Global energy futures : An integrated perspective with the TIME-model

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CONTENTS

SUMMARY

This report contains an integrated analysis of the Targets/IMage Energy (TIME) model. In a previous report (De Vries and Van den Wijngaart, 1995) the five submodels of the energy model were described in detail. Here, we describe a number of applications with the (stand-alone) TIME model.

After the introduction and a brief outline of the TIME framework in Chapter 2, Chapter 3 describes the calibration of the world version for the period 1900-1990. Given the exogenous drivers like population size and economic activities, the energy demand, fuel mix, fuel prices, energy investments and CO_2 emissions are calculated and compared with observed values. We discuss what assumptions had to be made to derive a suitable fit with the observed values.

Chapter 4 present the methodology for scenario construction. Furthermore, we discuss uncertainties and assumptions on structural change, energy efficiency improvements, long-term supply cost curves of fossil fuel resources and technology in energy supply options.

An application of the methodology of Chapter 4 is discussed in Chapter 5 where a reference scenario is constructed based on the IS92a scenario of the IPCC. In Chapter 6 some scenarios from other institutions are investigated by assessing their outcomes in terms of the underlying assumptions. In Chapter 7, we will discuss energy futures according to alternative perspectives or world views. Finally, in Chapter 8, we give some results of optimized mitigation strategies using the CYCLES module of TARGETS to assess the impacts of scenarios. We specially address the role of technological change in meeting climate change policy targets.

ACKNOWLEDGEMENTS

The research for this work has been done within the Global Dynamics & Sustainable Development group at the Dutch National Institute for Public Health and the Environment (RIVM). A more detailed description of the five submodels of the Targets-IMage Energy or TIME-model has been given in a previous report (De Vries and Van den Wijngaart 1995). The present report discusses briefly the model calibration for the world 1900-1990 and the background for a number of scenario experiments. It also shows results of optimization experiments.

The authors wish to thank the members of the Global Dynamics & Sustainable Development group for their contributions to chapters of this report. Arthur Beusen, Henk Hilderink and Bart Strengers helped to implement and test the model and to perform scenario experiments (Chapter 5-6). Marcel Berk has done much of the scenario data collection (Appendix B); Ruud van den Wijngaart has been instrumental in applying the model for policy-related issues. Detlef van Vuuren and Marjolein van Asselt have contributed to the formulation and application of cultural perspectives (Chapter 7). This research has also benefited from the work done by Sander Toet and Johannes Bollen as part of the cooperation with the IMAGE-project group. Painstaking 'field work' for the implementation of the model for the USA and India as part of model validation has been done by Hessel van den Berg and Richard Klugkist; it has been reported elsewhere (Berg 1994, Klugkist 1996).

We sincerely hope that this second report on the TIME-model will make a contribution to elements of the [inter]national discussions on possible energy futures. It is hoped that the various chapters in this report indicate what kind of uses one can make with an integrated systems dynamics model. The work is being continued as part of the IMAGE-project.

1. INTRODUCTION

A large variety of energy models have been developed over the past decades. Most of them are at the regional or national level, emphasize the supply side and combine engineering with economic insights and methods. The models have been and still are applied to investigate a whole array of questions - the prospects of nuclear power, the risk of oil import dependence, the development of acidifying and greenhouse-gas emissions, to mention a few.

Until the early 1970's, most energy models had rather narrow operational objectives and were developed and used by oil companies and utilities. With the controversies about nuclear power and the two oil crises, energy issues got a more public character and energy modeling became a tool for the formulation of national energy policy. Initially, the emphasis was largely on alternative supply options in the context of strategic and environmental trade-offs. Later on, in the 1980's, more attention was given to energy demand dynamics and the interaction between energy demand and economic growth and to environmental emissions and their impacts. Together with an increased emphasis on market dynamics, bottom-up analyses and price-effects have gained more importance.

The Targets/IMage Energy model TIME is a globally aggregated systems dynamics simulation model. It builds upon several sectorial systems dynamics energy models (Naill 1977, Sterman 1981, Davidsen 1988). It has five submodels : Energy Demand, supply of Solid, Liquid and Gaseous Fuels, and Electric Power Generation. The energy demand model in the TIME-model has been developed as part of the Escape- and, later, the Image2.0/2.1 model (Toet et al. 1994, Vries et al. 1994, Bollen et al. 1995). It is implemented for 13 world regions. The energy supply models, together with the minerals model and a simple economy model, have originally been developed as part of the Global Environmental Strategic Planning Exercise (GESPE) project (Vries et al. 1993). The TIME-model is implemented as one of the modules in the TARGETS1.0-model (Rotmans and De Vries 1997).

The model includes the following major features :

- activity-related demand for heat (in 5 sectors) and electricity, incorporating structural [economic] change;
- autonomous and price-induced change in energy-intensity ('energy conservation');
- exploration and exploitation dynamics of fossil fuels, including depletion and learning dynamics;
- price-based substitution of biofuels which are assumed to be subject to learning as well as depletion dynamics;
- electric power generation in thermal power plants, with a non-thermal alternative (nuclear, solar) penetrating the market based on relative costs and learning.

The model has been calibrated for the world 1900-1990. For scenario's the model is run for the period 1990-2100.

Why develop yet another [global] energy model? The main arguments for this are :

- within the TARGETS1.0-model, there was a need for a simple and transparent, yet comprehensive energy model which adequately simulates long-term (up to 100 year) dynamics;
- many energy models still are either supply- or demand-side biased; it was our aim to integrate these two aspects of the energy scene;
- we explicitly have used non-equilibrium systems dynamics principles and actor orientation (informational and physical delays, feedback structures);
- we have tried to capture the key dynamics of depletion, learning-by-doing and substitution in a generic form.

Within the taxonomy of Kydes et al. (1995), the TIME-model is best characterized as a process-oriented energy model. The macro-economic optimization models have a consistent treatment of energy-economy interactions and are quasi-static in the sense that prices make markets clear within a given time-interval. They are referred to as General Equilibrium (GE) models. They usually have a low level of detail in the energy sector. A common objective function for maximization is utility per caput.

On the other hand, the process-oriented models have quite some detail about the energy resources, technologies and costs - as with the TIME-model. Moreover, we have introduced behavioral rules which are based on information about the state of the system. This combination is related to the Applied General Equilibrium (AGE) approach which 'focuses on the explicit representation of microeconomic behavioral principles [] with less emphasis on explanatory power [] than on understanding of the functioning of the economy' (Fischer et al. 1988 pp. 9). It differs from most economic model formulations in that it has been developed within the framework and modeling software of systems dynamics.

Another often made distinction is between top-down and bottom-up modeling. Top-down and bottom-up modeling techniques have been used to answer the question of how much it would cost to reduce greenhouse gas emissions. Bottom-up modeling requires detailed specification of energy-related and other technologies. In this approach, the present and future probable mix of technologies in each economic sector are described by their costs, inputs, and outputs including emissions. The aggregation level may range from broad economic sectors down to individual plants. The advantage of this approach is that it allows specification of particular technical innovations, but on the other hand it requires huge numbers of technological coefficients and other data, which cannot easily be checked for consistency. The macro-economic top-down approach with embedded emission coefficients, projects future emissions as the outcome of specified production relationships, preferences and aggregate economic growth. This approach permits the effect of economic policies to be represented, through the dependence of emitting activities on prices and incomes. The aggregation level may range from simple models of the aggregate economy, through aggregate models couples to more detailed representation of the energy sector, through full dynamic general equilibrium models.

The two types of model were conceived and designed through different disciplines, for different purposes and lead to very different conclusions (Wilson and Swisher, 1993). Top-down analysts like Manne and Richels (1992), Nordhaus (1992), Peck and Teisberg (1992), and Burniaux et al. (1991) conclude that even moderate steps toward mitigating global warming will be very expensive for society. They support a wait and see policy. Bottom-up analysts like Lovins and Lovins (1991) and Williams (1990), conclude that much can be done to mitigate global warming at little or no cost to society and support a take action now policy stance. Wilson and Swicher (1993) conclude that the two ways of seeing and describing the world are conceptually incompatible, and their results fuel political debate, where the choices between 'wait and see' and 'take action now' will be made on political rather than scientific bases. This aspect is discussed in Chapter 7 and 8 by experimenting with different sets of assumptions which can be linked to certain worldviews. While we do not include the macro-economic effects of energy policy, the TIME-model has more components of a bottom-up approach than a top-down approach. It is therefore expected that results will suggest that action now will be cost-efficient.

With the present report and a previous report with submodel descriptions (Vries and Van den Wijngaart 1995), the Targets/IMage Energy or TIME model is open for discussion and critique. This report first gives an outline of the model. Next, in chapter 3, we present the methodology for scenario construction, which is applied in chapter 4 to construct a reference scenario. In chapter 5 some scenario's from other institutions are investigated by assessing their outcomes in terms of the underlying assumptions. In Chapter 6 some scenarios from other institutions are investigated by assessing their outcomes in terms of the underlying assumptions. In Chapter 7, we will discuss energy futures according to alternative perspectives or world views. Finally, in chapter 8, we give some preliminary results of optimized mitigation strategies using genetic algorithms.

There are various arguments why an early action is not necessarily a costly option (Grubb, 1996). First, there is a wide range of options and technologies for limiting emissions, at varying cost levels and with different prospects for cost reductions. Even when 'no-regrets' options, which can be implemented at no net costs, are exhausted, there are a wide range of options, including many cheap ones. Secondly, in macro-economic models technology development occurs usually independently of market conditions. However, this is not a widely accepted hypothesis among economists who work on technology issues. For example, Arrow (1962) noted that much knowledge is acquired through learning-by-doing, such that much technology development is induced by market circumstances. Thirdly, technological development tends to be strongly biased towards existing modes, which is called the lock-in effect (Arthur, 1994; Nakicenovic and Grubler, 1991). This causes that industries with a large market share can spend large R&D to protect their existing position, although a rapid emergence of new industries can not be excluded.

Fourthly, if emission constraints will be set, it may become optimal to act earlier, so as to stimulate the necessary technology and systemic developments (Grubb et al., 1995). Starting now to adapt to the needs of our long future, may be cost efficient. Fifthly, the inertia of capital stock in energy-producing sectors make rapid delayed changes costly. Power generation facilities, petroleum refineries, etc., have a lifetime of 30-40 years, suggesting possibilities for almost complete transitions over such a period at low-cost. Some causes of CO_2 emissions lie even in more fixed structures such as poor building construction, urban sprawl, etc. Thus, current infrastructural planning has implications for abatement potential and costs at the end of the next century. The impact of the inertia of capital stock is supported by a joint study of IIASA and the World Energy Council (IIASA/WEC, 1995), which concludes that policy choices in the coming years will have an impact not before 2020 due to the long lifetime of power plants, refineries, and other energy investments.

2. THE TARGETS/IMAGE1.0 ENERGY (TIME) MODEL: OUTLINE

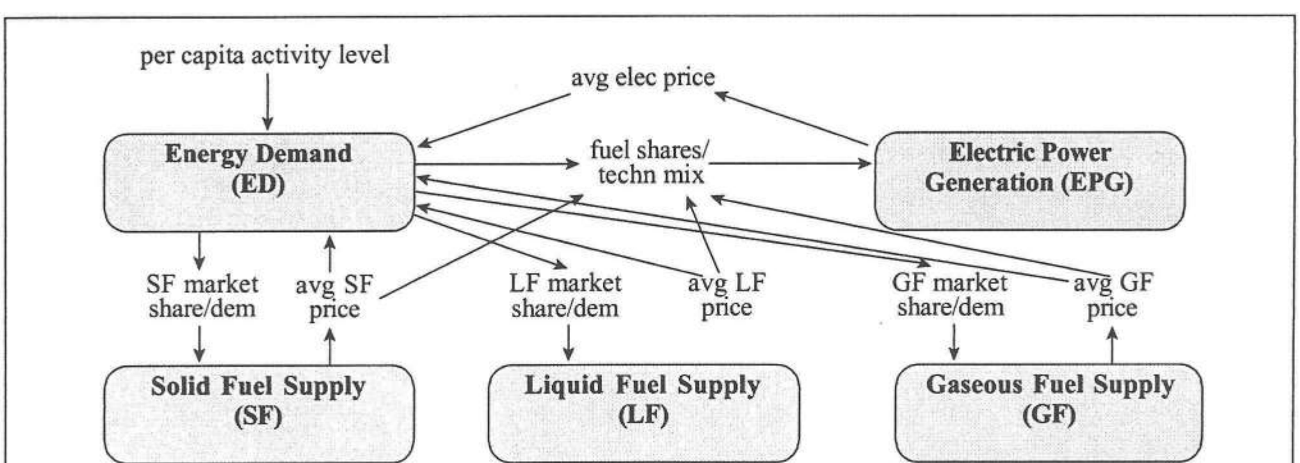
The TIME-model has been constructed as part of a larger, integrated assessment model. In first instance, it is at a global level of aggregation. It serves as a consistent representation of energy system dynamics in such a way that a set of [economic] activity levels is translated into a set of inputs and outputs. The inputs are the necessary resource flows to run the system : capital goods, labor, land and fossil fuels. The outputs are, besides satisfying energy services, the flows of materials which enter into the environment and impact its functions.

To this end, the model has five submodels: energy demand (ED), electric power generation (EPG), solid fuel (SF), liquid fuel (LF) and gaseous fuel (GF) supply (cf. *Figure 2.1*). Their major linkages are in the form of information flows: [anticipated] demand for secondary fuels and electricity and their prices. These models have been described in detail in a previous report (Vries and Van den Wijngaart 1995). The energy demand model is almost identical to the regionalized version developed for the IMAGE2.1-model; this is described in detail in Toet et al. (1994) and Bollen et al. (1995). The five submodels of the TIME-model have been developed in the systems dynamics software package STELLA II v. 3.0.4 ™. Then, the integrated model has been converted into the simulation environment 'M' developed at RIVM (Bruin et al. 1996) and is run as part of the TARGETS1.0-model.

The model represents energy demand and supply as an integrated system with prices as the main information signals which affect consumer and producer decisions. Prices are derived from production costs; they are made to reflect also other phenomena like taxes and subsidies by multiplication with fuel- and sector-dependent factors. Prices serve as signals for investment decisions within the energy supply sectors and about energy conservation.

The TIME-model is the energy submodel within the TARGETS 1.0 model. The TARGETS 1.0 - model describes population and health, economy, energy, water, land and biogeochemical cycles in an integrated way and at the aggregated world level (Rotmans and De Vries 1997). The major connections between the energy submodel (TIME) and the other submodels are: population and economic activity levels as inputs, and required investment goods and carbon-, sulphur- and nitrogen-oxide emissions as outputs. Most of the simulation experiments presented in this report have been performed with the integrated TARGETS 1.0 model. In some cases (notably the sensitivity experiments in Chapter 4) we have used a stand-alone version of the model. For the optimization experiments in Chapter 8, the TIME-model is used in combination with the CYCLES-submodel (Den Elzen et al. 1995). The two versions hardly differ but the stand-alone version has been run with the historical levels of population and economic activity, whereas the integrated version uses the simulated levels of population and economic activity as inputs. This gives slight discrepancies in the historical calibration.

Figure 2.1 Outline of the TIME-model



3. MODEL CALIBRATION: WORLD 1900-1990

We have calibrated the TIME-model for the world 1900-1990, partly based on calibrations of submodels for the regions USA and India (cf. Berg 1994, Klugkist 1996). The value of such a calibration is that :

- it gives an indication of how well certain historical observables can be reproduced and, if it fails, whether the discrepancies can be understood;
- it gives insight into the various ways in which the same [historical] information can be reproduced;
- it makes one aware of the [lack of] meaning of global averages which in turn serves as a heuristic for further modeling refinements and disaggregations.

It should be emphasized that a systems dynamics model like the TIME-model cannot be calibrated unambiguously. There are always multiple ways in which the few available historical observables can be reproduced. This is the consequence of modeling aspects of real-world dynamics which are not falsifiable in a strict sense (Randers et al. 1980, Graham 1984). Sometimes model variables are not well-defined at the world level. In other cases, the reduction of human behavior to a single set of simple rules is inadequate.

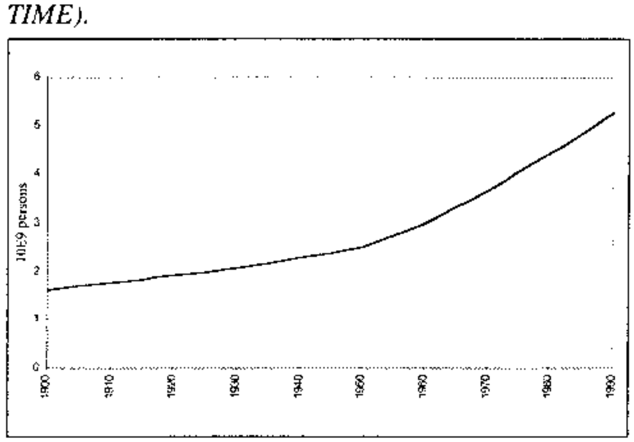
Model calibration is not validation. One way to validate the model would be to calibrate it for the period 1900-1970 and then simulate the period 1970-1990 and compare it with historical data. Unfortunately, the period 1970-1990 with its oil price shocks is rather unique. Another way is to focus on structural validation of the model. For the TIME-model this has been done by comparing the model outcomes with quantitative and qualitative insights from other energy experts and by testing the model for its long-term dynamic trend and response behavior. A third way of validation is to run the model without certain exogenous events (e.g. the oil price rise between 1973-1986) to explore the model dynamics per se.

Figure 3.1 summarizes the calibration results in the form of graphs which show model variables for the period 1900-1990. The historical time-series for population and economic activity level (GWP, Gross World Product) are reproduced with the TARGETS 1.0-Economy model and used as exogenous inputs (*Figure 3.1a-b*). With the same model we tried to reproduce the historical value-added time-series for the service and the industrial sector, because these are used as exogenous activity levels in the integrated model version. From *Figure 3.1b* it is seen that the simulated values exceed the historical values, especially for the services sector. We have used the TARGETS1.0-Economy model results instead of the historical data for the population and economy because the simulations presented here are also background experiments for the integrated TARGETS1.0-results (Rotmans and De Vries 1997).

Figure 3.1c-f show the simulation results and the historical time-series for secondary fuel and electricity use and primary fuel use. Historical data are from IPCC (1995), Klein Goldewijk and Battjes (1995) and various IEA, World Bank and UN statistical surveys. *Figure 3.1c* shows simulated and historical secondary fuel use, that is, both non-electric (heat) and electric, for all five sectors considered. It also shows electricity use separately. For both most simulation results are within 5-10% of the historical estimates for this period. Including the conversion losses leads to primary energy use and their shares.

Figure 3.1d shows the simulated and the historical coal production rate. The historical dip in 1965 is not reproduced but the trend is. As Figure 3.1e shows, the historical oil production rate is also simulated quite well but the real-world response to the oil crises is underestimated. Part of this is due to the fact that the historical slow-down in industrial and service output is not reproduced (cf. *Figure 3.1b*). *Figure 3.1f* shows the comparison between history and simulation for

Figure 3.1a: Historical world population (input in TIME).



