, China, and a region representing the rest of the world) to four (OECD, Reforming economies of the Former Soviet-Union and Eastern Europe, Asia, and Non-Asian developing countries – Latin-America, Africa and Middle-East) regions.

2. Exogenous variables:
   Based on the new regionalization, driving forces such as population growth, GDP growth and energy intensity development defining the A1B scenario were included in MERGE2 as well as other input data. Hydrocarbon resources assumptions were based on MESSAGE III resource assumptions that in turn are based on Rogner (1997). For details see appendix B.1.

3. Parameters:
   Parameters, which in MERGE2R4 determine the substitution between oil and gas – such as the oil-gas price differential and several parameters constraining oil and gas exploration and production – were changed to fine-tune the final energy share development in MERGE2R4 to make its final energy share development as similar as possible to the development according to the MESSAGE III model. See appendix B.2 for details.

4.3 A methodological thought

In this section, the argument is made that the emulation effort in fact can be interpreted as two intertwined forms of structural sensitivity analysis.

Steps 2 and 3 in section 4.2 can both be interpreted as part of a form of structural sensitivity analysis in the following sense.

If one interprets a model M_i (when MESSAGE III is called M_1 and MERGE2 is called M_2) as a function f_i that maps exogenous (input) variables (such as population growth or a carbon constraint) in domain D_i on output variables (like for example regional energy consumption) in range R, or formally

$$f_i : D_i \rightarrow R,$$

step 1 can be described abstractly as redefining $f_2(\cdot)$ such that its domain becomes equal to D_1.[4] The resulting function is defined as $f_2'(\cdot)$.

This notation helps to clarify why steps 2 and 3 can be interpreted as part of a form of structural sensitivity analysis.[5]

- In step 2 exogenous variables in the MERGE2 model are made equivalent to exogenous variables in MESSAGE III. Therefore step 2 is the first stage of a form of structural sensitivity analysis where the difference between y_1 and y_2 is analyzed, where

$$y_1 = f_1(d_1; \theta_1) \qquad \text{and} \qquad y_2 = f_2'(d_1; \theta_2),$$

---

[4] It would be more appropriate to distinguish between R_1 and R_2 because MERGE2/MERGE2R4 and MESSAGE III have different ranges. For reasons of convenience however, I assume in this subsection that both have the same range. This simplifies argumentation and does not alter the conclusion in this subsection.

[5] Structural sensitivity analysis is defined here as the sensitivity of model results with respect to changes in the set of equations and the equations itself. An equation is here considered to be a combination of an equation type and the value of its parameters.

with θ_i is the set of parameters in model M_i, and $d_1 \in D_1$.[6]

This form of structural sensitivity analysis resembles the model results comparison approach chosen by the Energy Modeling Forum (Gaskin and Weyant, 1993).

In this form of structural analysis, differences between y_1 and y_2 are the result of differences between the model structures (i.e. the set of functions, the function types and the parameters).

- In step 3 parameters in MERGE2 are changed to mimic the output of MESSAGE III model. Therefore step 3 can be interpreted as the first stage of a form of structural sensitivity analysis where differences between y_1 and y'_2 are being analyzed with y'_2 defined as

$$y'_2 = f'_2(d_1; \psi) \qquad \text{with}$$

$$\psi = \arg\{\min_{\varphi} ||f_1(d_1; \theta_1) - f'_2(d_1; \varphi)||\}$$

ψ is thus the result of "running the model backwards", i.e., finding parameters that generate a given output rather than finding the output that is the result of given parameters and exogenous variables. In this form of structural analysis, differences in results are entirely the result of differences between the set of functions and the function types, and not the parameter choice.

In theory these two modeling approaches answer different questions with regard to the sensitivity of model results for the chosen model structure. In practice, unfortunately, it turned out to be difficult to make a clear distinction between parameters and exogenous variables on the one hand, and equation type and parameter on the other hand. Therefore, and because of the limited effort made with regard to mimicking the MESSAGE III scenario, it is not possible to derive conclusions with regard to sensitivity of model results to the model structure or parameters at this point. Nevertheless, the modeling and mimicking effort, however limited, can be interpreted as the first step in a process of deriving the sensitivity of model results for changes in the model structure.

5 Comparing the MESSAGE III and MERGE2r4 scenario

5.1 Comparing energy consumption and CO_2 emissions

5.1.1 Final energy

As discussed in section 4 our emulation effort focused on the development of final energy shares in the world over time. After re-regionalizing, adapting the input data and a minor adaptation of parameters describing the substitution between oil and gas, the development of final energy shares as determined with the MERGE2R4 and the MESSAGE III is as shown in figures 1 and 2. Both show ongoing substitution of flexible, convenient and clean grid-delivered final-energy carriers such as electricity and gaseous fuels (Grübler *et al.*, 1995, §5.6) for solid fuels over time.

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[6] Parameters, in contrast with exogenous variables, are defined here as those constants in a model that are estimated given the structure of the model, i.e., determined in a process of calibration.

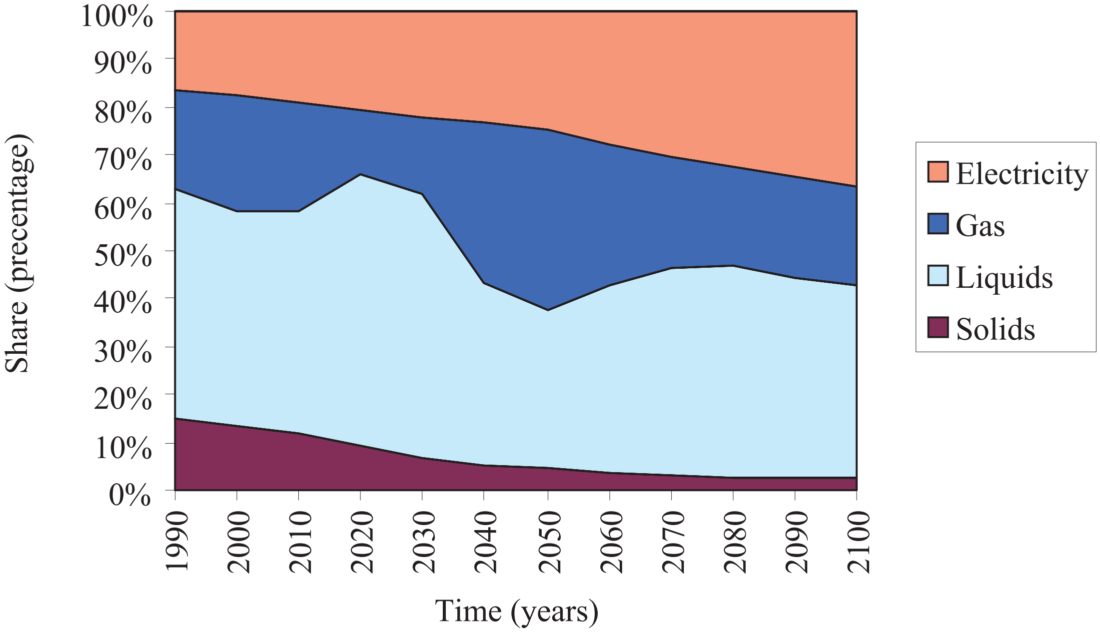

Figure 1: Final energy shares for the world as determined with the MERGE2R4 model given the A1B input assumptions

The three most important remaining differences between both final energy share scenarios are:

- The evolvement over time of energy shares, especially those of gas and liquids, in the MERGE2R4 model are less smooth than in the MESSAGE III scenario.

  Explanation: the "wave form" in the consumption of liquid fuels between the years 2020 and 2070 in MERGE2R4 is caused by a peak in oil consumption around 2020 that is followed by the introduction of liquid fuels from coal with a delay. Production from the latter source peaks at the end of the century. Eight unsuccessful attempts were made to smooth these developments with the help of the parameters describing oil-gas substitution and the extraction of fossil resources.

- The share of solid fuels in 1990 and in the beginning of the next century is significantly higher in the MESSAGE III run.

  Explanation: this difference is caused by the fact that non-commercial energy from biomass is not accounted for in the MERGE2R4 model and is included in the category solid fuels in the MESSAGE III model.

- The category "other final energy" is positive in the MESSAGE III run and zero in MERGE2R4 output.

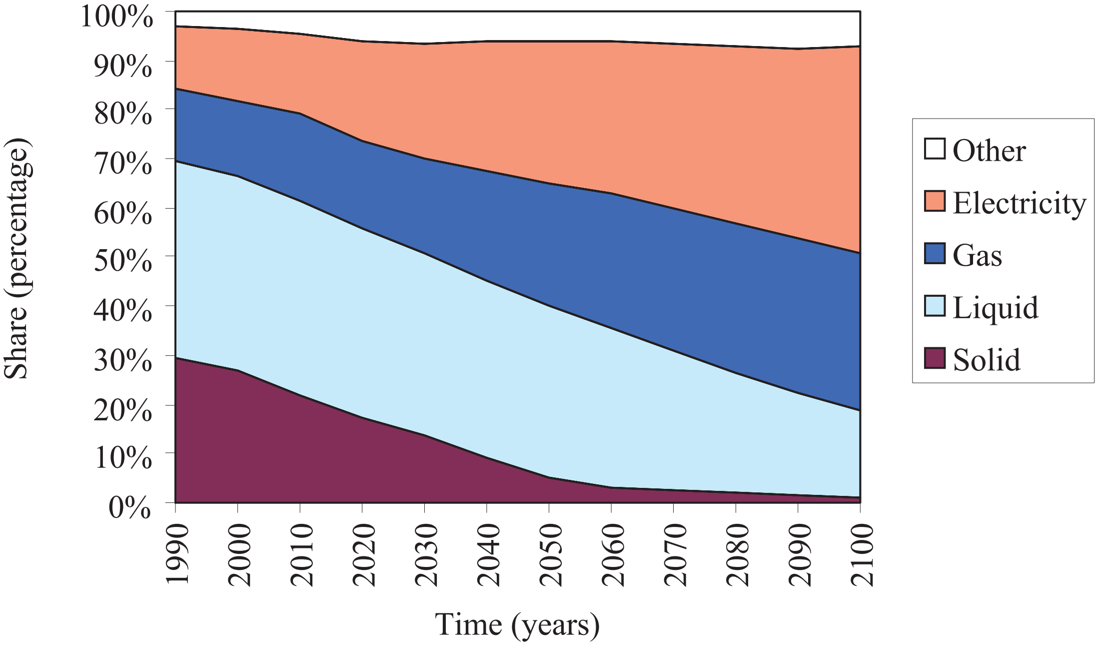

Figure 2: Final energy shares for the world as determined with the MESSAGE III model given the A1B input assumptions.

> Explanation: other final energy in MESSAGE III is heat. MERGE2R4 does not account for heat consumption and production explicitly. In the MERGE2R4 model energy in the form of heat is part of the electricity and the non-electric energy variables.

5.1.2 Primary energy

Final energy is generated by converting primary energy. Primary energy sources can be fossil fuels, biomass, or other carbon-free sources. Figures 3 and 4 depict energy production development in both model outputs per primary energy source as background information for the previous paragraph. Energy production is higher in the MESSAGE III scenario, partially due to the fact that oil and non-carbon energy production in MERGE2R4 is expressed in units of final energy (MERGE2R4 does not explicitly describe primary energy production for all primary energy sources). This is also the reason why the quantities in both models can hardly be compared in the framework of our emulation exercise. A full explanation of the differences is further hampered by the many different ways, especially for carbon-free resources, primary energy can be defined.

The developments of the shares of energy production expressed in terms of their primary energy sources are depicted in the figures 5 and 6. Again it is stressed that the quantities in both figures can not be compared directly for reasons already given.[7]

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[7] For the development of primary energy shares in a historic perspective see Grübler *et al.* (1995, §5.2).