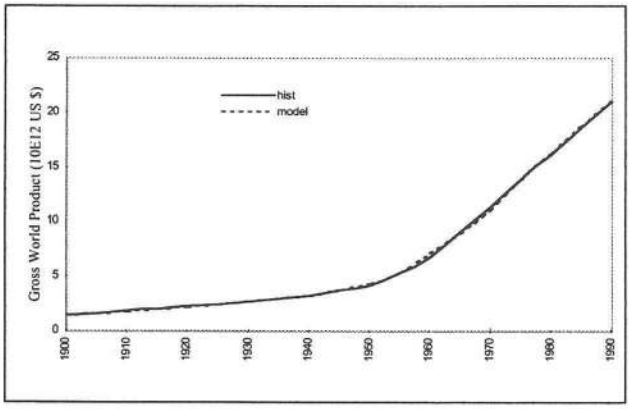


Figure 3.1b: Simulation of GWP (in 1990$) compared with historical estimates.

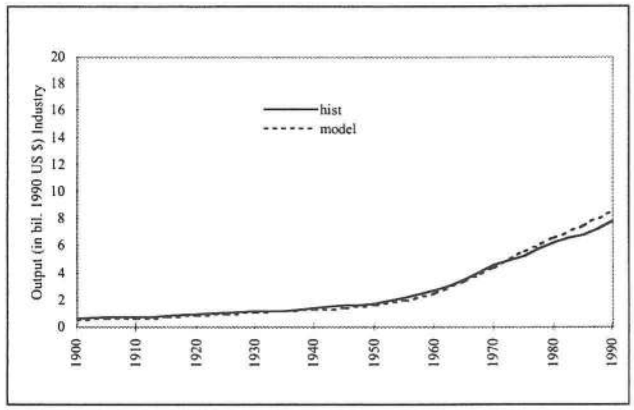


Figure 3.1b(I): Simulation of industrial output (in 1990$) compared with historical estimates.

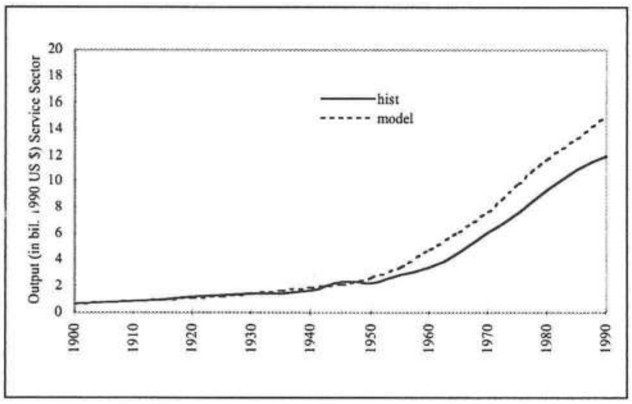


Figure 3.1b (S): Simulation of output from the service sector (in 1990$) compared with historical estimates.

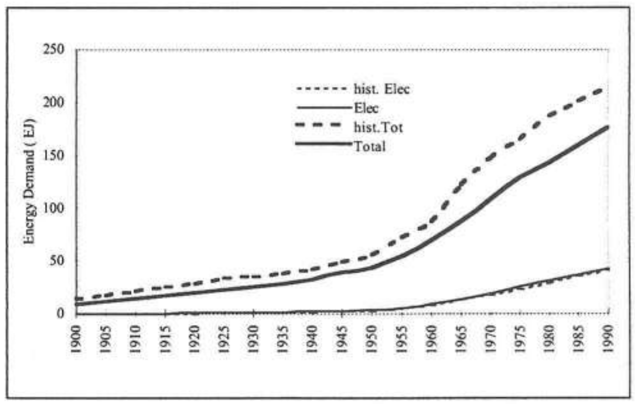


Figure 3.1c: Simulation of energy demand (electric & total) compared with historical estimates. The historical total is higher because the data include transport and own generation loses.

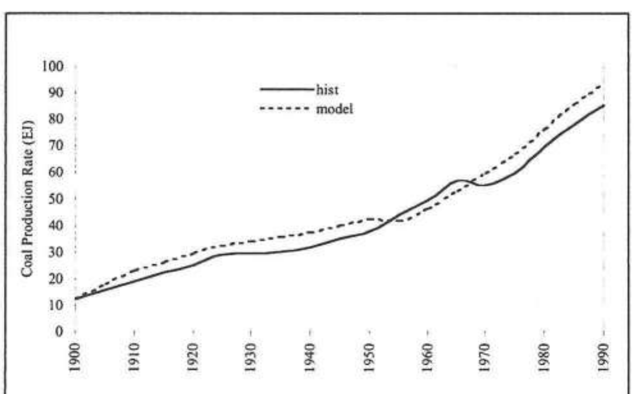


Figure 3.1d: Simulation of coal production rate compared with historical estimates.

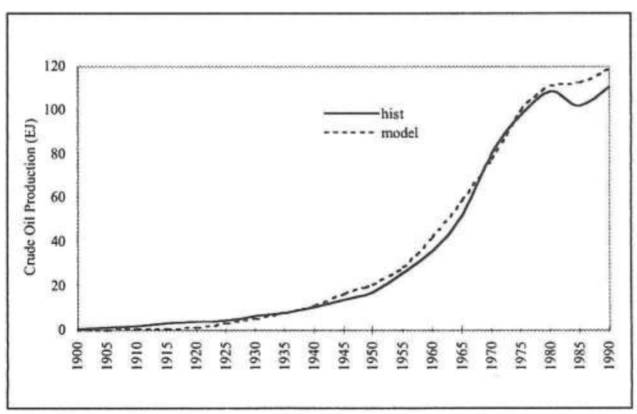


Figure 3.1e: Simulation of oil production rate compared with historical estimates.

the gas production rate. There is a consistent overestimation of the rate at which natural gas has been used. Finally, *Figure 3.1g* shows the pattern of primary fuel shares, including traditional fuels and hydropower and nuclear power. Traditional fuels and hydropower are closely linked to exogenous trajectories. The declining role of coal is well reproduced. The share of natural gas is, especially in the first part of the century, overestimated - consistent with the too high a production rate (cf. *Figure 3.1f*).

Figure 3.1h shows the historical and simulated CO_2-emissions from fossil fuel combustion - they coincide well with the published estimates of historical emissions (Klein Goldewijk and Battjes 1995).

Figure 3.1i shows the price paths for commercial fuels. The declining trend is in line with historical observations for most regions and is caused by the fact that technological improvements have more than compensated depletion effects. The same holds for electricity the average price of which has decreased even more rapidly (*Figure 3.1j*), because improving thermal efficiency have been coinciding with declining fuel costs. The peak in non-thermal i.e. nuclear electricity reflects the initial negative technological learning in the form of unexpectedly high cost increases for safety and environmental reasons.

Figure 3.1k shows the investment requirements as calculated with the TIME-model. There is hardly a reliable estimate for this variable, but the simulated values are in remarkable agreement with recent estimates for 1990 (Nakicenovic and Rogner 1995). The estimate of energy efficiency investments, very small, is derived from simulated marginal costs to conserve energy.

With respect to the model calibration for the world 1900-1990, the major conclusions are :

- it is possible to reproduce historical time-series of secondary of fuel use satisfactorily, provided exogenous estimates are made of the degree to which certain fuels could technically penetrate the market and of the discrepancy between actual and perceived market prices ('premium factor');
- the exploration and production history for fossil fuels can be reproduced adequately, provided the large oil discoveries in the 1940' and 1950's and the oil price hikes of the 1970's are introduced exogenously;
- estimates of the past rate of depletion and capital-productivity-increasing innovations lead to fossil fuel prices which are in reasonable agreement with the [scarce] data on historical [world] prices;
- electric power generation and its use of fossil fuels are reproducible if [scarce] information on fossil fuel price adjustments for this sector are made and if the historical nuclear power programs in the 1960's and 1970's are introduced as an exogenous R&D construction program.

In Chapter 5 we will discuss the sensitivity of the simulation results for certain of these assumptions.

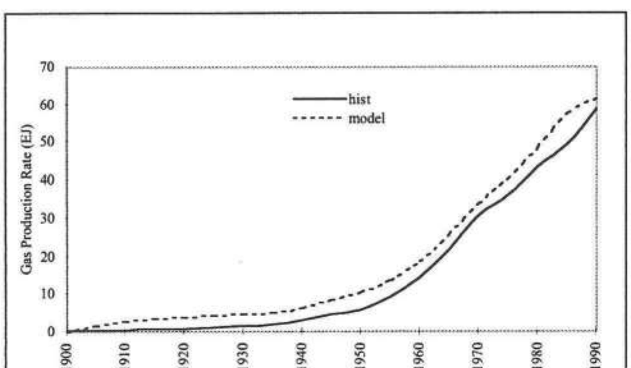


Figure 3.1f: Simulation of gas production rate compared with historical estimates.

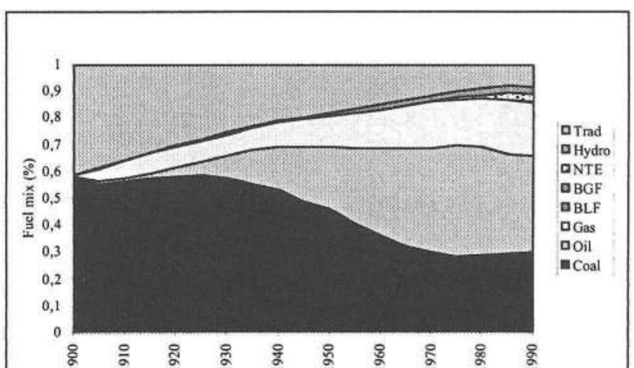


Figure 3.1g: Simulation of the primary fuel mix of energy use.

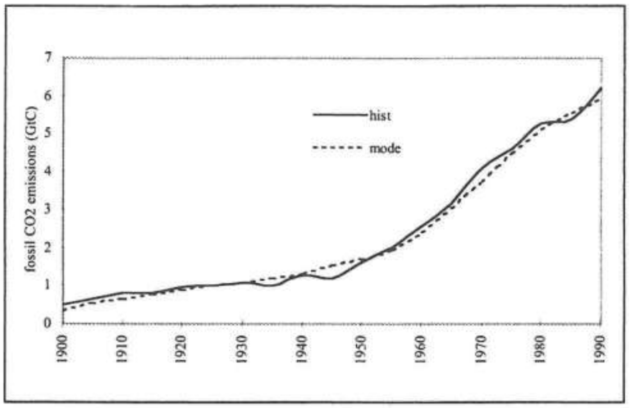


Figure 3.1h: Simulation of fossil fuel CO_2 emissions compared with historical estimates.

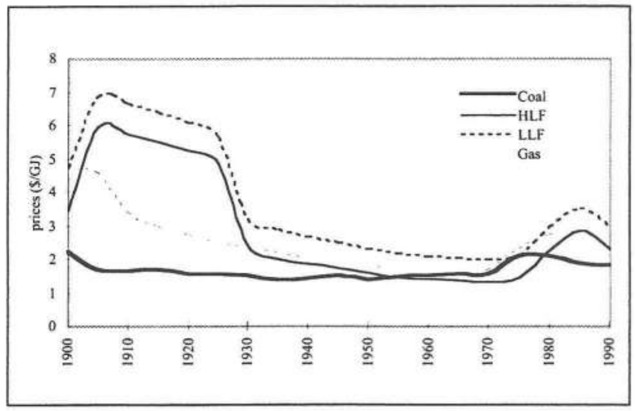


Figure 3.1i: Simulation of energy prices of coal, heavy and light liquid, and gas. The rise in the period 1900 - 1905 is due to model initialisation.

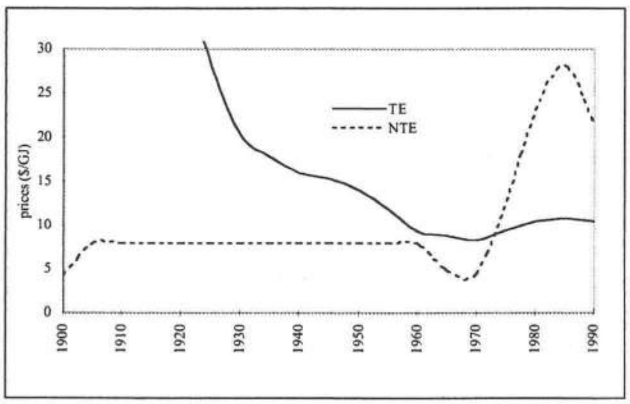


Figure 3.1j: Simulation of generation costs for thermal and non-thermal electricity prices. Generation costs of non-thermal electric (NTE i.e. nuclear) are only simulated after 1960.

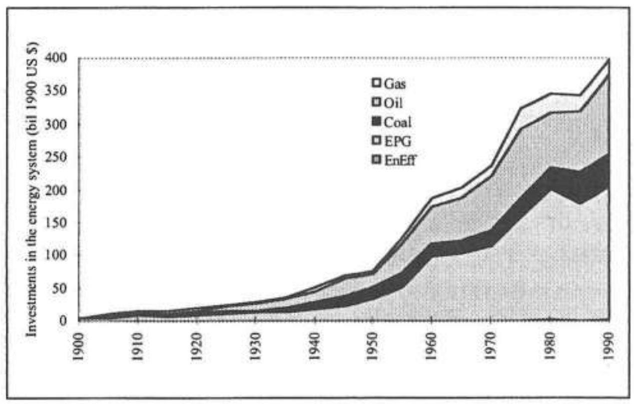


Figure 3.1k: Simulation of investments in the energy system (with EPG = electric power generation, and EnEff = Energy efficiency).

4. ENERGY SCENARIO CONSTRUCTION : METHODOLOGY AND MODEL PARAMETERS

4.1 The use of models

A model can best be seen as a mapping of parts of the real world of observables into a formal world of symbols. As such, it is a condensed and formal representation and interpretation of what is going on in the real world. Models are then used as tools to incorporate inferences, hypotheses and laws about the world, to some extent derived from experiments. As such, they serve the purpose of communicating human knowledge. It is useful to distinguish between strong and weak knowledge : the more knowledge is based on reproducible experiments, the stronger it is. Another useful distinction is between hard and soft : the more an observable or a process can be influenced by the human observer, the softer it is (cf. Vries 1989).

Using this terminology, one can easily see some strong and hard elements in a model like TIME. For example, the laws of conservation of mass and energy and the experimentally established values of fuel enthalpy do not give rise to scientific controversies. Although historical data will be incomplete and hence leave room for divergent interpretations, knowledge of many of the underlying physical processes is strong and hard. On the other hand, the model parts which attempt to simulate human behaviour with respect to, for example, investments in energy conservation or innovation-oriented research are to be considered weak and soft. They will necessarily be controversial in the sense that value- and interest-driven interpretations of the 'facts' will lead to different theories and assumptions. One can relate these differences to various levels of reality (see e.g. Vries and Van den Wijngaart 1995).

Without going into any detail (see e.g. Vries 1989, 1993; Janssen 1996), models can adequately be viewed as tools to be used in an interactive process among various actors which serve scientific, operational, communicative and strategic goals. The actors have their own organisational environment which they can influence (soft). Their influence domain is probably wider, e.g. oil companies can make decisions which affect gasoline retailers, governments etc. These influence domains may overlap. Part of the shared environment is an area of common interest, which can usually only be influenced to a quite limited extent, e.g. population growth or [inter]national carbon emissions.

[Energy] models are used within this context. They may be expected to reflect the interests and goals of the various actors (cf. *Figure 4.1*). Such actors are organised groups of individuals, with different information, motivations, abilities, opportunities and values. Therefore, it is not surprising that [energy] models are often not in the public domain, that actors use different [energy] models depending on their objectives, and that it is difficult to reach consensus on a model representation of the common interest area. Legitimisation of scientific [energy] models will naturally be confronted with a variety of problem perceptions, interpretations of past events and assessments of options and risks. The TIME-model is an attempt to construct a shared representation of parts of reality which can then serve a large variety of actors to explore and communicate ideas and expectations about the [long-term] [global] [energy] future.

Figure 4.1 The use of models.

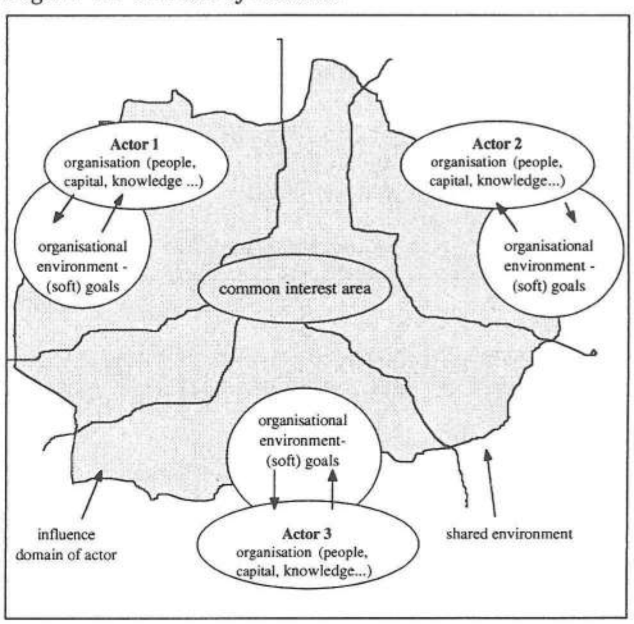


Figure 4.2 indicates for the TIME-model in a question format which assumptions and policy levers are to be addressed to construct a scenario. A distinction is made, unsharp to be sure, between those variables which mainly have to do with behavioural and institutional aspects, and those which focus more on technology and resources.

Both will have their specific uncertainties. One way to deal with the ignorance c.q. uncertainty and bias which is behind the various questions addressed in *Figure 4.2*, is to presume that they are resolved according to clustering of people around certain shared myths. This is discussed in Chapter 7.

Figure 4.2 Assumptions and policy levers addressed in the TIME-model.

Scenario contruction

1. Assumptions

Assumptions are estimates of model variables and parameters which are inherently or because of inadequate understanding uncertain ('weak knowledge'). Their choice reflects interpretation of historical events and valuation.

2. Policy levers

Policy levers are those variables and parameters which can be influenced by collective, political action ('soft'). Their choice presumes a set of objectives.

There are at least four, interrelated, aspects to the choice of assumptions and policy levers :
- behaviour and life-style : how do people respond to change, what kind of activities will characterise society 100 years hence ?
- institutional : to what extent will [central] governance be an option, and which instruments are available and how effective are they ?
- technology : with which technologies and efficiencies will these activities be performed, so what will their resource-intensity be ?
- resources : what are the [geological, chemical..] characteristics of the Earth's resources ?