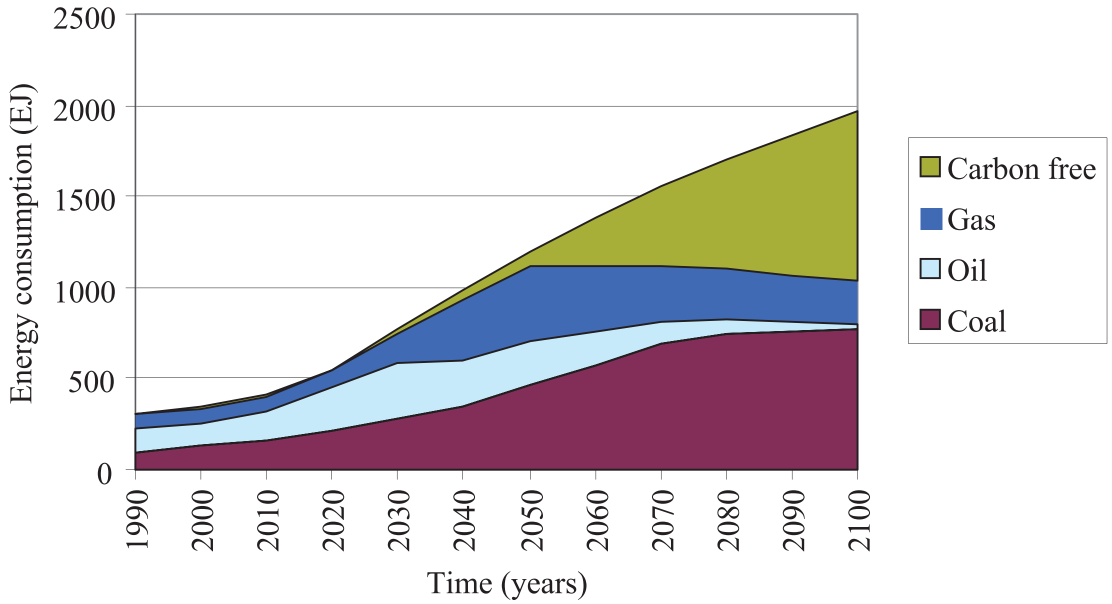

Figure 3: Energy production for the world as determined with the MERGE2R4 model given the A1B input assumptions. Oil and non-carbon based production expressed in terms of final energy. Other energy production quantified in terms of primary energy.

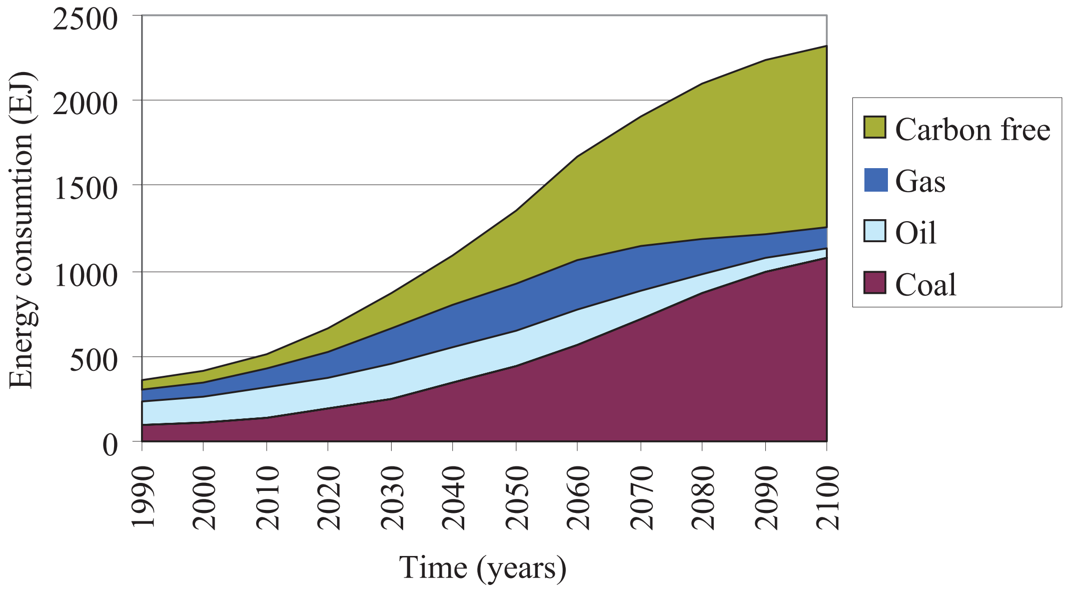

Figure 4: Energy production for the world as determined with the MESSAGE III model given the A1B input assumptions. All energy production quantified in terms of primary energy.

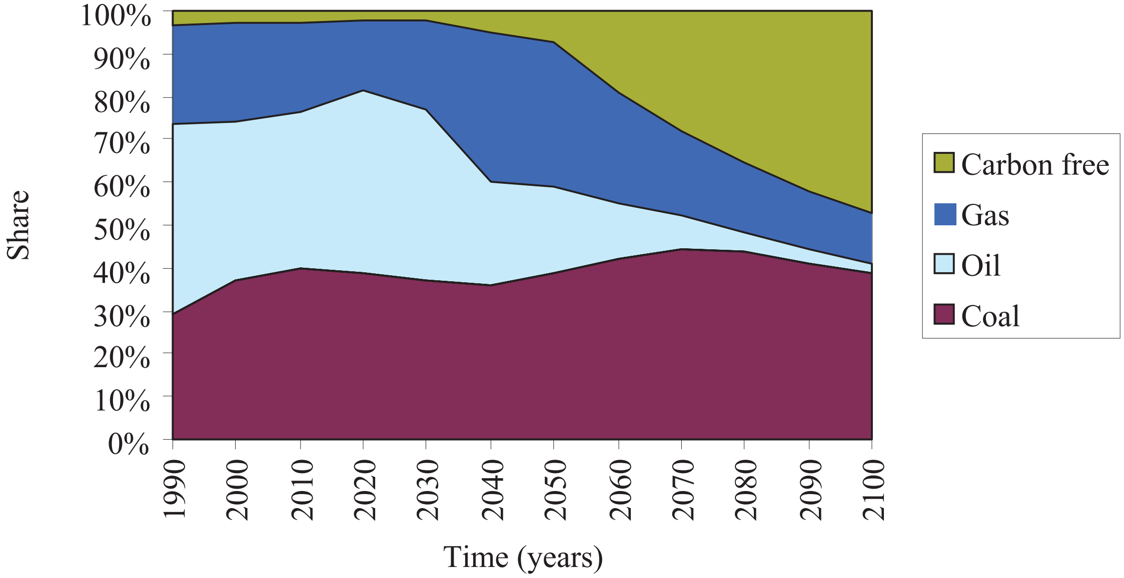

Figure 5: Energy shares for the world as determined with the MERGE2R4 model given the A1B input assumptions. Oil and non-carbon based production expressed in terms of final energy. Other energy production quantified in terms of primary energy

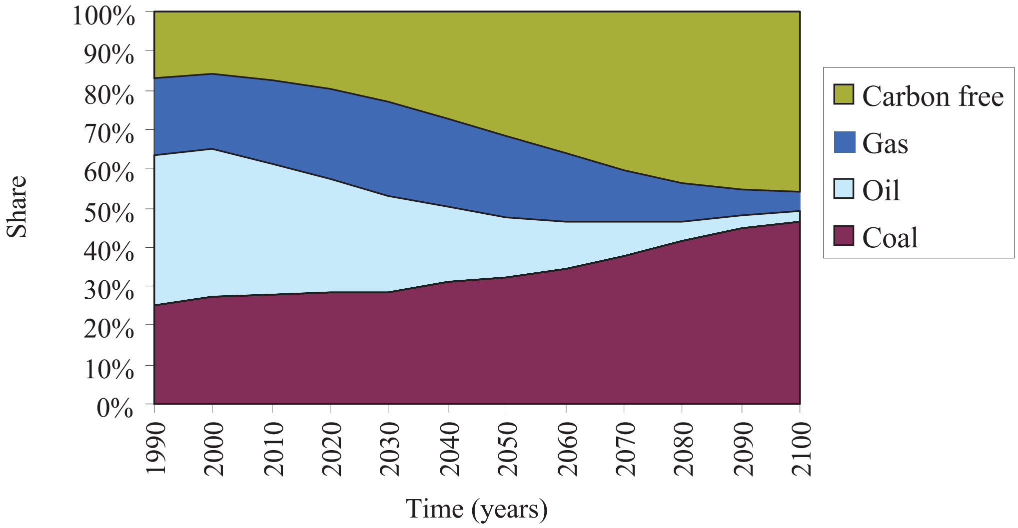

Figure 6: Energy shares for the world as determined with the MESSAGE III model given the A1B input assumptions. All energy production quantified in terms of primary energy

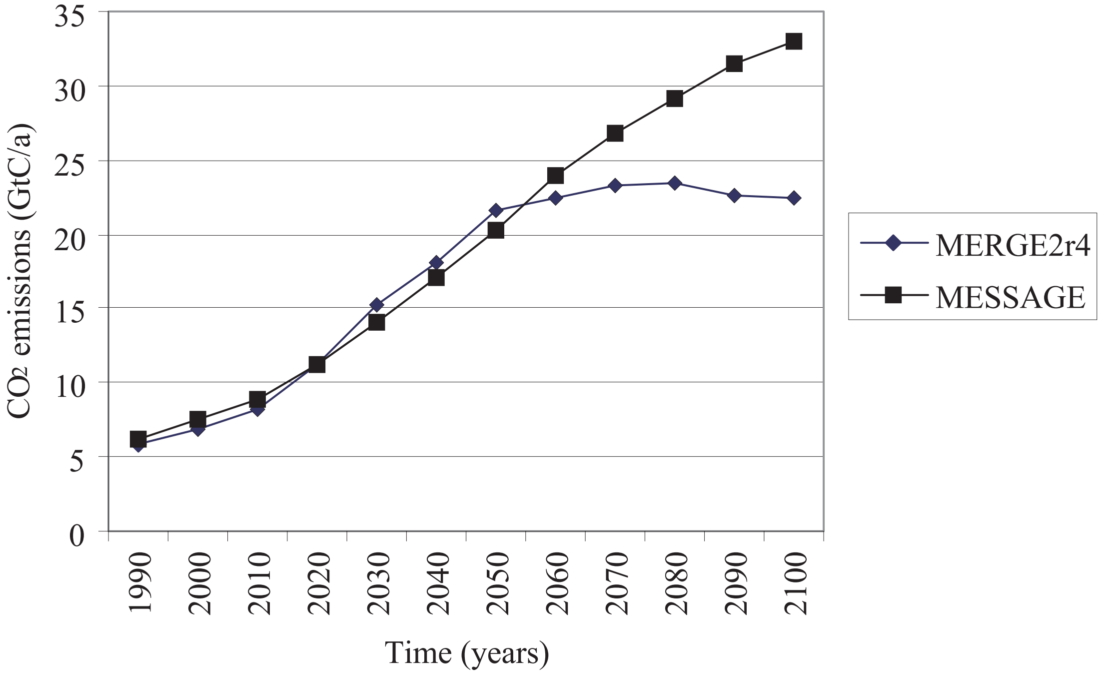

Figure 7: CO_2 emissions as determined with MESSAGE III and MERGE2R4 given the A1B input assumptions.

A closer look at the shares of primary energy sources in the generation of electricity revealed that a large amount of substitution of carbon-free resources for fossil fuel-based electricity generation techniques takes place during the second half of the 21^{st} century. This makes clear that the MERGE2R4 model, though not capable of describing technological change endogenously (for example, the price of energy from a technology does not depend on the capacity installed, like it does in some versions of MESSAGE III), can describe large shifts in the shares of energy conversion technologies by assuming falling exogenous electricity conversion costs for carbon-free technologies over time.

5.1.3 CO_2 emissions

The combustion of coal, oil and natural gas in both model runs results in CO_2 emissions as depicted in Figure 7. Emissions of CO_2 as described by both models are close to each other until the year 2050. After that time the relatively larger share of carbon-free resources and flattening share of coal in the MERGE2R4 scenario, both relative to the MESSAGE III scenario, causes the CO_2 emission paths to diverge.

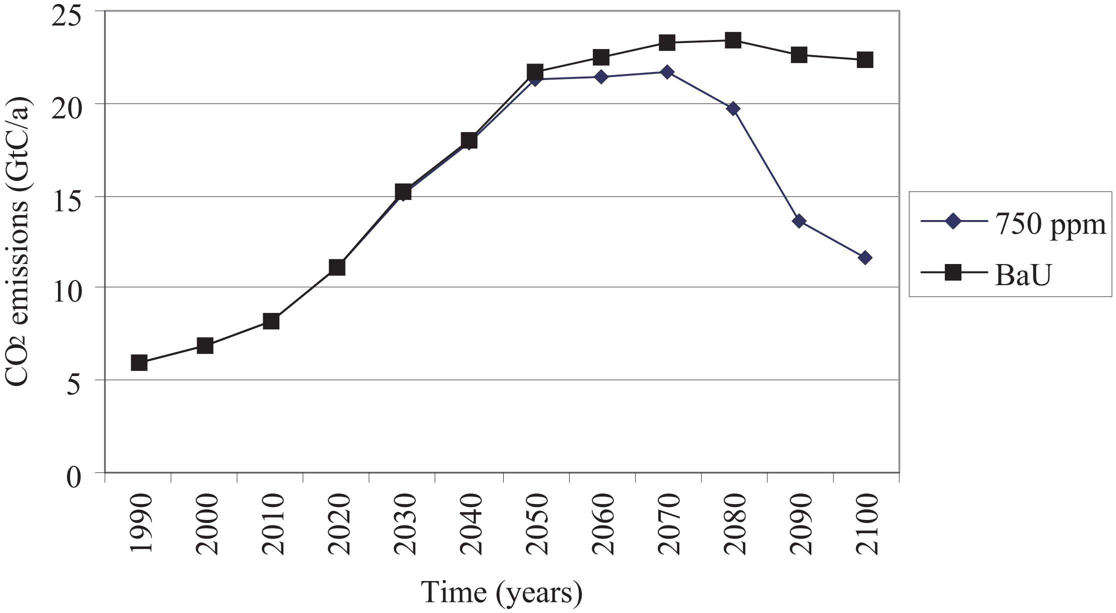

Figure 8: CO_2 emissions determined with the MERGE2R4 scenario for a non-intervention and a 750 ppm concentration stabilization cases given the A1B input assumptions.