The following is a rough classification of the assumptions and policy levers which are of relevance in the Targets/IMage Energy model :

Behaviour and Life-style & Institutional

1. Which activities will correspond with 1 $ of consumption, services, industrial production, GDP ?
- Energy-intensity of sectoral activities

2. What payback time will people require in their evaluation of energy conservation investments ?
- Payback time

3. What will be the prices and taxes and the perceived [dis]advantages of fuels which determine their relative market shares ?
- Fuel prices, taxes, premium/shadow factors,
- Fuel cross-price elasticities, substitutable fraction

4. What reserve-production ratio and profitability will oil, gas and coal companies desire ?
- RPR, Interest rate, Desired gross margin

5. Will safety and health measures affect productivity and costs of underground mining ?
- S&H-UC-measure

6. Will there be RD&D-programs for biofuels and non-thermal electric power generation and how effective will these be ?
- BF production function/learning and depletion,
- NTE learning

7. Will biofuels and non-thermal electric power be acceptable alternatives and seize their cost-related market shares ?
- Substitution elasticities

Technology & Resource base

1. What is the autonomous rate of energy-intensity decline ?
- AEEI rate

2. How will [rising] fuel prices affect the energy-intensity, or : At what [investment] costs can the energy-intensity be reduced ?
- PIEEI curve

3. What is the ultimate technical potential of energy-intensity reducing techniques ?
- Technical limit energy conservation

4. What are the long-term supply cost curves for fossil fuels ?
- Ultimate resource base, Depletion cost multipliers

5. How will learning and depletion dynamics influence the capital-output ratio of oil, gas and coal production [and processing, transport and distribution] ?
- Learning multiplier, Overhead-cost-factor

6. How do thermal efficiency and specific investment costs develop for thermal electric power generation ?
- Thermal Eff, SpecInvCost

7. What will be the expansion path of hydropower over the next 100 years ?
- Scenario Hydropower

8. How will learning and depletion affect costs of biofuels and non-thermal electricity ?
- Learning multiplier

Within the present model, the following three aspects are crucial (cf. *Figure 4.2*):

- relation between energy demand and [the nature of] economic activities;
- size and quality of technically recoverable fossil fuel resources (coal, oil, gas);
- rate and extent of learning-by-doing in developing new technologies (energy-efficiency, biofuels, non-thermal electric).

In the following paragraphs, each of these is briefly discussed with the objective to relate prevailing estimates and insights to the parameters in the TIME-model and their value domain. It should be stressed that this discussion is not meant to present an up-to-date and comprehensive overview [1].

4.2 Energy demand and [the nature of] economic activities

Figure 4.3 sketches for each of the three factors which are distinguished in the TIME-model and which determine the over-all energy-intensity (in GJ per unit of activity), what kind of considerations should be taken into account (see also *Figure 4.2*). It is obvious that one can never come up with estimates which take all these considerations into account in a consistent and empirically robust way.

The upper part in *Figure 4.3* indicates that the stage and nature of economic growth is the major consideration in assessing the structural change component. Factors like the degree to which commercial fuels replace traditional ones and the viability of public transport systems are important sub-items. The middle graph mentions some factors which influence the Autonomous Energy Efficiency Improvement (AEEI). RD&D-efforts and -success in a variety of areas, technology c.q. technological breakthroughs and the general climate for science and technology support and diffusion are key elements here. As the lower graph indicates, the Price-Induced Energy Efficiency Improvement (PIEEI) is largely determined by [relative] fuel price [expectations] and government interference in the form of taxes and subsidies. We will deal with these three factors in more detail in subsequent paragraphs.

It should be noted from the outset that many studies do not distinguish the three factors but instead focus on the decline in over-all energy-intensity, usually expressed in MJ per US $ of GDP. A further complication is that in the TIME-model the energy-intensity is in end-use energy demand per unit activity whereas many analyses either implicitly or explicitly define it as primary energy use per unit of activity. The difference is not only in the assumption that end-use demand equals final use but also in the assumptions on the conversion from primary to secondary - and especially on electricity conversion.

A recent and rather comprehensive overview of scenario-studies has been made for the IPCC (Alcamo et al. 1994). It shows that almost all analyses assume a significant decrease in the over-all energy-intensity, of 0.45 to 1.45 %/yr between 1990 and 2100, as a result of the aforementioned three factors. The expected decline in the period 1990-2010 varies between 0.5 %/yr and 1.6 %/yr. Regional scenarios indicate similar expectations (see e.g. IEA 1991, EC 1995).

Schipper and Meyers (1993) have done extensive research on the determinants of energy consumption. They find that at the sectoral level it is difficult to separate the structural change and the price-related changes in energy-intensity from autonomous trends. They observe that the levelling off of energy prices has led to an 'efficiency plateau' and expect that the decline in over-all energy-intensity in the OECD in the Trend-scenario is only half as fast between 1985 and 2010 as between 1972 and 1985 (1.2 %/yr instead of 2.3 %/yr). The rate of reduction could double 'with higher energy prices and vigorous policies and programs' (pp. 301). The same holds for the former USSR and for the Less Developed Countries: the trends in energy-intensity reduction can be significantly accelerated by a combination of higher energy prices and energy conservation and technology programs. This too is dealt with in subsequent paragraphs.

4.2.1 Structural change : the relation between final energy demand and economic activity

No doubt, economic activity levels are with population size the most important driving force behind the derived demands for energy, minerals, transport and water. The so-called Industrial Revolution was accompanied by an enormous migration of people from rural areas to urban areas which in its turn was made possible by an increase of agricultural productivity. Mechanization of agriculture but to a much larger extent the emergence of industrial manufacturing has led to an

[1] See e.g. the Scientific American Special Issue : Energy for planet Earth (september 1990) for an older but still comprehensive and useful introduction on most of the energy-related questions and issues.

Structural Change as function of per caput activity level (SC-multiplier)

±

+++ ←——————————————————————→ ---

initial industrialisation: materials-intensive | more food/materials processing (added info)

switch from traditional to commercials fuels

increasing mechanisation / automation

more added features of products (comfort, health, safety, environment)

emergence of new processes/products/activities

bicycle, pc's, subway, educ & medical services, entertainment...? | pc's, plastics, office equipment, airco, microwave, HDTV, mircrowave oven, tourism... ?

rising labour productivity and subsequent capital-labour substitution

life-style
technology

Technology as exogenous, growth-rate determined (AEEI-multiplier)

±

+++ ←——————————————————————→ ---

high activity growth= high turn-over of capital | low or declining activity growth

rapid expansion communications technology

breakthrough : materials technology, biotechnology | breakthrough in energy supply: fission/fushion, fuel cells...

innovative, entrepreneurial climate (Schumpeter, Kondratiev...) | bureaucratic, large-scale supply-oriented climate

[expectation of] sustained increasing/ high energy prices | [expectation of] low energy prices of price volatility and/or conflicting signals

liberal trade regime with rapid technology transfer

effective government RD&D-support because of strategic or environmental pressures etc | no or ineffective government RD&D because of institutional weakness, loss of legitimisation etc.

technology
markets
governance

Fuel prices c.q. useful energy cost driving conservation (PIEEI-multiplier)

±

+++ ←——————————————————————→ ---

[expectation of] sustained increasing/ high energy prices | [expectation of] low energy prices or price volatility and/or conflicting signals

existence of technical and institutional infrastructure

effective government RD&D and subsidy (lengthening PBT, stimulating learning-by-doing...)

government policy : standards, regulation ....

learning-by-doing : reduction in conservation supply cost

liberal trade regime with rapid technology transfer | high AEEI : implies low price-responsiveness ?

markets
governance
life-style

Figure 4.3 Determinants of energy demand enormous increase in the use of fuels, electricity and minerals.

The first waves of industrialization had their characteristic processes and products, like coal mining and steam engines, the expansion of canals and later railways, the introduction of electric power and internal combustion engines etc. The latest wave, by some authors interpreted within the theoretical framework of Kondratiev waves (see e.g. Sterman 1991; Tylecote, 1992), is characterized by a decline in energy- and material-intensities in the industrialized regions. Apart from technological developments like the emergence of new materials, miniaturization, 'economies of scope' etc., a major reason is the changing character of people's activities both as producer and as consumer (see e.g. Clark and Flemings 1986 for the role of advanced materials). Ayres (1987a+b) has argued that increasingly the informational content is the major component of value added, and that this is at the basis of the declining energy-intensity in advanced economies[2]. Similarly, Grübler and Nowotny (1990) show that the freight-transport-intensiveness in GJ/$ in advanced economies is no longer increasing 'which stems from the gradual transition in the output mix of these economies in the direction of information- and value-intensive, but material-extensive, products and the availability of higher-quality and lighter substitutes in the form of advanced materials' (op. cit. pp.450). This change is closely related to what has been called the transition to the service-economy, the coming of the information-age etc [3].

Whatever the names given, there is no doubt that the industrialised nations are experiencing profound changes in their economies and that technological change is, again, one of the major propellants. Any meaningful discussion of future trends requires a more in-depth understanding of technological dynamics. Among the useful concepts are logistic substitution dynamics (see e.g. Grübler and Nowotny 1990, Marchetti 1995), the product life cycles, and technological breakthroughs as a function of [cumulative] R&D-efforts.

Another key area for research is the extent to which social and economic changes - coinciding with increasing income and with the aforementioned technological developments - interfere with the trend towards declining energy- and material-intensity. It may be counteracting : increasing size/weight of new cars has partly offset energy-efficiency increases and decreasing household size incurs diseconomies of scale [4]. It could as well be reinforcing. Recent analyses indicate an increasing divergence between the GNP-index and the Index of Sustainable Economic Welfare, the latter being a more comprehensive quality-of-life indicator than GNP (see e.g. Max-Neef 1992) [5]. If this becomes a more widely felt experience in the developed regions, it might lead to reduced emphasis on activity-growth and increasing support for 'green' technologies and investments. Another aspect relevant for a world energy scenario, is the role of changing trade pattern (e.g. OTA, 1990).

The picture is at least as complex with regards to the less industrialised countries. Many of them are experiencing an industrialisation process which in some respects is similar to the earlier one in Europe and North-America : surplus labour from rural areas is attracted by urban jobs in the growing industrial sector. There are also important differences, among them that much of the capital and the knowledge incorporated in it is provided by multinational companies which operate for the benefit of shareholders in the advanced economies. An interesting question is whether these economies are in this situation able to jump over the energy- and materials-intensive stage straight into the new era of high-tech and high-info. Grübler and Nowotny (1990) argue against the postulate of global convergence along historical development trajectories, pointing out that late-comers have important catching-up possibilities and that countries are quite heterogeneous with regard to process and product saturation levels. Model-based assessments of the

[2] Because errors in manufacturing processes become more costly for high value-added products labour productivity tends to go down - 'the obvious way out of this dilemma is to replace error-prone human workers by [more] reliable computer-controlled machines' (Ayres 1987 pp. 56) - which by the way may in turn increase the energy-intensity.

[3] There are indications that only government services like education and child and health care have low energy-intensity - and those activities, once they are completely drawn into the cash economy, have evident saturation levels (Norgaard 1995, private communication). Market services, on the other hand, may well be energy- and material-intensive.

[4] Ironmonger et al. (1995) project an increase of 2.4% of residential energy use per caput due to the expected further decline in Australian households.

[5] More in general, it should be emphasized that indicators for activity like GNP or Value Added give seriously wrong signals, especially if used for interregion or intercountry comparisons. New analyses with PPP-corrected GNP-values are shedding new light on this matter.

energy-intensity in former USSR and China, for instance, suggest a significant impact from structural change (see e.g. Chandler 1991).

This argument clearly makes sense for much of manufacturing. It may also be valid inasfar as transport infrastructure is concerned : canals and railways may never reach the densities they reached in Europe because the automobile-road system is a preferred alternative in most industrialising countries. However, it is not obvious that this is a less energy- and material-intensive development pattern than Europe's historical trajectory. It is equally hard to anticipate whether major construction works for dwellings and offices and major consumption trends following North-American life-style patterns will affect energy- and material-intensities negatively or positively. It is interesting in this respect that an econometric evaluation of the determinants of electricity consumption across 93 countries concluded that the strongest influence comes from the share of industry in GDP (Burney 1995).

The TIME-model is linked only in the most simple way to the complex evolution of the world economy. Shortcomings in the present formulation are :

- aggregation : the trends in the different regions are too diverse to be aggregated into single variables and parameters;
- the sectoral disaggregation : the distinction between e.g. industry and services becomes ever more blurred;
- the activity indicators : sectoral value added or expenditure cannot adequately be linked to physical developments [6].

Having said this, we present the assumptions on the structural change component. In a qualitative way they are based on the following considerations. We first discuss end-use of non-electric energy in the five sectors :

- if *consumer expenditures* per caput rise, historical analyses show a decline in the direct end-use of non-electric energy per $ (excluding transport). This trend in the global average may, however, be slowed down or even reversed for some time as consumers in less affluent countries with cold climates opt for more dwelling space and comfort. In industrialised countries, the falling number of inhabitants per dwelling also point to higher energy-intensity. As a further rise in income is expected to take place in the less affluent countries in warmer climates, the downward trend will probably resume;
- the *industrial sector* in the OECD-region has shown a clear tendency towards lower non-electric end-use of energy per $ of value added. The combination of saturation and dematerialisation has coincided with transfer of energy-intensive production to countries with a more attractive resource base or less stringent environmental and/or labour regulations. Hence, one should be careful in interpreting regional trends vis-à-vis the global aggregate. There is clear evidence that in many less affluent countries energy-intensive production is maintaining or expanding its share in manufacturing value added (see e.g. Cosmetatos 1993). Nevertheless, it is widely expected that the downward trend will dominate the global end-use of energy per $ of value added;
- as with the residential sector, one may expect a decline in the direct end-use of non-electric energy per $ of value added in the *service sector* with rising activity levels. For a while, this trend too may be slowed down due to the aspiration towards more floor space and higher comfort levels in the less affluent regions. There are also indications that the private service and the public service sector show marked differences in this respect;
- the *transport sector* is both extremely important and complex. The trend towards ever higher shares of the automobile and the truck in person c.q. freight transport has increased the end-use of non-electric energy per $ of GDP - the activity indicator we use. This upward trend may be expected to continue for some time, or even accelerated due to increasing air travel, higher comfort levels (air-conditioning, bigger cars etc.), ageing, household fragmentation and urbanisation (see e.g. Statoil 1995). Analysis is made more difficult by the intricate relationship with developments in the manufacturing and service sector and the further growth of global trade. If the energy-intensity is to drop, the trends in the modal split have to change, for example through massive investment in new public transport systems. This might happen as a consequence of developments outside the energy system, e.g. congestion, urban pollution and the urge towards nature preservation;

[6] This shows up, for example, in the discussion about the use of Purchasing Power Parity (PPP) which suggests for the former USSR, Eastern Europe and the less developed regions a quite different relation between physical activities and monetary indicators than one derived from non-PPP corrected GDP-values. See e.g. Khatib (1995).

- the *sector 'other'* is both from an activity and from a statistical point of view a mixture which is hard to interpret. We intend to do a more detailed analysis of the agricultural component in this sector. Also, the question whether there is double-counting due to the inclusion of the energy supply industry needs further research.

End-use of electricity is dealt with at the aggregate level as the available data did not allow sectoral disaggregation. Electricity use per $ of GDP has risen enormously over the past 100 years. This is due to the versatility of electricity which leads to an ever increasing spectrum of applications. The share of electricity in total end-use of energy has risen continuously, too. It is widely expected that with rising activity levels these trends will continue. There are many reasons for it. First, ownership of appliances like lighting, refrigerators, televisions, copying machines, personal computers and air-conditioning has not yet reached saturation levels in many countries. There are strong forces at work to satisfy the desire for these appliances [7]. Secondly, new electricity-using appliances penetrate the market, for example the electrically heated waterbed, the sauna or the electric car. Thirdly, the trend towards mechanisation and automation and towards improved working conditions in factories and buildings often implies additional electricity-using equipment.

These considerations have led us to the structural change multiplier trajectories shown in *Figure 4.4*. The sectoral multipliers for non-electric energy and the multiplier for electricity are normalised to 1 in 1900 and shown as a function of the sectoral activity indicator. For the residential, services and other sector the multiplier is assumed to decline. For transport and electricity we assume the multiplier to rise first and then decline as a function of time[8]. For transport this is based on scenarios by Statoil which use income elasticities above 1 for passenger and freight transport in the period 1995-2020 for all but the OECD and the former Soviet-Union (Statoil 1995)[9]. For electricity we rely on several medium-term scenarios, among them the recent European Commission Green Paper (EC 1995). It expects an income elasticity of 0.8 for the EC - it will be higher for the less industrialised countries.

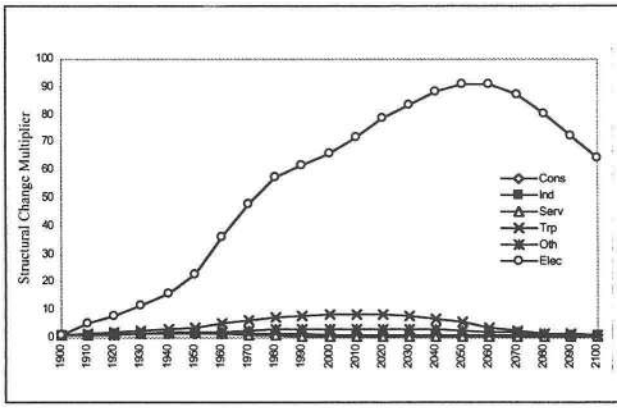


Figure 4.4 Structural change multiplier trajectories for heat (5 sectors = consumption (cons), industry (ind), services (serv), transport (trp) and others (oth)) and electricity, world 1900-2100 : calibration for the past, assumptions for the future.

From an econometric point-of-view, the structural change component is measured as the growth elasticity of energy use with respect to activity c.q. income growth. Such estimates include the autonomous technical change (AEEI) and are often based on the assumption of constancy[10]. Hence, it is hard to compare the econometric results with our model which excludes autonomous technological change and assumes elasticities to change with welfare c.q. time.

Recent research on industrial energy use in the U.S. manufacturing sector, 1973-1991, shows that energy use would have risen 50% if there had been no changes in industry structure and technical efficiency (LBL 1994 Annual Report). Actual use was in 1991 at the 1965-level, about 12 EJ/yr, because of a structure-related decline throughout the 1960-1991 period and an intensity-related effect from 1975 onwards. The latter contributed about 5 EJ/yr, the former about 3 EJ/yr to the over-all decrease since 1973.

[7] There is a strong tendency to equate the ownership of such appliances to 'development'. For a compelling analysis of human needs and the way in which western civilisation tends to focus on material satisfiers to fulfil them, see Max-Neef et al. (1991).

[8] In the simulation experiments to evaluate model sensitivity (Chapter 5) we have made the structural change multiplier a function of time, not of the sectoral activity level (GWP/cap etc.).

[9] For air transport, Statoil (1995) uses an income elasticity for all regions of 1.8-2 except in the Green Drivers scenario.

[10] For example, the income elasticities of transport energy demand with respect to GDP between 1973 and 1990 vary from an average 0.8 for Africa to 1.32 for Latin America (Statoil 1995). This is clear evidence that the income elasticity for mobility changes along the development trajectory.

4.2.2 Autonomous Energy Efficiency Improvement (AEEI) : the role of technology as if energy price [expectations] do not matter

The energy-intensity of most materials and products in GJ/ton has been declining over the last 100-200 years while fuel costs were falling, too. In terms of $ of economic activity, the situation is less clear. The very decline of energy-intensity for bulk materials has often lowered their costs and thus increased their use. In combination with the previously discussed structural change, the net result at the macro-level of GJ per $ of GNP has been that the countries leading the industrial development process have experienced a maximum in their energy-intensity somewhere between 1880 and 1960 and that the presently industrialising countries show the same behaviour but at lower over-all levels.