5.2 MERGE 2's extras

As discussed in section 2.4, both models include to some extent different characteristics that differ in attractiveness in relation with the objective the models are used for. In the context of the question what extras the MERGE2R4 could offer relative to the MESSAGE III model, ignoring potential disadvantages at this point, two new runs with the MERGE2R4 model were done: (i) a CO_2 concentration stabilization run to stress the advantages of the availability of a climate module and (ii) a run where carbon emissions of the OECD countries were limited to 80% of 1990 emissions by the year 2010, without allowing for carbon emission permit trade, to show the implications of such a reduction scheme on the market of fossil fuels.[8]

Ad (i). In figure 8 the emissions of CO_2 in the stabilize-CO_2-at-750ppm case are shown together with CO_2 emissions in a non-intervention case. Due to the availability of a climate module and the intertemporal optimization characteristics of the MERGE2R4 model, an intertemporally efficient emission reductions path has been determined.[9]

Ad (ii). For this case CO_2 emissions in the OECD were constrained by the year 2010 to a level of 20% lower than their 1990 emission level, without allowing for carbon emission trade. Figure 9 shows the difference between emissions in this run and a non-intervention run.

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[8] Carbon emission permit trade could have been allowed in this model but was not.

[9] For a discussion on the interpretation of the term 'intertemporal efficiency' see Arrow *et al.* (1996) and O'Riordan (1997).

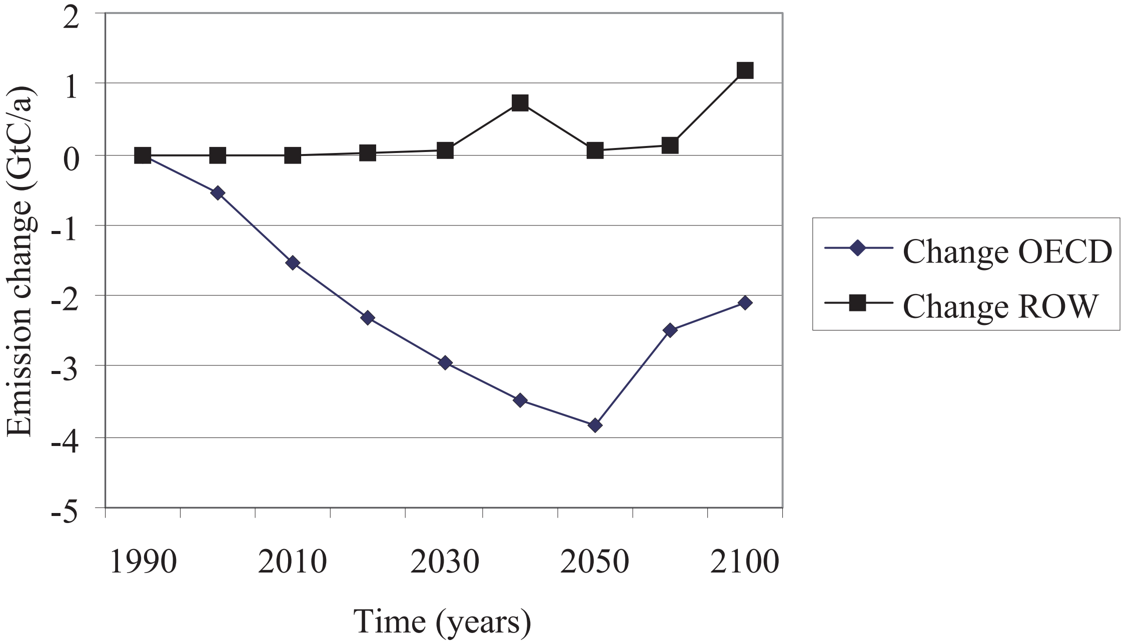

Figure 9: Difference in CO_2 emissions between a non-intervention case and a unilateral emissions reduction in the OECD case as determine with the MERGE2R4 given the A1B input assumptions.

Total world emissions between 1990 and 2050 are 16% lower in the constrained case compared to the non-intervention case. By definition CO_2 emissions in the constrained case in the OECD are lower than CO_2 emissions in the non-intervention case. Emissions in the non-OECD countries, however, are slightly higher in the constrained case. The higher emissions in the non-OECD countries in the constrained case are caused by lower demand for fossil fuels in the OECD. This lower demand forces prices of fossil fuels on the world market downward. These lower prices in turn push demand for fossil fuels in the rest of the world upward, causing emissions of CO_2 to rise in the rest of the world. This is part of an effect that is called carbon leakage.[10]

Reprogramming of the MERGE2R4 model for both runs took approximately 5 minutes. Therefore the extras come with hardly any effort.

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[10] Only the price-based carbon leakage effect is described in the MERGE2R4 model. For a full discussion of the different channels allowing for carbon leakage and numerical analyses of carbon leakage see Manne (1994), Felder and Rutherford (1993) and Richels and Sturm (1996).

6 Concluding observations

The following observations were made from the comparison of the outputs of the MERGE2R4 model and MESSAGE III model.

1. Overall resemblance between model results has been achieved.
2. Resemblance between trends in final energy share development of MESSAGE III were improved by manipulation of a key parameter – given equalized driving forces and assumptions with regard to fossil fuel reserves and resources – without giving up much of the resemblance between their respective primary energy share development over time and CO_2 emission paths (section 5).
3. The MERGE2R4 model runs in 1 hour on a PC with a Pentium 90 microprocessor and in 12 minutes on IIASA's Unix machine. Due to its structure and size MERGE2R4 can be reprogrammed very fast if alternative runs do not ask for fundamental (for example methodology related) changes (sections 4 and 5.2).
4. Though MERGE2R4 does not describe technological change endogenously it is able to describe radical changes in shares of energy technologies (section 5.1.2).

Based on these observations, keeping in mind the macro-economic characteristics of MERGE2 type of models as described in section 2.2.1, the conclusion that the MERGE2R4 model, based on the MERGE2 model (Manne and Richels, 1995), could be both suitable and useful for investigating preliminary research questions to reduce time spent in exploring new research fields with the MESSAGE III (Messner and Strubegger, 1994) model. the MERGE2R4 model includes interregional trade, feedback of climate change damage costs, and energy costs. Therefore with the MERGE2R4 and the MESSAGE III model together long-term energy and climate change issues can be assessed in a broader research context than with MESSAGE III alone.

A Appendix A: The A1B scenario

In this appendix a quantitative description of the development of the main driving forces of the A1B scenario are given. The names of the regions are abbreviated to OECD, REFS (Former Soviet-Union and Eastern Europe) ASIA, and DEVS Non-Asian developing countries (Latin-America, Africa and Middle-East).

Potential GDP growth:

```
TABLE GROW(*, * )  POTENTIAL GDP GROWTH RATES - ANNUAL PERCENT
      OECD  REFS  ASIA  DEVS
1990  2.30  -3.1  6.05  3.57
2000  2.19  2.25  7.94  5.00
2010  2.12  7.70  8.81  8.33
2020  2.04  9.90  7.25  7.39
2030  1.91  5.69  5.13  5.54
2040  1.75  2.97  3.81  4.54
2050  1.65  2.29  3.13  2.94
2075  1.57  1.76  1.75  1.80
2100  0.80  0.80  1.00  2.00
```

Energy intensity decline Energy intensity of a system or region is measured as energy requirement per unit of economic activity. The energy intensity of a region for example can be measured by its primary energy consumption including noncommercial energy divided by its gross domestic product (Grübler *et al.*, 1995, p. 15).

The "autonomous energy efficiency" improvement (AEEI) in the MERGE2 model summarizes all non-price related sources of reductions in the economy-wide energy intensity per unit of output (Manne and Richels, 1992, p. 32).

```
TABLE AEEI(*,*) AUTONOMOUS ENERGY EFFICIENCY IMPROVEMENT - PERCENT PER YEAR
      OECD  REFS  ASIA  DEVS
1990  0.82 -0.37  2.07 -0.71
2000  1.16  1.38  3.83  1.43
2010  1.39  4.90  4.84  3.98
2020  1.02  6.57  3.65  3.11
2030  1.01  4.22  2.77  1.68
2040  0.94  2.27  1.28  1.52
2050  0.87  1.65  1.53  0.95
2075  0.73  1.45  1.22  0.80
2100  0.26  0.26  0.32  0.64
2125  0.26  0.26  0.32  0.64
2150  0.19  0.19  0.26  0.32
2175  0.19  0.19  0.26  0.32
2200  0.19  0.19  0.26  0.32
```

Population

```
TABLE POP(*,*)  REGIONAL POPULATION IN BILLIONS
      OECD  REFS  ASIA  DEVS  WORLD
1990  0.85  0.41  2.79  1.19  5.26
2000  0.91  0.41  3.26  1.51  6.11
2010  0.96  0.42  3.62  1.87  6.88
2020  1.00  0.43  3.93  2.24  7.61
2030  1.04  0.43  4.14  2.55  8.18
2040  1.06  0.43  4.23  2.79  8.53
```

2050	1.08	0.42	4.22	2.98	8.70
2075	1.09	0.38	3.72	3.09	8.29
2100	1.11	0.33	2.88	2.72	7.05
2125	1.11	0.33	2.88	2.72	7.05
2150	1.11	0.33	2.88	2.72	7.05
2175	1.11	0.33	2.88	2.72	7.05
2200	1.11	0.33	2.88	2.72	7.05

B Adapting the MERGE2 model: details

B.1 Adapting inputs: driving forces and hydrocarbon resources

In this appendix changes of the input data of the MERGE2R4 model – necessary to let the input data of the model resemble the input assumptions of the MESSAGE III-A1B scenario – are being discussed in more detail. Adjustments that need more attention when further runs are made are marked with (*) at the beginning of the description. The adjustments are categorized based on the input file structure of the MERGE2R4 model.

B.1.1 Macro.tab

- I assumed for the initial capita/GDP ratio 2.65 for the OECD region and 3 for the other regions. Original MERGE2 data: USA 2.65; Other OECD 2.8; and other regions 3. This parameter is used used to the value of invested capital in 1990.

- (*) The ELVS parameter is defined as the share of the value of electricity produced in the value of total energy production, due to the Cobb-Douglas form energy sub-production function in the nested CES production function.

  I maintained the original values for the electric value share in 1990:

	OECD	REFS	ASIA	DEVS
ELVS	0.40	0.40	0.40	0.40

  MESSAGE III has the following implicit ELVS data in the base year:

AFR	CPA	EEU	FSU	LAM	MEA	
ELVS	.387	.400	.430	.362	.330	.276
NAM	PAO	PAS	SAS	WEU	CWM	
ELVS	.420	.480	.299	.340	.422	.443

- For the international oil price in 1990 (INTPR) I assumed \$3.7/GJ for the OECD and \$3.4/GJ (22\$/boe) for the rest of the world was chosen. These assumption are based on MERGE2 input data.[11]

  The non-electric reference price for 1990 (PNREF) was set equal to \$4.25/GJ for the OECD. This estimate was loosely based on MERGE2 input data.

  Accordingly, the tax for non-electric energy (XNTAX) for OECD was set at \$0.75/GJ. This parameter is loosely based on MERGE2 input data. Other values for XNTAX as

---

[11] '\$' in this paper is an abbreviation of "US 1990 dollars".

in MERGE2. The choice of the parameters INTPR and PNRF for Asia demand a closer look.[12]

- Maximum decline rates of the amount of energy generated with traditional technologies and the maximum expansion rates of the amount of energy generated with advanced technologies are maintained as in the MERGE2 model.
- The income elasticity of coal consumption (CLGDP) in MERGE2 is 0. Adopting volume of -0.5 for this parameter MERGE2R4 implies coal is assumed to be an inferior good, i.e., it reflects the relative inconvenience of this energy carrier, a feature that was built into MESSAGE III.
- GDP growth as in the A1B scenario. I.e. I defined the input variable "potential GDP" in MERGE2R4 to be equal to the GDP as determined based on the GROW variable as depicted in section A. GDP itself is an endogenous variable in MERGE2R4. In the reference case of Manne and Richels (1995) the potential GDP and the endogenous GDP differ approximately 3% at the maximum by the year 2100 for each region.
- Energy intensity decline rates are relatively high in the A1B scenario, especially in the REFS region.

B.1.2 Trade.ref

- We limited gas imports for ASIA and DEVS as in MERGE2 because it is not expected beforehand that DEVS (that includes many OPEC countries) and ASIA (relatively high transportation costs) will be major natural gas importing regions. An analysis of the shadow prices of the associated constraints will give an indication for the realism of this constraint.

```
 TABLE GASM(*,*) GAS IMPORT LIMITS (EXAJ)
          OECD     REFS     ASIA     DEVS
2000      4.7      1000      1         0
2010      1000     1000      1         0
2020      1000     1000      1         0
2030      1000     1000      1         0
2040      1000     1000      1         0
2050      1000     1000      1         0
2075      1000     1000      1         0
2100      1000     1000      1         0
```

B.1.3 Elec.tab

The file elec.tab contains electric energy price and potential capacity assumptions.