There are not many estimates available of the energy-efficiency increase corrected for structural change and price-induced effects - as has been previously stated, these components are hard to separate. For many energy-intensive products (steel, cement, aluminium, oxygen, ammonia, ethylene) the energy-intensity in GJ/ton has been declining continuously at rates between 0.3 and 1.5 %/yr (Molag et al. 1979). For the USA the AEEI-factor in industry is under the name of process refinement estimated in the order of 1-2 %/yr (Ross and Steinmeyer 1990). In the chemical industry in the EC, energy use per unit of output dropped with 2.8 %/yr between 1980 and 1991, partly due to restructuring and innovation (EC 1995). For some products/processes the thermodynamically lower bound is being approached. In such cases, a completely novel approach or a switch to new materials with the same or superior functional qualities may cause a further decline in terms of end-use energy per unit of activity.

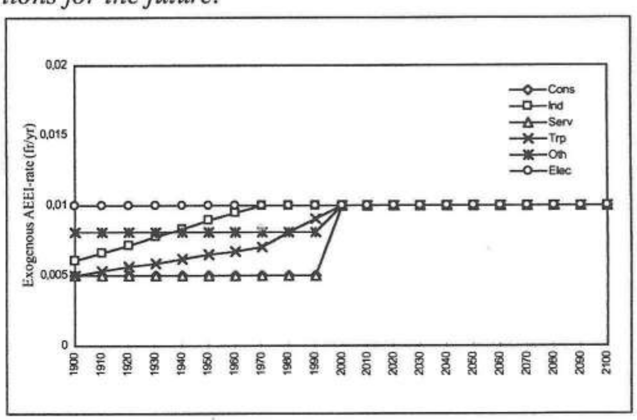
Matsuoka et al. (1995) give an overview of AEEI-values used in recent energy models. They range from 0 to 1.1%/yr in global energy models and from 1.12 to 2.85%/yr in energy efficiency scenarios. It is partly a matter of focus : "Where there is no great attention paid to energy conservation, the annual rate is between 0 and 0.5%, whereas if large energy savings are assumed, this rises to 1.0%". According to Matsuoka et al. the feasible range is between 0 and 1.5%/yr for the long term.

In view of the aggregation level used in the TIME-model, we have related the assumptions on the AEEI-factor to past trajectories as derived from the model calibration. *Figure 4.5* shows the exogenous time-paths for the AEEI-factor, expressed as a fraction/yr decline in the difference between the actual value and the lower bound. For the future we assume for all sectors a constant 1%/yr decline towards the lower bound, which has been set at 0.2 except for electricity where it is set at 0.4. The trajectory is exogenous because the dynamics behind the AEEI-factor is too complex to be modelled and would require links with the PIEEI and economic variables [11].

In the TIME-model the AEEI-factor shown in *Figure 4.5* is applied at the margin. Hence, the actual AEEI-factor lags behind depending on the rate of growth in activity. This captures the fact that the most important element of the AEEI-factor is the gradual replacement of old capital stocks (dwellings, plants, offices, cars) by new and more efficient ones.

For the OECD-regions, historical analysis for the period 1973-1992 indicates that large reductions in fuel use per km for travel and freight were offset by the growth in activity levels. A further upward pressure on fuel use has come from a shift towards autos, trucks and air travel. Besides, since the early 1990's energy-intensity decline only slowly or not at all. This trend is especially marked in Japan, where energy use for transport per caput increased with almost 50% between 1973 and 1991 because the drop in energy-intensity was small and cars and trucks took the major share of the growth in transport (LBL 1994 Annual Report).

Figure 4.5 Exogenous trajectories for the AEEI-factor, world 1900-2100 : calibration for the past, assumptions for the future.



[11] As the AEEI has to do with technology diffusion, one may also use a logistic function. However, at an aggregate level the initial growth phase would be in the first part of the 20th century for which data are too scarce to benefit from such detail.

4.2.3 Price-Induced Energy Efficiency Improvement (PIEEI) : the role of secondary fuel and electricity prices

Since the two oil price hikes in the 1970's it is a proven fact that energy prices do affect energy use, i.e., that the fuel-price-elasticity is less than zero. Trends in energy use since the world oil price fell again in the late 1980's also suggest that this link is reversible to some degree. However, recent research found that for non-transport oil demand in the OECD there is imperfect price reversibility : the response to price cuts has been significantly smaller than to the price increase of the 1970's (Dargay and Gately 1995). Another aspect of this hysteresis phenomenon is that a new price increase may give a smaller response because of reduced adjustment possibilities. Both these phenomena have been taken into account in the TIME-model (cf. Bollen et al. 1995, Vries and Van den Wijngaart 1995).

The literature abounds with estimates of the price-elasticity of energy demand. It is often found that they differ widely across sectors and countries and that they are not constant. In view of imperfect reversibility and changing options and costs of energy-efficiency measures, it is hardly justified to use [constant] price-elasticities. The TIME-model uses a different framework with a bottom-up approach. The implicit - and changing - price-elasticities are found to be in the order of magnitude of estimates in the econometric literature.

For the TIME-model one has to estimate the steepness of the conservation cost curves, that is, the marginal investment costs at which a certain fraction of the end-use of energy can be reduced in a given year. These investments are assumed to be elicited by [the expectation of] rising fuel and electricity prices. Such investments may have a retrofit-character but they may also show up in new dwellings or plants. We have used bottom-up engineering analyses to estimate these curves. *Figure 4.6* shows the curve for a value of 40 for the so-called steepness parameter α [12]. The default-values for α are 30 except for industry (40) and electricity (50).

Secondly, we need to estimate the rate at which the conservation cost curve declines due to economies-of-scale, innovation etc. in energy-savings equipment. This is a dynamic model feature

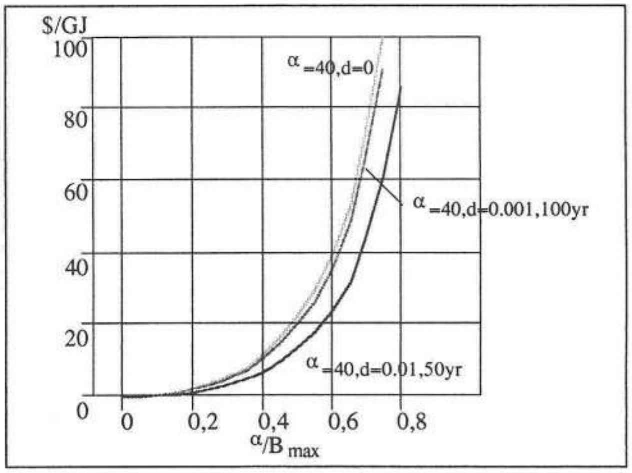


Figure 4.6 The marginal investments required to save 1 GJ of end-use energy as a function of the degree to which the upper limit B_{max} is approached. The curves are shown for steepness parameter (α = 40) and with annual decrease rate α of 0 (upper curve), 0.1%/yr for 100 years (middle curve) and 1%/yr for 50 years (lower curve).

which is hard to corroborate empirically. However, such cost declines do occur and are part of the explanation of the aforementioned hysteresis phenomenon. We assume an exogenous decline over time. *Figure 4.6* indicates how the conservation cost curve changes if a d-value of 0.1 %/yr is applied for 100 years and of 1 %/yr for 50 years, respectively. In the reference simulations we have set the decline rate at 0.2 %/yr for both heat and electricity. This results in a 10-20% fall in energy conservation costs as far as the relatively cheap measures are concerned.

Thirdly, the actual energy conservation investments made are based on the criterium that the product of desired payback time and annual energy cost savings should not exceed the average investments required for these savings (Bollen et al. 1995). The desired payback time is a socio-economic parameter which can be influenced by, for example, information, subsidies or the threat of oil shortages or environmental catastrophe. In the default simulation we use rather low values, between 1 and 3.5. The interest rate to finance energy conservation investments is kept constant in the model. Hence, we do not capture the fact that it may be as much the ratio of the price of energy and the price of capital as the change in the energy price that affects energy conservation measures. Similarly, we neglect a - plausible - relationship with [changes in] income [distribution].

[12] A rule of thumb is that the value of α indicates the marginal investment costs per GJ saved at which about 62% of the end-use of energy in the reference situation can be saved.

An example of mobility patterns in low-density industrialised nations is Canada (National Environmental Indicator Series, SOE Bulletin No. 95-3 Spring 1995). The number of passenger kilometres has steadily increased from 80 billion in 1950 to 470 billion in 1992, only interrupted in the early 1980's by an economic recession. More than 80% of this was travelled by car, planes being the second transport mode. Society responded to the oil price increases of th 1970's with rising car fuel efficiencies : about a doubling between 1975 and 1982. Thereafter, fuel efficiency has remained constant "owing primarily to the increasingly higher costs of additional efficiency and consumer demand for safety, cargo and passenger space, better handling, and acceleration as priorities over efficiency" . The net result of price and technological changes has resulted in almost constant over-all fuel costs for a given distance between 1965 and 1993. The vicious circle according to which the automobile drives out its alternatives once a certain threshold is reached, is clear in Canada : urban transit use is less than the increase in automobile use between 1990 and 1992.

4.2.4 Fuel prices and market shares : premium factors and constraints

Secondary fuel prices determine their relative shares in the non-electricity end-use energy markets and in the thermal electric power generation market. The premium factors reflect the difference between the actual [world aggregate] market price and the price as perceived by the users. As such it is a measure of non-market considerations which influence consumer choice, e.g. convenience, availability and reliability, limitations in supporting technologies, [expected] environmental problems. Because the model does not consider transport and distribution costs, part of the wedge between actual and perceived prices should be interpreted as real add-on costs. In the TIME-model we have used the premium factors to calibrate the market shares. For Liquid Fuels (LF/oil) the premium factor is set at 1.

Figure 4.7a-b show our assumption on the premium factors over time. For solid fuel they start increasing after 1950 when the relative advantages of oil and gas became more evident and oil and gas became widely available. Two conclusions stand out. First, we have to make the perceived price of coal much higher than the historical values for coal costs c.q. prices to reproduce the rapid penetration of other fuels in the past. Premium factors are up to 100%. One reason is that the simulated coal costs c.q. prices are only a crude estimate of a [non-existent] world average - in many parts of the world transport, distribution and storage costs will have led to higher prices at the end-user. A second conclusion is that the lacking infrastructure for [natural] gas did not allow the fast market penetration which relative production costs would have dictated. Hence, the decline in the premium factor in our simulations in fact represents the introduction of transport and use technologies without which gas could not be used.

For the future, we assume the premium factor for coal to decline because coal for end-use markets will increasingly be converted to more convenient and system-compatible forms (e.g. hydrogen). This, of course, is only one possible scenario. Moreover, we are not yet dealing explicitly with the costs which go with such forms of upgrading coal. As to natural gas: we assume that premium factors play no role any more. If any, one might expect a negative premium factor in view of the high convenience value for gas.

Figure 4.7a Premium factors for solid fuel (coal) as a value to be added to the market price(cf. Figure 3.1i).

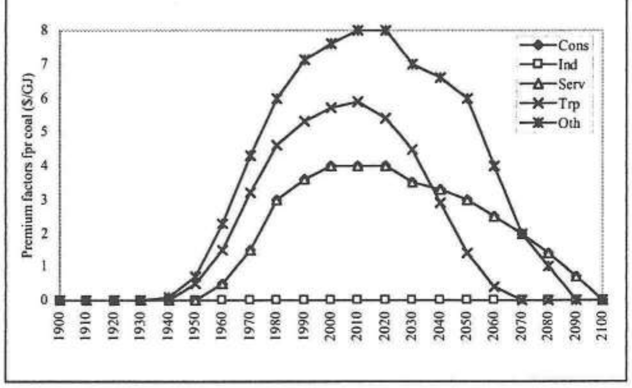
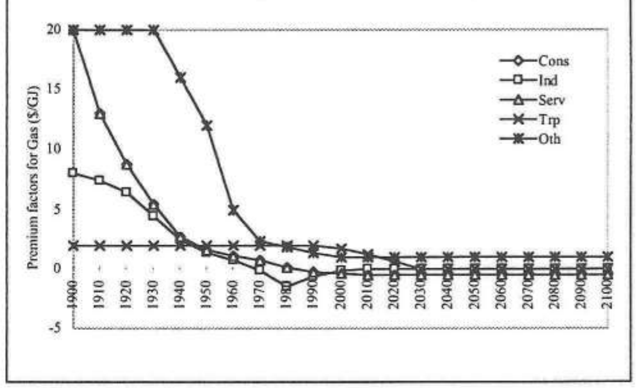


Figure 4.7b Premium factors for gaseous fuel as a value to be added to the market price.

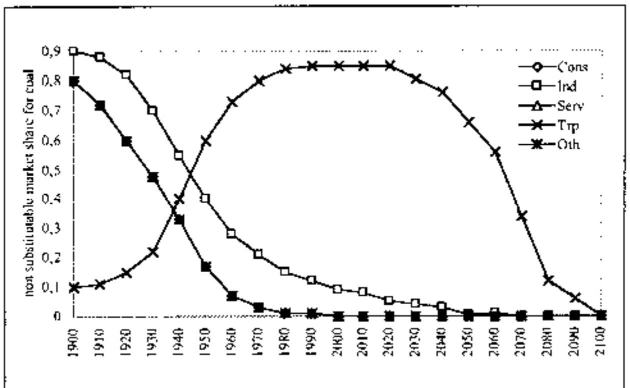


However, this assumption implies that producer costs solely determine market prices - which may be false, e.g. when gas prices are linked to oil and coal prices and availability. A second consideration in calculating secondary fuel market shares is that some secondary fuels could not be used - or cannot be used in the future - because of system limitations.

For the past, an example is the impossibility to use oil for transport before the advent of the Otto-engine and the corresponding oil refinery developments. In the TIME-model this phenomenon has been modelled by excluding a part of the market from price-driven substitution. It is a way of taking technological systems and styles into account. It is another representation, besides the use of premium factors, of the historical observation that other factors than officially recorded prices govern market penetration.

Figure 4.8 indicates our assumptions. The residential and the transport markets are assumed to have been governed in the past by coal-based technologies. Increasingly, oil and later gas became competing fuels. For transport the increasing dominance of the oil-based cars and trucks is reflected in our assumption that price-based competition between the three secondary fuels (coal, HLF, gas) only takes place in 15% of the market. For the future we assume this dominance to decline as other, e.g. methane- or hydrogen-based vehicles, are successfully developed. We do realise that this formulation is only a first step in modelling more adequately the complex evolution of technological [energy] systems.

Figure 4.8 Market constraints : the curves for the residential (and services and other) and the industry sector indicate which part of the market was/is available for coal only; the curve for the transport sector which part of the market was/is available for oil only.



4.3 Long-term supply cost curves for fossil fuel resources

The debate about the size and quality of [energy] resources has a long history. In some periods, the general mood was dominated by concern about imminent depletion - as in the famous essay by Jevons written in 1886, in which he warned for the exhaustion of British coalfields and in the report to the Club of Rome, Limits to Growth (Meadows et al. 1974), in which depletion of natural resources was a major cause of industrial collapse. In other periods, it was a non-issue or the general attitude was that undiscovered resources were vast.

Serious investigators of the resource depletion issue realised that many factors have to be considered (see *Figure 4.2* and *4.3*). A rather general framework is the product life cycle model which, applied for resource exploitation, assumes a sequence of resource deposits being explored and exploited, with a wave of exports being followed by increasing imports. Within such a meta-model (e.g. Ayres 1987), the global exploitation cycle for resources like coal, oil and gas can be understood as a sequence of regional cycles. Another insight is that it is the resource quality, in terms of depth, seam thickness, composition and location, that matters more than the ultimate occurrence. This also, in combination with geological probability and prevailing technology and prices, determines which part of the resource base is considered to be the technically and economically recoverable identified reserve.

For convenience, it is often assumed that the cheapest resource deposits are exploited first. In the past, this has obviously not been the case at the world level - just think of the Appalachian coal deposits discovered when Jevons announced an impending depletion of Britain's coal, or the giant oil and gas discoveries in the Middle-East when the USA was already one third its exploitation cycle. There are several reasons for this : haphazard exploration, strategic protectionism, political interests, large distances between deposit location and user markets, and fuel quality characteristics.

Because of the downward trend in transport costs, one may argue that in a world dominated by free trade the assumption of 'cheapest deposits first' may be increasingly correct. For oil there is already effectively one world market. Ellerman (1995) asserts that a world coal market has developed over the past 20 years due to a significant increase in the seaborne trade for coal. For natural gas, this is not yet the case due to high transportation costs [13].

Within the TIME-model, global markets for all fuels (including biofuels) are implicitly assumed. It is incorporated in the assumptions of a single depletion and rate of learning-by-doing multipliers. The capital-output ratio of [surface-]coal, oil and gas exploitation is divided by the depletion multiplier (going from 1 to 0 with cumulative discovery and production) and multiplied with the learning multiplier (going from 1 to 0 with cumulative production) (cf. Appendix A and Vries and Van den Wijngaart 1995)[14].

Estimates of fossil fuel resources and reserves abound in the literature. The major model assumption is about size and quality of the resource base : how much is available at which costs[15]? In the TIME-model formulation this curve is a function of a reference value of the Capital-Output Ratio (COR) in some reference year (1980) and a depletion multiplier. This depletion multiplier is normalised (1 in 1980). It declines to 0 for coal when the ratio of undiscovered resource and total resource becomes 0. The COR for coal is divided by this multiplier value. For oil and gas the multiplier rises up to 100 when the ratio of undiscovered resource and total resource approaches 0. The COR for oil or gas is multiplied with this multiplier value.

Unfortunately - and understandably - estimates of the costs at which these deposits can be exploited are scarce and hence uncertain and controversial. In the reference simulation we have based our estimates on the supply cost curves for oil and gas in *Figure 4.9*. The first 20% of our curves (15000 EJ for oil, 6500 EJ for gas) are based on literature estimates (see Vries and Van den Wijngaart 1995; Kassler 1994 Figure 10 pp. 8); the remaining 80% is chosen in such a way that the IPPC-IS92a scenario results are reproduced. For underground coal the estimate is based on Edmonds and Reilly (1986) and on published figures for expected future coal prices -

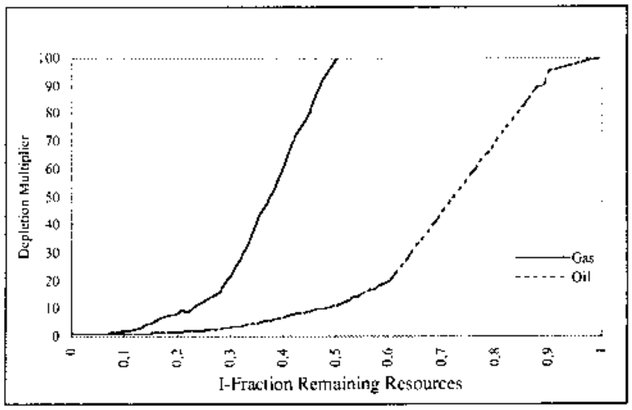


Figure 4.9 The depletion multiplier for oil and gas (factor with which the Capital-Output Ratio is multiplied).

which leads to *Figure 4.10*. The value of the x-axis refers to the 1900-estimate of total coal resources : 230.000 EJ. For surface coal the COR is assumed to be a function of increasing depth, which is itself assumed to rise to 1200 meter when the ratio of undiscovered resource and total resource approaches 0 - as is shown in *Figure 4.11*.