- The electricity production capacities for 1990 were extracted from the MESSAGE III input files. I included the MESSAGE III categories Biomass and RenElec in the MERGE2R4 category Hydro (existing carbon-free technologies)

---

[12] INTPR, PNREF and XNTAX are used for calibration of the nested CES production function on 1990 data.

```
TABLE   ECAP(*, * , ET)  ELECTRICITY PRODUCTION CAPACITIES - TkWh/yr
             HYDRO   GAS-R  GAS-N   OIL-R    COAL-R  COAL-N  NUC-R  ADV-HC ADV-LC
1990.OECD    1.262   0.737   0      0.612     2.841    0     1.583    0      0
1990.REFS    0.315   0.591   0      0.269     0.725    0     0.255    0      0
1990.ASIA    0.309   0.063   0      0.169     0.771    0     0.087    0      0
1990.DEVS    0.467   0.193   0      0.285     0.195    0     0.019    0      0
```

- The technologies Coal-r, gas-r, nuc-r and gas-r represent existing powerplants. Electricity generated in these plants is very cheap because investments costs are already made. But this also means that the capacity must disappear in the first decades of the 21st century. I copied the assumptions on the reduction of this existing capacity made by Manne and Richels in the MERGE2 model:

	gas-r	oil-r	coal-r	nuc-r
1990	all data from MESSAGE database			
2000	50% of 1990	50% of 1990	100% of 1990	100% of 1990
2010	0	0	75% of 2000	100% of 2000
2020	0	0	66% of 2010	50% of 2010
2030	0	0	50% of 2020	0

B.1.4 Nele.tab

The file nele.tab contains model inputs defining the maximum annual as well as total availability of non-electric resources.

- The following non-electric energy production capacities for 1990 were extracted from the MESSAGE III input files.

```
TABLE NCAP(*, * , NT)  NONELECTRIC PRODUCTION CAPACITIES - EXAJ
             GAS-LC GAS-HC  OIL-LC  OIL-HC  CLDU  SYNF  RNEW NE-BAK COAL
1990.OECD     28.5    0     33.0      0      8.72  0      0    0     37.9
1990.REFS     29.99   0     25.6      0      9.89  0      0    0     18.6
1990.ASIA      4.42   0     12.72     0     18.22  0      0    0     29.02
1990.DEVS      9.8    0     68.4      0      2.15  0      0    0      4.7
```

I compared 1990 fossil fuel production figures in MERGE2 *the original one* and MESSAGE III[13]

World production of fossil fuels in 1990 in EJ

	MERGE2	MESSAGE
Oil	31.1	33.02
Gas	30.4	28.56
Coal	39.3	37.99
non electr. coal	11.5	8.15

The differences might have been caused by different production statistics or different heat content parameters or both.

- Capacity of the carbon-free non-electric back stop technology (NE-BAK) is assumed to be unconstrained in MERGE2 and MERGE2R4, though limited by an expansion rate constraint.

---

[13] The MESSAGE III-non-electric coal figure was determined as follows: total primary energy consumption of coal in EJ minus [heat rate (10.5) times electricity from coal in TkWh derived from MESSAGE III data].

- Hydrocarbon resources. The reserves and resources in the MESSAGE III-A1B scenario are based on Rogner (1997).[14]

  To make the resource and reserve assumption in the MERGE2R4 model similar to the resource assumptions in the MESSAGE III-A1B scenario I had to match the 5 (oil) to 10 (coal) cost-categories in Rogner (1997) to a smaller number of categories in the MERGE2R4 model labeled low cost/high cost and proven/undiscovered (oil and gas), or proven/undiscovered for one cost category (coal).

  The transfer of extraction costs assumptions caused difficulties due to the fact that extraction costs tend to change over time. Rogner (1997) offered some help:

  > "All [...] reserve and resource categories are valued as if all future productivity gains [...] were realized immediately." (Rogner, 1997, p. 3, point 3)

  This means that the moment of extraction is assumed implicitly if one assumes productivity improves over time. This means that one way or the other the extraction of reserves in higher categories must be constrained in earlier periods in the MERGE2R4 model. The parameters RDF and PRV in MERGE2R4 do exactly that, but still inconsistencies can occur when resources are being discovered too fast or too slow given their implicitly assumed prices.

  Because the number of categories in the MERGE2R4 model is smaller than in Rogner (1997)/MESSAGE III, loss of information in the transfer of MESSAGE III reserves and resources input data to MERGE2R4 could not be avoided. Due to the vast amounts of fossil fuel produced and used in the A1B scenario I decided to give up information on price accuracy to make the inclusion of all categories of fossil fuels possible. Therefore, I decided to match the resource and reserve categories for oil, gas and coal in Rogner (1997) with the categories in MERGE2 as follows:

Oil reserves and resources The oil reserve and resource categories in Rogner (1997, tables 4 and 10) and MERGE2R4 were matched as follows:

MERGE2r4 category	Rogner's categories	price per barrel
proven-lc	I	12$
undisc-lc	II	12$
undisc-hc	III,IV,V	27$

Natural gas reserves and resources Natural gas reserve and resource categories in Rogner (1997, tables 7 and 10) and MERGE2R4 were matched in the following way:

	Rogner's categories	price per barrel oil eq.
proven-lc	I	10$
undisc-lc	II	10$
undisc-hc	III,IV,V,VI	30$

Coal reserves and resources The coal reserve and resource categories in Rogner (1997, tables 8 and 10) and MERGE2R4 were matched as follows:

MERGE2r4 cat.	Rogner's categories	Price per barrel oil eq.