The depletion multiplier in combination with assumptions on technological learning and transport costs determines the price-path for [crude] oil and [natural] gas. The degree of learning has been estimated on the basis of the 1900-1990 calibration[16]. It is difficult to find specific literature on this topic (cf. IIASA/WEC 1995, Vries and Van den Wijngaart 1995). For oil and gas learning-by-doing is supposed to start in 1900 at a learning coefficient of 0.1 - as a result, most of the cost reductions through innovations are supposedly realised. This may be erroneous, as recent innovations in offshore-technology seem to indicate. For surface coal mining a learning coefficient of 0.9 from 1950 onwards is assumed which is equivalent to 10% cost reduction per doubling of cumulative production. In underground mining, the process of labour-capital substitution is assumed to rise as an exogenous time-path and factor-productivity is assumed to decline with decreasing fraction of reserves remaining. Labour wages are set at a fixed fraction of global per caput consumption.

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[13] To move gas in an onshore pipeline might cost 7 times as much as oil; to move it 5000 miles in a tanker may cost nearly 20 times as much (Jensen 1994).

[14] Learning-by-doing has been incorporated in the model through loglinear learning. The learning rate is often expressed by the progress ratio *p* which indicates the factor with which *y*, a cost measure, decreases upon a doubling of *x*, an accumulated learning measure : $p=2^{-\pi}$

$$y=y(0)x^{-\pi} \wedge \log y=\log y(0) - \pi \log x$$

We refer to 1-p as the learning coefficient.

[15] This long-term supply cost curve is defined here as the anticipated production costs (incl. both depletion and learning factors) as a function of cumulative resources c.q. production.

[16] This may be a faulty assumption in view of recent activities like offshore exploitation and liquefaction technology which are relatively immature and have shown important cost reductions through technological progress (see e.g. EC 1995).

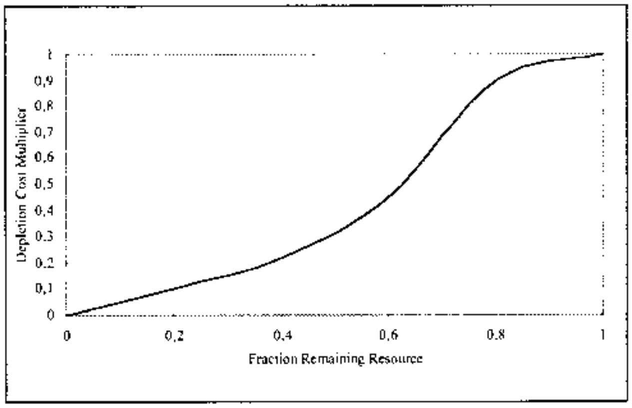


Figure 4.10 The depletion multiplier for underground coal (factor by which the Capital-Output Ratio is divided).

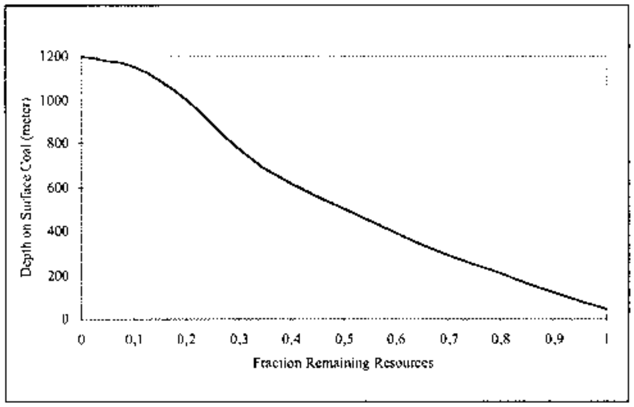


Figure 4.11 The depletion effect for surface coal : increasing depth if resources are produced (the Capital-Output Ratio is a function of depth).

4.4 Energy supply systems : technology and costs

There is rather wide agreement that over the next hundred years the world's energy supply system will experience transitions - as it did in the past. Most widely discussed are the switch from fossil to non-fossil sources, notably to land-based biofuels and electricity from solar and other renewable sources. The key uncertainties here are the performance and costs of these options and their penetration dynamics (see *Figure 4.2* and *4.3*). In the present paragraph we briefly discuss the prospects for commercial biofuels, hydropower and non-thermal power generation technologies.

Within the TIME-model, new energy supply systems are aggregated into three options: liquid biofuels (BLF) which replace liquid fuels if they are competitively priced; gaseous biofuels (BGF) which substitute for natural gas; and a single non-thermal electricity generation option (NTE). The latter is an unspecified mix of nuclear and renewable sources; parameter choices can be made in such a way that they reflect the composition of this mix. Each option is characterised by an engineering-type of production function. Hydropower is modelled separately.

4.4.1 Liquid and gaseous 'commercial biofuels'

At present, 13-14% of world energy demand is met by biomass (WEC 1993). It comprises largely of what is called 'traditional biomass' : fuelwood, charcoal and forestry and agricultural residues (including manure and straw). In the TIME-model the use of traditional biomass sources is modelled as an exogenous time-series using a correlation with GDP/cap. This is for a variety of reasons inadequate. We intend to improve this part of the model; for the moment we do not deal with it any further.

Large-scale use of biomass as substitute conventional fuels is referred to as 'modern biomass' or 'commercial biofuels'. It is an estimated 10-15% of the total biomass use and consists of the use of e.g. wood residues, bagasse and urban wastes as well as energy crops. *Table 4.1* gives an overview of literature estimates on modern biofuels.

The major routes to produce commercial energy from biomass are, it seems, growing crops in large-scale plantations (sugar cane, miscanthus, poplar, eucalyptus a.o.) and convert them into ethanol or generate electricity in a gasification / combined-cycle unit.

In the TIME-model it is assumed that commercial biofuels can compete with Light Liquid Fuels (LLF: gasoline, kerosene, Diesel) and with natural gas. A major market is the transport sector where a mixture of ethanol and gasoline has already been successfully penetrated in Brazil and the USA. Only Heavy Liquid Fuel is used for electricity generation; biofuels can only penetrate here in the form of gaseous fuels.

The production function for the cultivation of energy crops is based on capital, labour and land as production factors. It has two features. First, capital is substituted for labour when labour wages rise with increasing income. With a delay, optimal factor allocation occurs on the basis of relative factor costs. Secondly, yields are assumed to increase as a loglinear function of cumulative production.

The available data did not allow an empirical

Table 4.1 Literature estimates on the characteristics of modern biomass.

Source	Qualification	EJ/yr	Costs/yields
WEC 1993	ethanol from crops		30-280 GJ/ha
	ethanol from wood/straw		10-150 GJ/ha
WEC 1993	Current Policies scenario 2020 :	5-10	
	Ecologically Driven scenario 2020 :	17-24	
Johansson et al. 1993	hydrous ethanol from sugar cane		6.3-8.6 \$/GJ
Battjes 1994	wheat		20-60 GJ/ha
	sugar cane		120-140 GJ/ha
	miscanthus		50-220 GJ/ha
	tree crops		40-140 GJ/ha
	electric from eucalyp/miscan/poplar		11-42 \$/GJe
IIASA/WEC 1995	2050	47-124	160-250 GJ/ha
	2100		250-420 GJ/ha

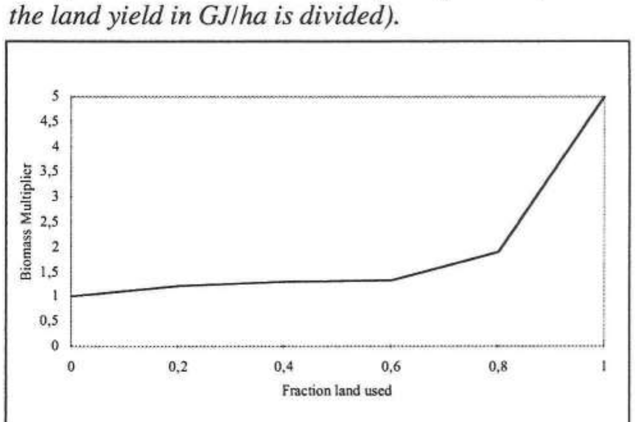
underpinning of these dynamic relationships. We gauged the initial biofuel price (30-40 \$/GJth) and the learning coefficient (0.1) in such a way that costs decline to the levels assumed in the IPCC-IS92a scenario (~ 70\$/bbl = 10 \$/GJth). The associated assumptions about the other variables are: the average land price (50 \$/ha), the capital-labour substitution elasticity (0.6), the cross-price elasticity (0.25) and the reference labour productivity (2 ton/manday). All these have been kept constant. Labour wages are assumed to be a fixed fraction of per caput consumption, set at 70%. Labour costs rise but this is partly offset by capital-labour substitution. The decreasing quality of land is assumed to reduce yields with a factor of two when a production level of 250 EJ/yr of BLF and/or BGF is reached. This is shown in *Figure 4.12* where the x-axis indicates the ratio of actual and potential biomass production and the y-axis the factor with which yields decline. Further research is needed.

4.4.2 Thermal Electricity (TE) generation : conversion efficiency

Over the past decades, the rise in thermal efficiency of electric power plants has stabilised in the industrial nations of the world at levels around 40%. Reasons behind this are the increasing share of coal as a fuel and the more demanding environmental constraints, e.g. cooling towers and flue-gas desulphurisation. However, it is widely acknowledged that there is a great potential for further increases, certainly at the world level.

The first option is technology transfer to those regions where less efficient technologies are still dominating. The second option is the penetration of combined heat-and-power schemes (cogeneration, district heating). Depending on the allocation procedure, the conversion efficiency can climb to 85-90%. This option is not yet implemented in the TIME-model. The third option are new technologies. Combined-cycle gas-fired power plants are already operating at 50% thermal efficiency at significantly lower capital costs than the coal-fired equivalent

Figure 4.12 The depletion multiplier for liquid (BLF) and gaseous (BGF) modern biofuels (factor by which the land yield in GJ/ha is divided).



(Williams and Larson 1989). Another option are fuel cells. One development trajectory anticipates scaling up to 100 MWe before the year 2010, when electricity can be produced at conversion efficiencies in the range of 50-65% and at kWhe-cost between 6 and 9 1993¢/kWhe (Blomen 1989). Conversely, efficiency improvements may be slowed down if coal is the major fuel and desulphurisation or gasification have to be applied for environmental reasons.

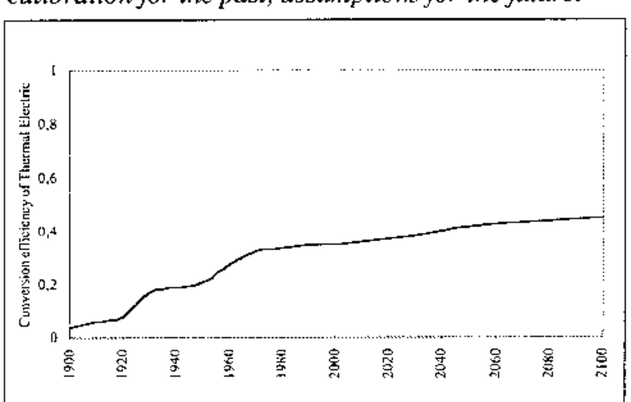
Hence, projected trajectories for the conversion efficiency in thermal power generation range from the present world-average 38% to 42% by 2100 in case of limited improvement and coal as the major fuel, to 60% by 2100 in case of large-scale penetration of technologically advanced options. In the TIME-model there is no explicit relation between thermal efficiency improvements and the development of specific investment costs (in $/MWe). The latter are exogenously set.

For the reference simulation we assume that average global conversion efficiency increases from the present 38% to 45% at the end of next century, as is shown in *Figure 4.13*. This is, no doubt, technically feasible if gas - either natural or from coal - is available and/or fuel cell technology is successfully developed. Average specific capital costs for thermal electric power generation are assumed to decline from 590 $/kWe in 1990 to 525 $/kWe in 2100.

4.4.3 *Hydropower expansion*

Hydropower is one of the important renewable energy sources. Unlike similar options like wind and wave power, it has a long history. Hydropower production expanded from 79 TWhe in 1925, 40% of

Figure 4.13 Exogenous trajectories for the Thermal Electric (TE) conversion efficiency world 1900-2100 : calibration for the past, assumptions for the future.



total electricity generation, to 1426 TWhe in 1974, 23% of total generation (Raabe 1985). In 1990, production was 2250 TWhe or 20% of total electricity production.

Many estimates of the technical potential of hydropower have been made. Such estimates are based on information on the catchment area, the average water discharge and the local topography of the world's rivers. *Table 4.2* gives some literature estimates of potential and expected capacity c.q. production. Some 17% of the harnessable potential is from three rivers : the Zaire, the Yangtse and the Brahmaputra. Almost 50% of this potential is in six large nations : China, former USSR, USA, Zaire, Canada and Brazil (Raabe 1985). With an estimated technical potential of 19000 TWhe/yr and the assumption that 40-60% is economically viable and environmentally acceptable, the world's long-term economic potential is some 6000-9000 TWhe (Moreira and Poole 1993).

If all present plants under construction are in operation, the global installed capacity is 650 GWe [17]. Estimates of future expansion have become more modest in view of the environmental, social and economic constraints large hydropower schemes are confronted with. Land use is important : the historical average of inundated area per MWe installed in Brazil is 46 ha. Hundreds of thousands of people have been displaced; water quality and public health have been affected. Also the emission of greenhouse gases due to changes in land cover may be significant in major hydro-projects.

Hydro-electricity is among the cheapest electric power generation options. Costs are largely capital costs which range from 500 to 2000 $/kWe depending on site specifics, with scale and head as major determinants. Many of the larger hydropower schemes can generate electricity in the range of 1-2 ¢/kWhe at specific investment costs in the order of 500-600 $/kWe (Edmonds and Reilly 1986, Nakicenovic 1993). Electricity from small so-called mini-hydro schemes may cost five times as much. Moreira and Poole (1993) give values of 750 to 2000 $/kWe installed.

[17] To give an idea of uncertainties : the UN Energy Statistics Yearbook 1987 gives for 1987 585 GWe net installed hydro-capacity including and 564 GWe excluding self-producers, i.e., 35 GWe higher than the estimate in Nakicenovic (1993) for 1988.

Table 4.2 Hydropower potential.

Source	Qualification	MWe a)	TWhe/yr
Edmonds&Reilly 1986	theoretical potential	[8500]	27000
Moreira&Poole 1993	theoretical potential	[14350]	44000
	technical potential	[6200]	19000
	long-term econ potential	[2000-3000]	6000-9000
Raabe 1985	2000-value :	[1300]	4000
Nakicenovic 1993	2020-2025 estimate :	[1450-1850]	4500-5500
	2050 estimate :	[2050]	6300
	1990-value :	~ 600	2250

a) conversion for numbers between brackets : Loaf Factor = 0.35

There is a tendency for costs to increase due to longer construction times, less suitable sites, longer distances from consumer centres, and environmental and remigration issues. Also, shorter operating lifetimes due to higher than expected sedimentation rates increase costs. For Brazil a long-term supply cost curve suggests that the next 60-80.000 MWe can produce electricity at less than 2.5 ¢/kWhe, after which costs rise steeply (Moreira and Poole 1993).

A reasonable range of projected values of installed capacity is 1650-2100 GWe in the second half of next century. We assume in our reference scenario that the curve for Brazil - which may be too optimistic in view of cost underestimates in the past - is also valid for the world at large. For the installed capacity we choose a trajectory between 1650 GWe and 2500 GWe by the year 2100, i.e., between 3 times and 4.5 times the presently installed capacity. Average capital costs are set at 1500 1990$/kWe as of 1990; the load factor is kept constant at 0.35 although this could change depending on hydropower's role in the system as a whole (e.g. storage) or on the linkages with agricultural schemes (e.g. irrigation).

4.4.4 *Non-Thermal Electricity (NTE) generation : renewable sources*

There is a wide variety of technological options to use renewable sources like solar radiation, wind and tidal power and geothermal energy for electricity generation. The consensus view seems to be that photovoltaic solar systems and wind turbines have the best prospects for large-scale penetration in the course of the next century (see e.g. a recent overview by the WEC, 1993). We briefly discuss these two options, assuming that they are representative. *Table 4.3* gives an overview of literature estimates.

Edmonds and Reilly (1986) extensively discuss the learning curve for heliostats, photovoltaic arrays and large wind turbines. The respective learning coefficients are estimated, based on past experience and engineering projections, to be in the range of 0.2, 0.1-0.2, and 0.15 respectively. For solar and wind they also expect an increase in marginal costs per unit of electricity in the order of 30-100% because of the need for electricity storage and the decline in site quality. Capital costs may decline to 400 ('breakthrough') resp. 1400 (large storage system included) 1979$/kWe by the year 2020.

Johansson et al. (1989) give a detailed cost-estimate for photovoltaic electricity. Depending on the [future] conversion efficiency and the plant size, costs are between 6 and 12 1988¢/kWhe. Most studies in the 1980's assumed learning coefficients for the manufacturing costs in $/peakWatt in the range of 55% if the scale-effect is included. A more recent estimate (Carlsson and Wagner 1993) expect a 15% drop in kWhe-cost for amorphous silicon technology. Polycrystalline cells and concentrator technology are expected to more expensive. For the latter the longer-term potential cost reduction is estimated to be in the order of a factor 1.5 to 2.5, based to a large extent on economies of scale. Similar estimates are given by Ahmed (1994).

Table 4.3 Electricity from renewable sources.

Source	Qualification	TWhe/yr	Costs
Photovoltaics			
Edmonds&Reilly 1986	1985-value :		1000 1979$/kWe (5-8¢/kWhe)
	2020-value :		400-1440 1979$/kWe (4-10¢/kWhe)
	load factor 0.2		
Johansson et al. 1989			6-12 1989¢/kWhe
Carlsson&Wagner 1993	1990-value:		8700-10000 1989$/peakkWe
	future :		15-60% lower
Nakicenovic 1993	2020-value :	>1400	4-8 1990¢/kWhe
	2030-value :	<8000	
WEC 1993	current status :		5000-9000 1990$/kWe
	2020-value :	420-1380	1150-2100 1990$/kWe
	(photovoltaics only)		
Flavin&Lenssen 1994	USA 1994-value :		5-10 1993¢/kWhe
	USA 2020-value :		4-6 1993¢/kWhe
Wind			
Grubb&Meyer 1993	global availability :	53000	
	2020-value :	<1000	
Nakicenovic 1993	global potential :	5000-7600	
	2020-value :	650	
WEC 1993	global potential		
	(onshore)	20000	770-1200 $/kWe (4.5-10.3¢/kWhe)
	2020-value :		30-40% lower (3-7.5¢/kWhe)
		376-967	180-474 GWe

For wind power, with capacity factors between 0.54 and 0.5, capital costs are expected in most studies to fall below 1000 1979$/kWe. Grubb and Meyer (1993) estimate the global wind power availability at 53000 TWhe, taking into account population-density related limitations. Actual penetration could be limited by the grid absorption capacity.

It appears that, in the view of many experts, the important solar-energy based options for electricity generation are large-scale facilities (100-500 MWe) - thermal or photovoltaic - which could produce electricity at costs in the range of 4 to 8 ¢/kWhe. At the same time, windturbines will penetrate the market at roughly similar generation costs. The development trajectory is much harder to estimate, and there is a wider difference in views. It is assumed that small-scale facilities (10 kWe - 10 MWe) are introduced in niche markets, e.g. in regions and markets without access to a central grid; this will allow further learning towards large-scale plants to be operated by utilities. The learning coefficient are largely implicit. A rather wide range of estimates exist in the literature for the learning coefficient (see eg. Trainer, 1995). Using a value of 0.18 implies that investment costs will reach the lower WEC-estimate of 1150 $/kWe if cumulative sales exceed 10.000 MWe (WEC 1994). Because this cost estimate corresponds with some 700.000 MWe in 2020 (Ecologically Driven scenario; assuming a 25% load factor), the WEC apparently applies a lower learning rate. We take 0.1 as the default value for the non-nuclear NTE-options.

In the TIME-model the NTE-option is a mixture of various options. It is characterised by its capital costs, which decline thanks to learning-by-doing, and a fixed load factor. Additional costs for storage are not taken into account. If the NTE-capacity exceeds the required base-load capacity, its load-factor will drop.

The model is calibrated for the historically important NTE-option : nuclear fission power. We simulate past nuclear investments as a pulse of non-thermal capacity orders between 1960 and 2000, peaking in 1980 at a level of 24.000 MWe/yr (Vries and Van den Wijngaart 1995). This coincides with historical nuclear capacity build-up worldwide and serves to give the required 'learning pulse' to the non-thermal options.

We have assumed in the reference scenario a time-path for the learning coefficient such that NTE-generation costs are in the order of 6 1990¢/kWh around the year 2050. The resulting time-path for the progress ratio is 0.95 in 2000 down to 0.9 until 2030 after which it rises slowly to 1 (the progress ratio is 1 - learning coefficient). The load factor for NTE is assumed to decline to 0.65 and from then on remain constant (*Figure 4.14*), assuming that the additional system costs, e.g. for storage, are included in the capital cost figures.

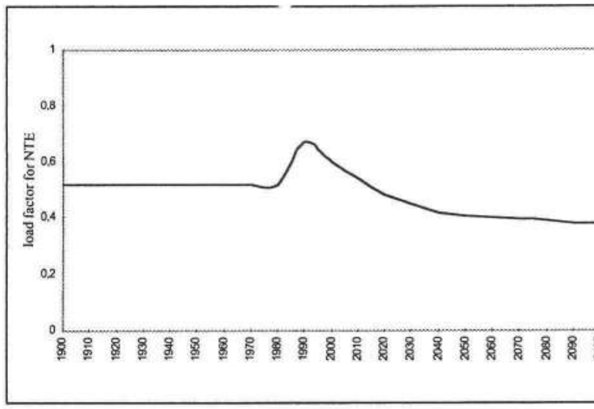


Figure 4.14 Exogenous trajectories for the Non-Thermal Electric (NTE) base load factor world 1900-2100 : calibration for the past, assumptions for the future.

5. SCENARIO [RE]CONSTRUCTION: ASSUMPTIONS AND RESULTS FOR A REFERENCE SCENARIO

5.1 Introduction

First, we discuss the construction of a reference scenario. It is unclear what the definition is of the so-called 'reference', 'Conventional Wisdom' or 'Business-as-Usual' scenario's in many reports. Usually, it means that the modellers have fed their model with parameter values and assumptions which are more or less agreed upon by the [energy] experts [18].

Over time, insights with regard to energy supply and demand change significantly. In the 1970's, partly in response to the OPEC-induced oil price hikes, the nuclear breeder reactor and coal liquefaction and gasification were widely debated and supported with massive R&D-programs. Strategic oil supplies and resource depletion were major issues. In the 1980's, it became clear that there was an enormous potential for energy savings and the discussion focused on the determinants and the potential of decoupling energy use and economic activities. In the aftermath of nuclear accidents and with the emergence of the enhanced greenhouse-effect on the political agenda's, the initiatives in the 1970's to develop renewable energy sources got a new boost in the 1980's. In the debate on potential constraints to economic growth, the emphasis shifted from the [re]source side to the environmental sink side. Then, the collapse of the former Soviet-Union, the 1990 Gulf War and the wave of deregulation and privatisation have again led to adjustments of energy demand and supply forecasts.

Out of this pattern of shifting foci and insights, one has to make a choice of what are considered as the relevant long-term issues. For the construction of a 'reference' scenario, one would like to use rather 'neutral' assumptions which are acceptable within the expert community. This is especially important for those parameters for which the model outcome has turned out to be sensitive - as is discussed in the previous chapter. For the present simulation experiments, we consider the IPCC IS92a-scenario (Leggett et al. 1992) as representative for a business-as-usual energy future.

The major trends in the reference scenario are based on characteristics found in many of the scenario's :

- activity-demand elasticities for the transport sector and for electricity are rather high, implying that [global] energy-intensity for these sectors continues to rise for another 2-3 decades (cf. *Figure 4.4*);
- past trends in the AEEI continue, at levels between 0.5 and 1.5 %/yr (cf. *Figure 4.5*);
- the response to rising energy prices is significant and reversible, but price-elasticity is assumed to decline as marginal costs per unit of energy saved increase;
- secondary fuels do substitute each other with relative [perceived] prices for consumers as the driving force; there is however a delay and the degree of substitution is constrained in some sectors for some fuels to reflect certain technological pathways;
- the share of electricity in total end-use of energy rises;
- depending on exogenous RD&D construction programs, alternatives to fossil fuels penetrate the markets for secondary fuels and for electric power generation; an important but not the sole driving force are the relative prices c.q. costs.

5.2 The reference scenario : assumptions

Using the TIME-model to [re]construct scenario's, it is useful to cluster the assumptions which are required for simulation experiments. We distinguish four clusters :

1. structural change : the nature of economic activity and the resulting demand for useful energy (end-use energy, energy services) (cf. paragraph 4.2.1);
2. energy-efficiency : the relationship between useful energy (heat / non-electricity) demand and the input of secondary fuels (solid, liquid, gaseous) (cf. paragraph 4.2.2 and 4.2.3);
3. electricity generation : the relationship between useful electricity demand and the input of secondary fuels and alternative sources of electric power (cf. paragraph 4.4.2 and 4.4.4);

[18] At a deeper level, most [energy] models do of course also reflect more tacit agreements on how the world should be interpreted and interacted with. This, however, is less topic of debate and is also less prone to sudden changes of insights. An interesting example is the notion of 'energy services'. It took some 15 years before officially used energy models have incorporated, at least to some extent, the notion that fuels as such are not what consumers want.

Table 5.1 Model parameters involved in scenario experiments.

cluster 1	StructChange EnInt			
cluster 2 TECH	AEEI (fr/yr)	LowerBound on AEEIFactor	PIEEICurve Steepness	Decr PIEEICurve (fr/yr)
cluster 2 ECON	Des PayBackTime (yr)	NonSubCoalOilFr Cross-price elasticities	SFpremiumtax ($/GJ) LFpremiumtax ($/GJ) GFpremiumtax ($/GJ)	carbontax ($/GJ)
cluster 3 TECH	TE ConvEfficiency	NTELearningCoeff NTEMultLogPar	BaseNTELoadF	
cluster 3 ECON	EPPremiumSFLF	Cross-price elasticities		NTE R&DProgram (MWe/yr)
cluster 4 TECH	OilProdDeplMult GasProdDeplMult	UndCoalDeplMult AvgCoalDepth	SCLearnCoeff BLFLearningCoeff BGFLearningCoeff	MaxBLF(EJ/yr) MaxBGF(EJ/yr)
cluster 4 ECON	exog CapLabRatio UC	CoalLabCostCorr UndCoalWages	LandPriceBLF LandPriceBGF BLFMultLogPar BGFMultLogPar	RelBLFLabCost RelBGFLabCost BLFR&DProgram BGFR&DProgram

4 fuel supply : the market price of solid, liquid and gaseous fuels which result from assumptions about long-term supply cost curves c.q. depletion, technological learning-by-doing and labour costs of conventional coal, oil and gas and of biomass-based fuels (cf. paragraph 4.3 and 4.4.1) .

Table 5.1 indicates for each of the four clusters the model parameters which are considered in the simulation experiments in an attempt to [re]construct global energy scenarios. Names of variables refer to previous discussions in Chapter 4 and Appendix A. TECH parameters refer to mainly technical aspects, ECON parameters to economic aspects.

Cluster 1: structural change addresses the demand for end-use energy (heat, electricity) as a function of sectoral shifts and intra-sectoral changes in activities and product and process mixes (cf. par. 4.2.1)[19]. A meaningful differentiation between energy-intensive and energy-extensive forms of economic development deserves more research and debate before they are used to construct different scenario's. Hence, for all scenarios we introduce the structural change multiplier as an exogenous function of time, as shown in *Figure 4.4*[20].

As to **cluster 2: energy-efficiency**, there are two levels at which one can change assumptions :

- technological: the rate of Autonomous Energy Efficiency Improvement (AEEI) and the lower bound on it, the cost of energy efficiency as given by the Price-Induced Energy Efficiency Improvement (PIEEI), and the rate of decline of the energy-efficiency cost curves, and
- socio-economic: the required c.q. desired payback times, the premium- c.q. tax-regimes for secondary fuels and electricity, and the degree to which a certain fuel can actually penetrate the market.

Whereas the former group of assumptions reflects different views on the technical rate and potential for improvement in energy-efficiency, the latter focuses on economic criteria and prices. The two sets are not mutually independent but there will be a tendency to leave the socio-economic parameters unchanged if one holds an optimistic view on technology (cf. Chapter 7).

[19] In theory, 'end-use' or 'useful' refer to the energy services. Here, it indicates the demand for non-electricity energy excluding secondary fuel conversion losses c.q. the demand for electricity, before any autonomous or price-induced energy-efficiency increase. It is a non-observable quantity and the actual energy services delivered per MJ will change over time.

[20] This is not the case for the simulation experiments in Chapter 7, on cultural perspectives. There we have used the integrated TARGETS1.0-model in which the structural change multiplier is an explicit function of per caput sectoral activity level (cf. Bollen et al. 1995).

The AEEI and PIEEI have been discussed in paragraph 4.2 (cf. *Figure 4.5-4.6*). The parameter which constrains the potential penetration of e.g. coal is as much of a technological as a socio-economic nature, because it involves both the technical and the social aspects of coal-using devices. The chosen values for the premium factors and the technological constraints on fuel penetration have been discussed in paragraph 4.2.3 (cf. *Figure 4.7-4.8*). The policy parameter in this cluster is the carbon tax. The fuel cross-price-elasticities have been kept at the values derived from the historical calibration.

Cluster 3 : electricity generation is an important one because electricity is expected to provide an ever larger share of useful energy demand. Here, too, are two elements :

- technological : this concerns the development of the conversion efficiency of thermal power plants and the technological learning-by-doing as well as the operational characteristics of the non-thermal (NTE) option, and
- the price at which utilities can purchase coal as compared to the average market price.

Here, again, the two are not independent and are in fact related in ways which are not explicit in the model. The latter has to do with the conditions under which utilities can buy coal - distance, quality, environmental standards, employment all play a role. The former reflects above all the assumptions about how fast and to which levels the specific investment costs of non-thermal electric power plants (solar, wind, nuclear...) will fall over the next century.

The assumptions on thermal efficiency and hydropower have been discussed in paragraph 4.4.2 and 4.4.3 (cf. *Figure 4.13*, *Table 4.2* and *4.3*). The NTE-characteristics also include an assumption about the average load factor at which these plants can be run in base-load. If it is low - which will probably be the case with a large share of intermittent sources and no storage system - electricity costs will be higher. Our assumption has been discussed in paragraph 4.5 (cf. *Figure 4.14*). The cross-price elasticity between TE- and NTE-generated electricity is set at 0.6 and not varied in the present experiments. The fuel cross-price-elasticity's for thermal power plants are also kept constant at the values derived from historical calibration.

The policy variable in this cluster is the RD&D program to stimulate non-thermal electricity options. If this program is introduced over and above its past value (nuclear), it will induce faster learning and as a result NTE will penetrate the market at a faster rate. We have not used this variable in the present evaluation but it is part of ongoing research on optimal strategies (cf. Chapter 8).

The last **cluster 4 : fuel supply**, reflects expectations about the supply side. In view of large uncertainties and diverging views, authors often abstain from long-term price calculations and instead use exogenous fuel price paths both for conventional and for alternative fuels. Assumptions can be changed at two levels :

- technical-geological-ecological : the crucial variables here are the quality decline of the resource with increasing cumulative production, the technological learning-by-doing in surface-coal mining, and for biofuels the potential energy flux as well as the learning-by-doing impact on yields, and
- economic : determinants of the production function which are, for coal and biofuels, the development of the capital-labour ratio and the relative labour costs.

The depletion and learning parameters have been discussed in paragraph 4.3 (cf. *Figure 4.9-4.11*). Some major uncertainties have to do with the production function for biofuels. These have been discussed in paragraph 4.4.1 (cf. *Table 4.1*).

The RD&D programs to stimulate biomass-based fuel options are a policy variable. If such programs are introduced, they will induce faster learning and as a result biofuels will penetrate the market at a faster rate. In the reference run only a minor program between 1980 and 2000 is introduced, reflecting the gasohol programs in Brazil and the USA.

A summary of the model assumptions used for this reference scenario which is meant to reproduce the IPCC-IS92a-scenario, is given in Appendix A. Having discussed the energy-related model parameters, one also has to fix the set of exogenous driving forces : per caput pathways of GWP, Value Added in industry, Value Added in Services and Consumption Expenditures. These have been set in accordance with the over-all TARGETS1.0-simulation experiments for the reference case and are shown in *Figure 5.1* [21].

[21] As has been explained in Chapter 3, for the calibration experiments the historical values and the simulated ones of Figure 5.1 have been used.

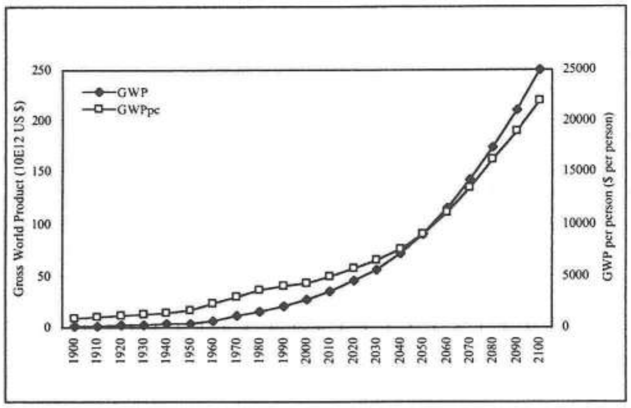


Figure 5.1a Assumptions about the exogenous activity levels 1990-2100 (and the historical trajectories used for the 1900-1990 calibration)

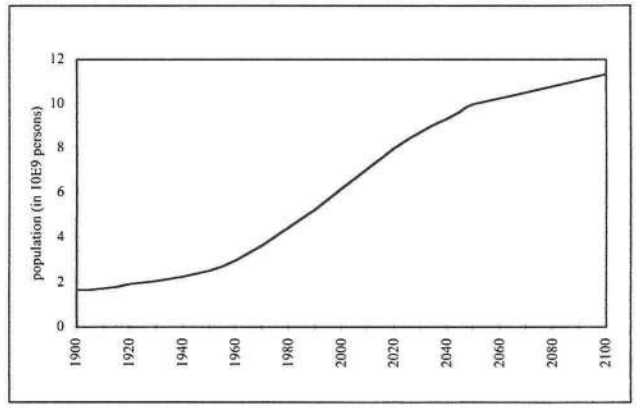
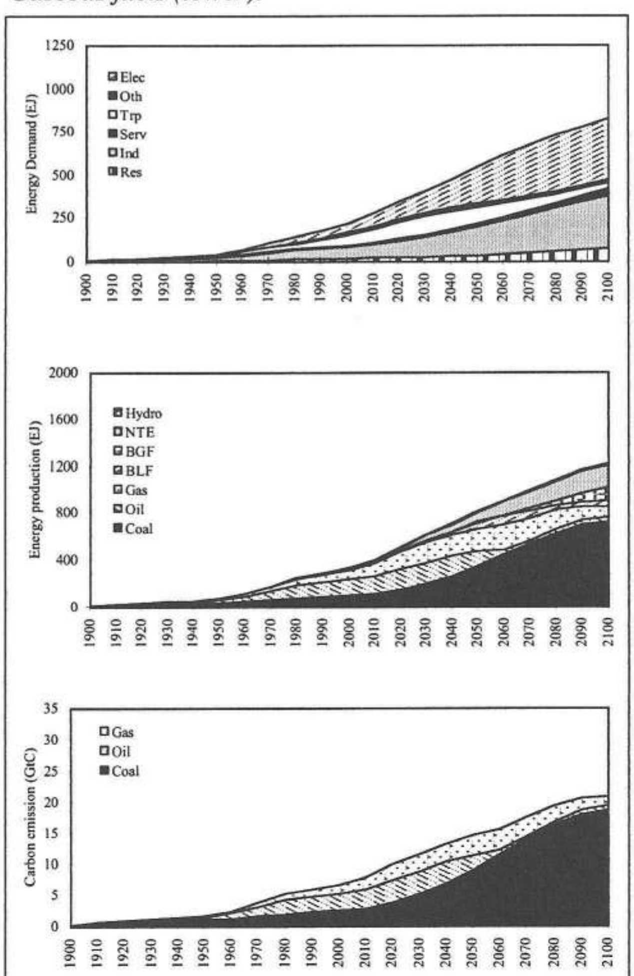


Figure 5.1b: Assumed population size trajectory.

Figure 5.2 Simulation of sectoral non-electricity (heat) energy demand and of electricity demand (upper), of energy production from seven sources (middle) and the resulting carbon emissions from Solid, Liquid and Gaseous fuels (lower).



5.3 The reference scenario : simulation results

The assumptions outlined in the previous paragraph lead to the sectoral use of secondary fuels and of electricity as shown in *Figure 5.2*, left graph. Demand for end-use energy (heat and electricity) before autonomous and price-induced energy-efficiency improvements grows to over 2000 EJ/yr by 2100. Actual use of secondary fuels and electricity is about 800 EJ/yr. This demand is what actually is met by the energy producing sectors. Electricity demand rises to 350 EJ/yr and its share in final demand climbs from the present 18 % to over 40 % in 2100.

Figure 5.3 shows how the energy-efficiency multipliers develop over time. The marginal AEEI-factor decreases towards the lower bound value, followed with a brief delay by the average AEEI-factor. The autonomous reduction in sectoral energy-intensity between 2000 and 2100 ranges from 22% (electricity) to 40% (heat). Because energy costs for consumers increase, there is an additional reduction in the energy-intensity of 3% for electricity to some 40% for the transport sector[22]. These results are broadly similar to the IS92a-data as far as available from published reports. Our analysis suggests that the anticipated tripling of final energy use to 800-850 EJ/yr is plausible with an average 2.3 %/yr GWP-growth, if one uses the assumptions on the IPCC-IS92a scenario.

The results for electricity generation are shown in *Figure 5.4*. About 360 EJe is generated of which over 50 % in non-thermal (NTE) power plants.

[22] It should be recalled that a switch to electric transport is not [explicitly] included.