---

[14] In the A1B scenario not all categories Rogner identifies are included as reserves or resources. For oil 5 out of 8 categories and for natural gas 6 out of 8 categories are included. To be specific: hypothetical and speculative unconventional resources were left out (Rogner, 1997, fig. 1, tables 1,7).

```
Proven          Grade A hard coal     15$ (direct use; OECD)
                                      12$ (direct use; other regions)
                                      50$ (synthetic fuels,)
Undisc.         Rest of hard &        15$ (direct use; OECD)
                brown coal            12$ (direct use; other regions)
                                      50$ (synthetic fuels)
```

The resulting coal, natural gas and oil resource base input data in MERGE2R4 are:

Reserves and resources

```
TABLE  SDAT(EI,X,*)   SUPPLY DATA - EXHAUSTIBLE
                      HYDROCARBON RESOURCES (EJ)
              OECD      REFS       ASIA     DEVS      WORLD
RSV.OIL-LC    607.1     728.5      376.8   4576.3      6288.4
RSC.OIL-LC    460.5     577.8      276.3   1226.7      2541.3

RSV.OIL-HC      0         0          0        0          0
RSC.OIL-HC   1892.5    1980.4     1084.4   6242.8     11199.6

RSV.GAS-LC    887.6    1666.4      339.1   2508.0      5401.1
RSC.GAS-LC    824.8    1913.4      427.0   1519.8      4685.0

RSV.GAS-HC      0         0          0        0          0
RSC.GAS-HC   8269.3    6736.8     3265.8   6937.8     25209.7

RSV.COAL       7452.86    4605.7    1800.41   1800.41   15659.3
RSC.COAL     60544.02  121590.5   56524.5    7201.64  245860.6
```

Costs And the resulting associated costs are:

```
 TABLE NCST(* , NT) NONELECTRIC COST COEFFICIENTS - $ PER GJ
          CLDU    SYNF      RNEW    NE-BAK    GAS-LC  GAS-HC  OIL-LC  OIL-HC
OECD      2.5     8.333     6.0     13.333     1.75     5.3     2.1     4.7
REFS      2.0     8.333     6.0     13.333     1.75     5.3     2.1     4.7
ASIA      2.0     8.333     6.0     13.333     1.75     5.3     2.1     4.7
DEVS      2.0     8.333     6.0     13.333     1.75     5.3     2.1     4.7
```

Differences between MERGE2 and MESSAGEIII with respect to fossil fuel resource and reserve assumptions. The MESSAGE III and MERGE2 reserves and resource assumptions differed significantly. As an example I present here the assumptions with regard to oil adopted in both models:

```
Example: world oil resources (in exajoules)
MESSAGE III / Rogner (1997):
Category:           I         II         III         IV          V         sum
Price ($/barrel): <12       12-19      19-25       25-35      35-38
Content (EJ):     6280      2554       3514        5778        1884      20000

MERGE2
Category:                  proven-lc   undisc.lc     undisc-hc           sum
Price ($/barrel):              12          12            18
Content (EJ):                7362        3416          3416              14194
```

I have the impression the resource base in MERGE2 is in terms of secondary energy (see Manne and Richels, 1992, p. 32). But the estimates in Rogner (1997) are in terms of primary energy. Differences between them can therefore be partly explained by the energy loss during transformation from primary to secondary energy, e.g. at refineries. This means that 10% of the differences can be explained in this way. Another part of the difference can be explained by the fact that losses of energy up to 25% during exploration of unconventional resources were not accounted for yet in the Rogner (1997) MESSAGE III data.

In comparison with the MERGE2 model the MERGE2R4 model has now more resources for gas and oil but they are also much more expensive. Costs of coal resources in MERGE2 were maintained. This means that prices of coal are underestimated in comparison with the Rogner (1997) cost and resource data. Due to the small number of reserve categories, especially for coal, this could not be prevented. But the number of cost categories in the MERGE2R4 model can be changed in the future relatively easily.

B.1.5 Climate.tab

We maintained the original MERGE2 non-energy related emissions of CO_2, CH_4 and N_2O input data (described by parameter NONEMGR and summarized in table NOMEN). These data can be based on IIASA sources in the future.

B.1.6 General

A check for inconsistencies in the 1990 energy data, not being part of the emulating exercise, by comparing electric energy use and non-electric energy use in 1990 for (i) the world and (ii) OECD in MERGE2 and Region I (Annex 2 in MESSAGE III) revealed the following differences:

```
Units:  GWyr

MERGE   elec     OECD    776          MESSAGE elec     OECD    683
                 WORLD  1350                           WORLD  1106
        non-elec OECD   3559                  non-elec OECD   3215
                 WORLD 10758                           WORLD  7581
```

These differences might be explained by (i) the different treatment of non-commercial energy in both models, or (ii) use of of different assumptions with regard to electricity conversion efficiency. A full explanation would demand for a careful comparison of the elements of the quantities depicted above.

B.2 Adapting parameters: fine-tuning

To make the output of MERGE2R4 with respect to final energy shares as close as possible to the MESSAGE III output as presented in section 5, the only parameter we changed was the oil-gas price differential parameter. This parameter assures that only at a certain cost oil and gas are perfect substitutes in generating non-electric energy. To emulate the MESSAGE III-A1B scenario we reduced this parameter from $1.25 per GJ to $0.6 per GJ. This reduction allowed for more substitution between gas and oil for non-electric purposes and smoothened the development of the shares of final energy.

Several changes in the parameters constraining the exploration and production of natural gas and oil were not successful in bringing the development over time of the shares of final energy in the MERGE2R4 model closer to the MESSAGE III output than shown in figures 1 and 2.

C Suggested reading with regard to the MERGE2 model

The following publications could be useful for obtaining a better understanding of the MERGE2 model.

- Manne and Richels (1995) present results and a very general description of the MERGE2 model, but they omit a description of its economic theoretic features.
- Manne and Richels (1992) give a thorough description of the Global 2100 model, a predecessor of the MERGE2 model, which description of the conversion technologies of electric and non-electric energy are similar to those in MERGE2. Also, this book discusses some of the economic theoretic features of the MACRO part of MERGE.
- Rutherford (1998) gives an intuitive appealing description of the Sequential Joint Maximization algorithm used to solve for a market equilibrium in the MERGE2 model.[15]
- Manne (1996) gives a detailed example of a general equilibrium model including uniformly mixing pollutants in Negishi format to be solved with the Sequential Joint Maximization algorithm in its most simple form. It is the most simple model based on the same methodology as the MERGE2 model possible.
- Manne and Olsen (1996) describes a stochastic version of a smaller version of the MERGE2 model.
- Ermoliev *et al.* (1996) give a treatise on the Sequential Joint Maximization algorithm in which they prove the algorithm generates a general equilibrium. They also derive conditions for convergence of the algorithm.
- Gunning and Keyzer (1995) give a general overview of formats, in which general equilibrium models can be formulated and they discuss their advantages and disadvantages of their application.
- In Manne (1995) arguments are presented in favor of the descriptive vs a normative approach with regard to the choice of the pure rate of time preference in long-term integrated assessment models.

---

[15] The context of algorithms to based on the theorem of Negishi to solve for the equilibrium is presented in Kehoe (1991, §3.2).

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