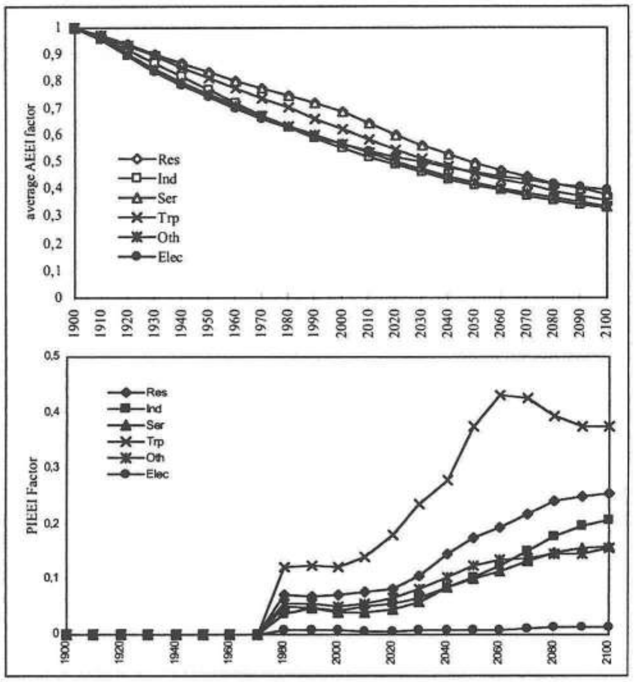


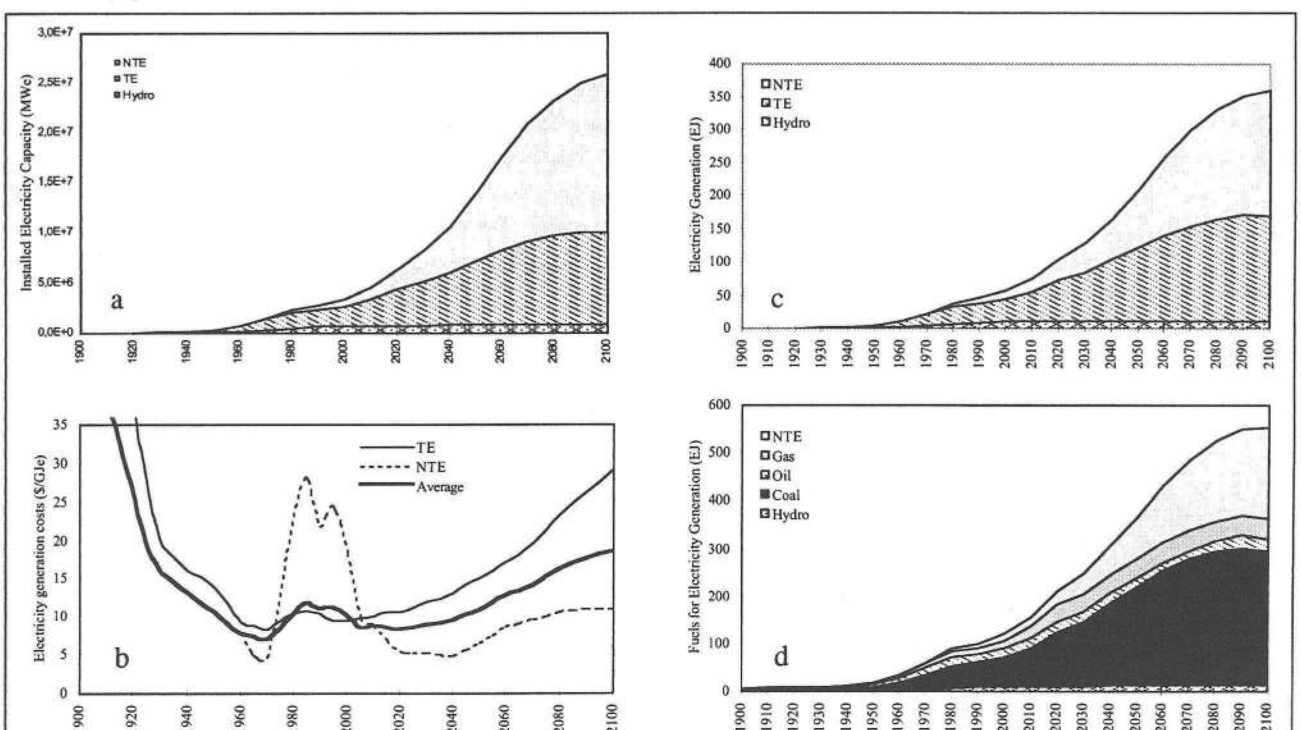
Figure 5.3 Development of the AEEI- and the PIEEI-factors over time for six end-use sectors.

Expansion of hydropower is assumed to be quite modest. Installed capacity increases to about 25.000 GWe by 2100; about two third of it is non-thermal capacity. The thermal electricity is for over 90% generated by burning coal [products] with only minor roles for Heavy Liquid Fuel (HLF) and Gaseous Fuel (GF, including gaseous biofuels). The costs of coal-fired electricity will rise significantly over the next century, but the rather cheap alternative (NTE) tends to stabilize the average electricity price for the consumer.

The assumptions which were derived from the 1900-1990 calibration and from literature about the supply of coal lead to the cost- and price-paths for coal shown in *Figure 5.5*. Surface-mined coal emerges as a competitive option during the next century. As such, it counteracts the rather steep increase in the cost of underground coal which is caused by depletion and by rising labour costs once capital-labour substitution becomes more and more difficult. This results in a smooth rise in average coal price. As said before, the model simulation does not take liquefaction and gasification of coal into account. Thus, the calculated prices and required investments have not a straightforward correspondence with the IPCC-IS92a-scenario.

As *Figure 5.5* shows, coal production increases almost fivefold to about 700 EJ/yr, about the level in the IPCC-IS92a scenario. The share of surface-mined coal only starts rising after 2060; research has to go into coal mining costs as this is probably an

Figure 5.4 Simulation of electric power generation : installed capacity (a), electricity generation costs (b), electricity generation (c) and fuel and NTE inputs (d).



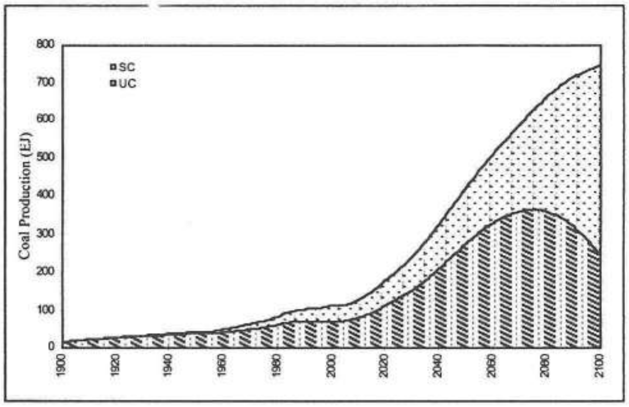
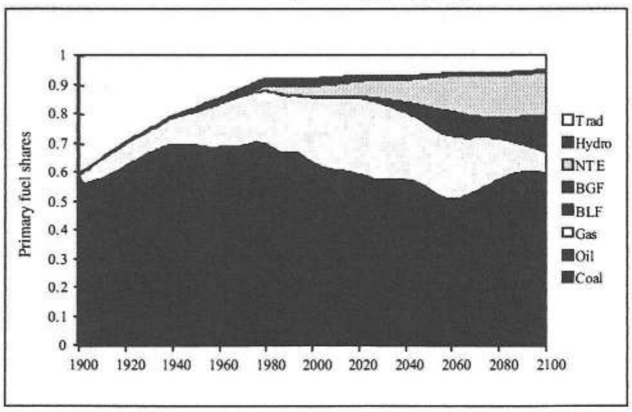


Figure 5.5 Simulation of coal supply, both underground and surface mined.

underestimation. In *Figure 5.6* it is seen how the share of coal drops until 2010 after which it starts rising. Coal accounts for almost two thirds of energy supply by 2100. *Figure 5.6* also shows the production cycles of conventional oil and natural gas, both of which will be depleted by the end of next century in the sense that biofuel-based substitutes have largely taken over because of lower production costs.

Simulated price paths for coal, crude oil and natural gas are shown in *Figure 5.7*. The IPCC-report estimates 29.500 EJ of coal to be available at mine-mouth price of 1.3 \$/GJth. The IPCC-IS92a scenario assumes 9300 EJ of oil to be available at 3.5 \$/GJth and another 2330 EJ at higher prices. For gas it states that 10.800 EJ is available at 3 \$/GJth and another 2500 EJ at higher prices. The IPCC-scenario's do not contain consistent information on fuel price-paths, but a rise like the one shown here is certainly within the range of forecasts.

Figure 5.6 Shares of fossil fuels and non-fossil alternatives in the primary energy supply.



The price of LightLiquidFuel (LLF) and of Gaseous Fuel (GF) is stabilizing after 2060 at a level of about 15 \$/GJ [23]. This is because of the penetration of substitute fuels which are based on biofuels. The rise in oil and gas prices induces within the model the penetration of gaseous biofuels, to an extent and at a rate which is in fair agreement with what is said about this in the IS92a-scenario.The simulations suggest that biofuel technologies with these characteristics would penetrate without the need for major demonstration projects to stimulate the necessary cost reductions; only small demonstration projects are assumed. The decline in BioLiquidFuel (BLF) prices works as a backstop on the price of LightLiquidFuel (LLF) [24].

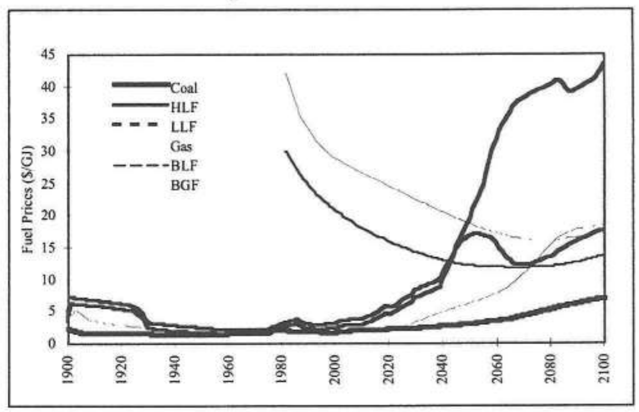
By the year 2100 some 15.000 EJ of oil (IS92a : 12.000 EJ) and about 18.000 EJ of gas (IS92a : 13.000 EJ) has been produced in the simulation. Produced and discovered since 1900 is 31.000 EJ of oil and 17.000 EJ of gas - large amounts in view of most expert judgments on what is ultimately recoverable (cf. paragraph 4.41). By then, its not worth the money to do any further exploration in view of the emerging liquid biofuels as a cost-competitive alternative. Under these assumptions oil and gas are being used several decades into the next century, largely for transport (*Figure 5.2*).

Figure 5.8 shows also some characteristics for the system as a whole : energy-intensity, capital invest-

[23] 1 \$/GJ is equivalent to about 7 \$/bbl.

[24] The continuing rise in the HeavyLiquidFuel (HLF) price is a result of the cost allocation formalism (Vries and Van den Wijngaart 1995).

Figure 5.7 Prices of various fuels change which drives fuel substitution. As fossil fuel resources are depleted, fuel costs rise but the rise in Light Liquid Fuel (LLF) and Gaseous Fuel costs are stabilized by the cost reductions in BioLiquidFuels and BioGaseousFuels.



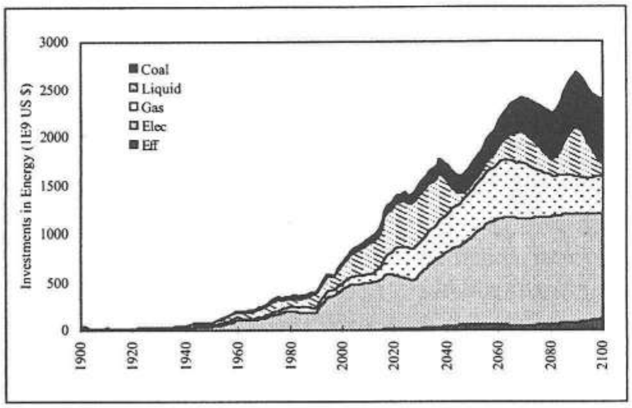


Figure 5.8a: Investments in energy.

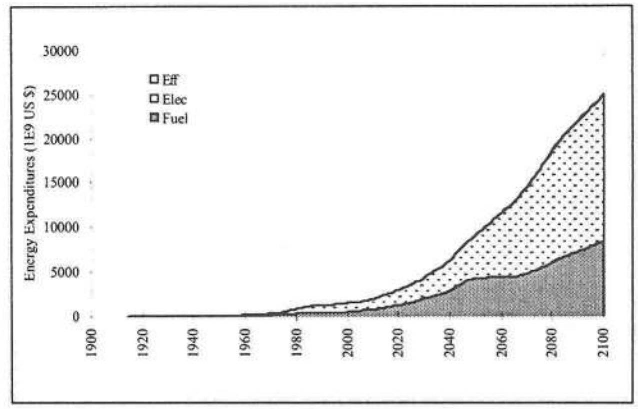


Figure 5.8b: Due to rising fuel and electricity prices, the expenditures on energy will rise, also as a fraction of GWP.

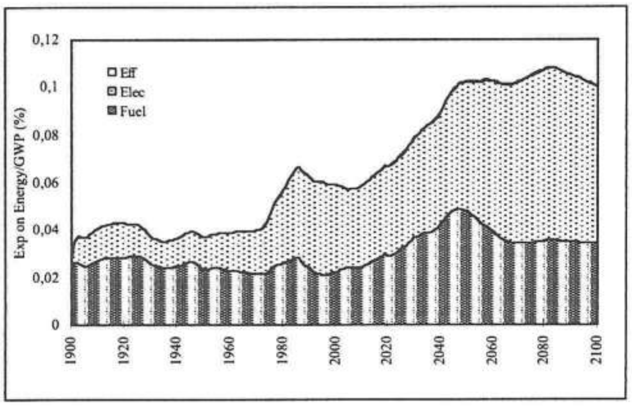


Figure 5.8c: Energy expenditures.

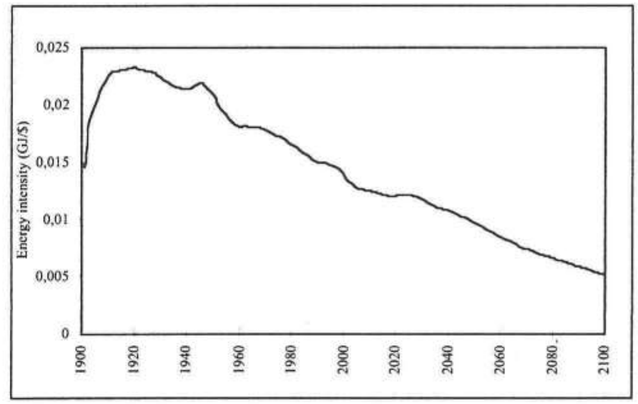


Figure 5.8d: Due to efficiency improvements a decline of energy intensity is expected.

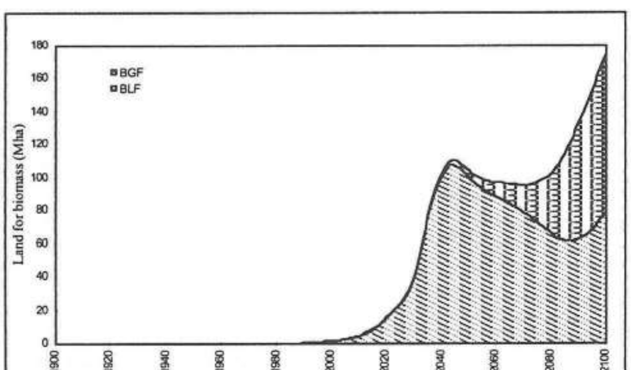


Figure 5.8e: Land requirements for biomass plantations.

ments and average energy price. There is a continuous decline in the energy-intensity calculated as the ratio of primary fuel supply and GWP, from the present 18 to 5 MJ/$ (*Figure 5.8d*). The investments into the energy system are reasonably close to some estimates for the 1990's, but the steep rise later on has not yet elsewhere been discussed (*Figure 5.8a*). Over-all cumulative investments are in the order of 19000 10^9 1990 US $ for the period 1990-2020. This compares reasonably well with the recent estimates of cumulative capital requirements of 16000 10^9 1990 US $ for a medium growth scenario (Nakicenovic and Rogner 1995). The oil [investment-]cycle can easily be discerned, although there is an interesting resurgence in oil investments as biofuels run into land constraints. Electric power generation is a major part of the investment flow due to the capital-intensive nature of the NTE-options. Energy-efficiency and biofuels demand relatively small investments. Investments in energy-efficiency, converted into annual expenditures after division by sectoral payback times, are almost negligible in comparison with the fuel supply costs. The reason is that only the most profitable conservation investments are made and that non-capital costs are neglected. If the energy saved were valued at their market prices, the contribution of energy-efficiency would be more outspoken.

The total expenditures on energy, defined as product of fuel and electricity use and their respective prices plus the expenses for energy-efficiency, increase rather smoothly (*Figure 5.8b*). However, seen as a percentage of GWP, they rise to at most 10% which is way above the level in the early 1980's (*Figure 5.8c*). Note that we do not make any statement about whether the economy can or will afford these investment levels. It is clear that they have to compete for other investments in e.g. agriculture and health. Note also that the both GWP and population paths are exogenous and not affected in any way by [energy] prices, investment levels and the like.

We have attempted to reproduce the IPCC-IS92a scenario as closely as possible. For gas and especially for oil the simulated consumption is higher in the first part of next century than in this scenario. The combination of oil price and biofuel price assumptions cause a rapid substitution in the period 2030-2040.

As *Figure 5.8e* shows the penetration of biofuels causes a rapid increase in land for biomass plantations. Yields increase in the simulation to 1200-1500 GJ/ha. Such yields are extremely high in view of most estimates (cf. *Table 4.1*). This suggests that other factor costs (land, labour, capital) are higher than in the IPCC-assumptions. However, the land requirement of 100-200 Mha is in the order of some other scenario's (Alcamo et al. 1994). Further research into the production function characteristics of biofuels is needed to get a better insights in their penetration dynamics.

Carbon emissions are expected to triple to almost 21 Gton/yr by the year 2100 which is comparable to the IS92a value of 19.8 Gton/yr (*Figure 5.2*). Most of this will come from the use of coal (SF Solid Fuel). The penetration of biofuels and non-thermal electricity generating options causes a reduced growth rate of carbon emissions.

5.4 Some sensitivity analyses

Before we discuss, in the next chapter, the reproduction of other global scenarios, we briefly show the results of some sensitivity analyses for the reference scenario. They are performed by changing the value of a model parameter in the reference run and reporting the relative change of a model variable for the years 2050 and 2100. Parameter changes start in 1990 and are for all sectors (non-electricity) and are the same for all sectors unless stated otherwise. The parameter values for the reference scenario can be found in Chapter 4 and Appendix A.

Energy demand c.q. use

First, secondary energy use depends on the assumptions about structural change, the AEEI-rate and the PIEEI-cost curve. Also important is the assumption on the desired payback-time. *Table 5.2* shows how simulated use of secondary fuels varies if these variables are changed with respect to their reference run values. For structural change we have run the model for two different SC-multiplier assumptions : either constant or half the reference value (cf. *Figure 4.4*). If the growth elasticity is assumed to be much smaller (0.5*ref), energy demand c.q. use is almost halved - again stressing the importance of this parameter.

The AEEI-rate and the PIEEI-cost curve parameter are varied between what we believe are outer bounds (cf. *Figure 4.5-4.6*). As the Table shows, the effects of changes in these parameters are rather modest. The main reasons are that :

a) part of the potential energy conservation through AEEI is already realized in 1990 and this potential gets progressively smaller as time goes on; and
b) with the limited energy price increases in the reference run, energy conservation through PIEEI is rather small and becomes progressively smaller as the price-elasticity tends towards zero. Of course, if the conservation cost curve is assumed to decline much faster and/or the desired payback times are taken much longer, the price-induced energy conservation will be much larger as the fourth and fifth row in Table 5.2 indicate.

Another parameter which affects the energy-intensity is the lower bound on the AEEI-factor. The reference value varies between 0.2 and 0.4, based on historical calibration in combination with other parameters. If a higher value is chosen, the AEEI-factor will become less important. This has a market influence of secondary fuel use.

The markets shares of the commercial fuels is largely determined by their relative price and the cross-price elasticity. The value of the elasticity is between 0.6 (transport) and 1.5 (industry). It turns out that secondary fuel use is rather insensitive to the choice of the cross-price elasticity. This is understandable: changes in fuel market shares only indirectly influence total fuel use.

One last parameter we changed is the degree to which non-oil secondary fuels can penetrate the transport market. If the constraint is removed for the period after 1990, it leads to larger market shares for solid and gaseous fuels which in turn affects prices and hence demand. This effect is negligible, as the last row in *Table 5.2* shows.

It is important to realize that in the integrated TIME-model, a reduction in demand for secondary energy carriers affects the price paths and hence, through the PIEEI-factor, secondary energy use. The price effect can give rise to 10-20% changes. This in turn may reduce demand.

One additional simulation experiment has been done. What will happen with the SC-multiplier for electricity constant and for all heat half the reference-value ? This is one possible transition to an 'all-electric' society : the share of electricity in final demand rises from 25% in 1990 to 59% in 2100 instead of 40% in the reference case. The resulting CO_2-emissions in 2100 are reduced by 3.8 GtC or about 20% as compared with the reference case. It gives an indication of what successful introduction of e.g. electric cars could mean.

Electricity demand c.q. use and generation

Within the electricity generation model, we have explored five changes with respect to the reference run. *Table 5.3* shows the results. The first two have to do with electricity demand and are comparable to the ones in *Table 5.2*. It is seen that our assumption of a steep conservation cost supply curve - that is, a small price-elasticity for electricity - causes electricity demand to be almost insensitive to any change in the electricity system c.q. in the electricity price. Halving this parameter has only a minor impact on electricity use. As a consequence, a change in the desired payback-time is of minor influence as well.

The third change is that the average thermal efficiency of power plants rises to 70% instead of 45% by the year 2100 (cf. *Figure 4.13*). This could be because of successful implementation of combined-heat-and-power schemes, fuel cells and the like. As one would expect, it reduces the fossil fuel inputs with almost one third. It also causes a 10-15% decline in the average electricity price which, however, has only a minor impact on electricity demand c.q. use as said above.

Fourthly, how develops electricity use and fuel input if the present premium on coal is removed over the next 20 years ? This could be the result of removing subsidies or introducing some kind of [carbon] tax. As is seen in *Table 5.3* the resulting higher coal price would lead to an increase in oil and gas use for electricity generation in the order of 45-70% while coal's share would drop with almost one quarter by 2100.

Fifthly, if the non-thermal alternative has a much slower or a much faster rate of learning-by-doing, how would electricity use and fuel input change with respect to the reference run ? In the reference run, we assume modest learning until 2040 after which it is offset by cost-enhancing developments and learning stops. As *Table 5.3* shows, sustaining a modest

Table 5.2 Secondary energy use (non-electric) in 2050 and 2100 as fraction of the reference scenario values for different assumptions on Energy Demand-model parameters.

Variable :	Parameter change	2050	2100
StrCh-multiplier	constant after 1990	1.26	1.69
	0.5 * ref-value	0.51	0.53
AEEI-rate in %/yr	0.5 %/yr	1.15	1.24
	1.5 %/yr	0.88	0.85
PIEEI-cost curve parameter	0.5 * ref-value	0.9	0.88
	1.5 * ref-value	1.09	1.11
Decrease of energy-cons cost curve	1 %/yr (instead of 0.1)	0.90	0.79
Desired Payback-time	0.5 * ref-value	1.08	1.12
	2 * ref-value	0.90	0.86
cross-price elasticity	0.5*ref-value	0.98	0.92
	2 * ref-value	1.02	1.08
lower bound	after 1990		
	0.5 * ref-value	0.85	0.78
	2 * ref-value	1.30	1.41
Fraction oil non-substitutable	0 in 2020	1.05	1.02

Table 5.3 Electricity use and fuel input use in 2050 and 2100 as fraction of the reference scenario values for different assumptions on thermal efficiency, premium factor for coal and NTE-learning coefficient.

Variable :	Parameter change	El-use 2050	El-use 2100	SF input 2050	SF input 2100	LF input 2050	LF input 2100	GF input 2050	GF input 2100
Steepness parameter PIEEI	0.5 * ref-value	0.99	0.99						
	2 * ref-value	1	1.01						
Desired Payback-time	0.5 * ref-value	1	1						
	2 * ref-value	0.99	0.99						
thermal efficiency	to 70% in 2100	1	1	0.71	0.72	0.72	0.74	0.72	0.69
premium on coal price	0 by 2020	1	1	0.80	0.76	1.67	1.43	1.69	1.68
NTE learning coefficient	0.95 *) in 2020, thereafter constant	1	1	0.97	0.82	0.96	0.82	0.96	0.81
	0.8 in 2020, thereafter constant	1	1	0.74	0.34	0.71	0.35	0.72	0.32
NTE-TE cross-price	0.5 * ref-value	1	1	1.04	1.14	1.05	1.13	1.04	1.15
elasticity	2 * ref-value	1	1	0.93	0.77	0.92	0.78	0.92	0.76
Base NTE Load factor	to 0.8 in 2020, thereafter constant	1	1	0.61	0.47	0.61	0.49	0.61	0.44
	to 0.5 in 2020, thereafter constant			0.89	0.79	0.89	0.81	0.89	0.77

*) 0.95 means a 5% cost reduction on every doubling of cumulative output

learning rate causes a decrease in the use of fossil fuel for electricity generation and leads by 2100 to nearly 20% lower fossil fuel input. If the learning rate is assumed to be sustained at a rate of 20% cost decline per output doubling, it would reduce fossil fuel inputs with two thirds by 2100. Evidently, this is one of the most important parameter assumptions with regard to future fossil fuel use and CO_2-emissions, given that our model assumes relative generation costs of NTE to be the major determinant of its penetration.

Another parameter to be explored is the cross-price elasticity between TE and NTE capacity. It determines the fraction of NTE investments in the total as a function of relative generation costs. Presently, it is set at 0.8. As Table 5.3 shows, fossil fuel input is not very sensitive to its value for the first decades but it could accelerate the introduction of NTE if in combination with a high learning rate.

Here, too, it should be noted that the results include the feedbacks which result from changes in fuel prices through different rates of electricity conservation and of learning and from different depletion patterns for fossil fuels.

The penetration rate of the NTE capacity is quite dependent on its cost and therefore on the assumption about the base-load factor which is realized for this capacity. If it is nuclear, with an assumed base-load factor of a high 0.8, the costs of NT-electricity are relatively low despite its high specific investment costs. However, if the non-thermal alternative consists of capital-intensive options like wind- or wave-power or solar photovoltaics and has a low average base-load factor, these costs will be much higher and the resulting penetration rate is much slower. [25] Table 5.3 indicates that the input of fossil fuels is 40-55 % lower if NTE can be operated at a high 0.8 base-load factor. Once again, the simulation result incorporates the effect on electricity use through different price-paths. Of course, more research into these aspects of the transition to non-thermal electricity production as modelled here is needed.

Production of fossil fuels and biofuels

A third interesting area for sensitivity analyses is the fuel supply sector. The dominant assumption here is how production costs change with cumulative use (cf. *Figure 4.9-4.11*). We have varied the production

[25] This omits any consideration of electricity storage options. These could mitigate the impact of low base-load factors, but they are themselves quite capital-intensive.

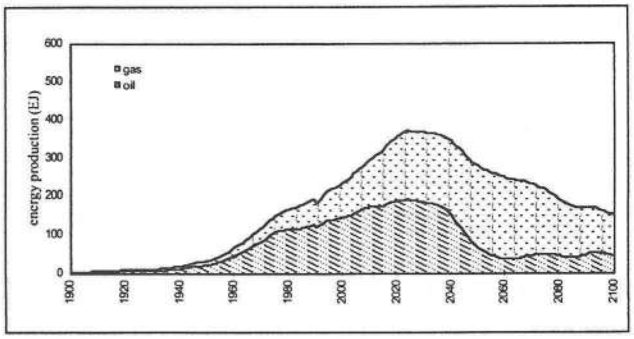


Figure 5.11 a: Oil and gas supply for the reference scenario (excl. biofuels).

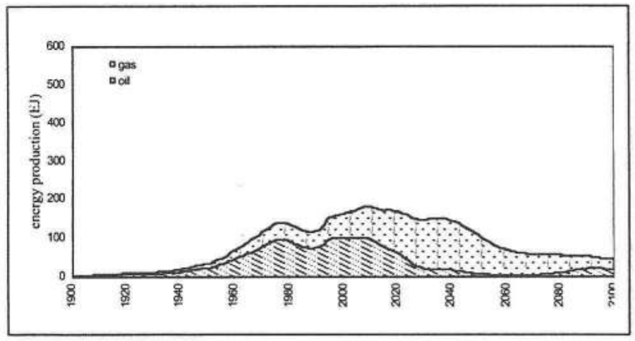


Figure 5.11 b: Oil and gas fuel supply for twice as fast an increase in production costs of oil and gas with depletion.

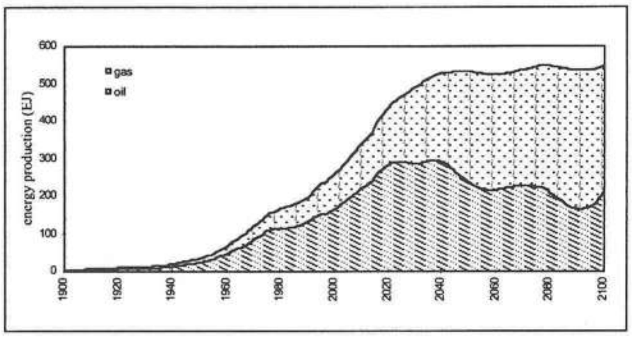


Figure 5.11 c: Oil and gas supply for half as fast an increase in production costs with depletion.

costs of oil and gas at the mid-point, i.e., when 50% of the ultimately recoverable resource is consumed, with a factor 2 resp. 0.5. As this is done by halving resp. doubling of the initial resource base, it slightly affects the calibration. The resulting primary oil and gas production profiles are shown in *Figure 5.11a-c.*

A key determinant of future energy production will be the cost of coal. Evidently, this depends not only on production costs but also on consumer preferences (including environmental aspects) and on technology (liquefaction/gasification, fluid-bed a.o.). In the model the most important determinants of coal use are the price and the technology-related market constraints. Price is mainly determined by the share of surface coal, surface coal learning and depletion effects, and underground coal labour costs and the capital-labour ratio.

Table 5.4 shows that a high learning coefficient for surface coal - which was set at 0.9 from calibration experiments - could significantly increase the use of coal in the long term. Coal use is similarly sensitive for a much lower cost increase with increasing depth, at least in the second half of the next century. Coal use is rather insensitive to the assumptions about the specifics of the production

Table 5.4 Coal use and CO2-emission in 2050 and 2100 as fraction of the reference scenario values for different assumptions on depletion multipliers, learning coefficients and capital-labour ratio and labour costs relative to per caput consumption.

Variable :	Parameter change	Coal use 2050	Coal use 2100	CO_2-emissions 2050	CO_2-emissions 2100
SC Learning Coefficient	0.95*)	0.98	0.92	0.99	0.94
	0.8	1.07	1.24	1.03	1.19
SC Depletion Multiplier (depth)	0.5 * ref-value	1.08	1.20	1.04	1.16
	2 * ref-value	0.95	0.84	0.99	0.89
UC Cap-Lab Ratio	0.5 * ref-value	0.97	0.95	1.02	0.96
	2 * ref-value	1.01	1.05	0.96	1.02
UC Labour Cost	0.5 * ref-value	1.07	1.06	1.00	1.06
	2 * ref-value	0.92	1.02	0.97	0.98

*) 0.95 means a 5% cost reduction on every doubling of cumulative output

function for underground coal. One reason is that its role in total coal production is diminishing by the time labour costs become really high.

Another important set of parameters has to do with biofuels. The presentation in *Table 5.5* in terms of change relative to the reference scenario is somewhat misleading as both BLF and BGF only start to penetrate the market around 2050 and hence the absolute amounts in the reference run are rather low around 2050. Biofuel (BLF, BGF) supply could grow much faster if the rate of innovation (learning-by-doing) is higher than the reference 10% cost reduction per output doubling. This is because then costs decline much faster which speeds up the penetration. The same holds for BGF. A lower rate of learning has the reverse effect but smaller.

We also explored the importance of two major cost factors : labour and land costs. In the present formulation of the biofuel production function, labour costs are assumed to be a fixed fraction of per caput consumption. It does affect the rate of biofuel penetration but less than the assumption on land cost, as *Table 5.5* shows.

A third aspect of biofuel production is the decline in yield as production expands into less productive regions. The reference assumption is that yields will have dropped by a factor 2 when BLF c.q. BGF output reaches 300 EJ/yr. If this limit - and the subsequent assumption on yield decline - is doubled, biofuel supply hardly changes because it will be felt only after 2100. If this maximum potential is halved, the impacts are seen already well before 2100 (Table 5.5).

Concluding remarks

The previous simulation experiments indicate that variables like fossil fuel input and CO_2-emission are especially sensitive for the values of c.q. assumptions on :

- end-use energy demand per unit of activity ('structural change');
- especially in the first part of next century : the potential and cost of energy conservation measures;
- the efficiency of thermal electricity generation options;
- especially in the second part of next century : the characteristics of key supply technologies like non-thermal electricity options and innovations in surface coal mining and commercial biofuel production; and
- behaviour and policy related parameters like the desired payback time for energy efficiency investments and coal subsidies.

It should be noted that these one-factor sensitivity experiments are only a first, rough exploration of the sensitivity of key output variables for certain model parameters and do not reflect feedbacks into the energy system through the economy. These could be very important, e.g. when capital shortages cause energy shortages or when innovation rates are influenced by economic growth rates.

Importance of prices and technology

Some interesting simulation experiments have been done to explore the relative importance of

Table 5.5 BLF and BGF production in 2050 and 2100 as fraction of the reference scenario values for different assumptions on the learning coefficient, the cost of labour and the cost of land.

Variable :		BLF supply		BGF supply	
	Parameter change	2050	2100	2050	2100
Learning coefficient	0.95 *)	0.60	1.04	0.32	0.50
	0.8	1.32	1.39	6.17	1.57
labour cost as fraction of cons/cap	0.5 * ref-value	1.03	0.85	1.19	1.35
	2 * ref-value	0.93	1.27	0.70	0.47
land cost	0.5 * ref-value	1.33	1.09	0.86	1.38
	2 * ref-value	0.83	0.85	0.003	0.04
Max potential	0.5 * ref-value	0.96	1.05	0.96	0.77
	2 * ref-value	1.02	0.99	1.02	1.05

*) 0.95 means a 5% cost reduction on every doubling of cumulative output

technology vs. prices [26]. We first have removed for the whole period 1900-2100 two external phenomena in the TIME-model : the premium factors and the exogenous oil and gas price increase between 1973 and 1985. These have been introduced for calibration purposes as has been explained elsewhere (cf. paragraph 4.2.2 and *Figure 4.7-4.7b*). The results are shown in *Figure 5.12* and *5.13*. There are some interesting differences with the historical calibration :

- the market share of gas almost doubles for the first part of the 20th century, largely at the expense of coal; oil has a slightly larger market share, too, and maintains its position between 1975 and 1990 (*Figure 5.12b*);
- oil and gas are more rapidly depleted which causes an earlier and steeper increase in their prices;
- energy demand is slightly higher between 1980 and 2020 (*Figure 5.13a*);
- coal has an earlier comeback from 2000 onwards with in its aftermath an almost equal penetration of commercial biofuels;
- carbon emissions are almost unchanged during the 20th century because the various impacts (including higher demand) cancel out; after the year 2000 carbon emissions are a few percent higher as coal's share increases but at lower demand levels (*Figure 5.13c*).

A general conclusion of this experiment is that the system tends to speed up the depletion cycle of the premium-valued fuels (oil, gas), if premium factor and exogenous price shocks are removed. Of course, these experiments are merely indicative because the parameterisation of oil and gas in the first part of the 20th century is full of uncertainty.

[26] This experiment was suggested in comments received from Dr. A. Grübler.

Figure 5.12a-c Simulated primary energy market shares for the reference run (upper), in a world with no premium factors and no 1973-1985 oil crises (middle) and with no technical constraints on market penetration as well (lower).

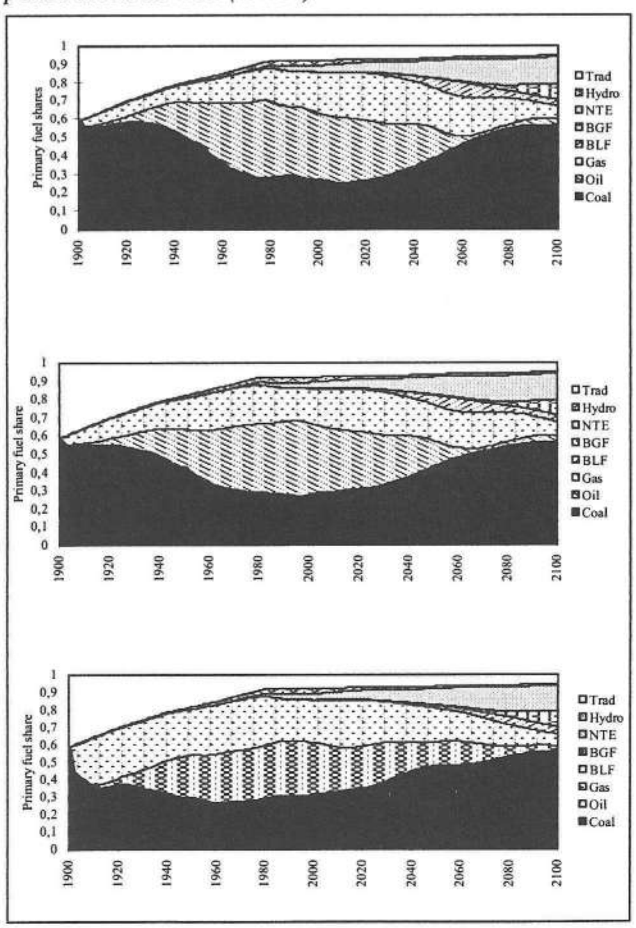
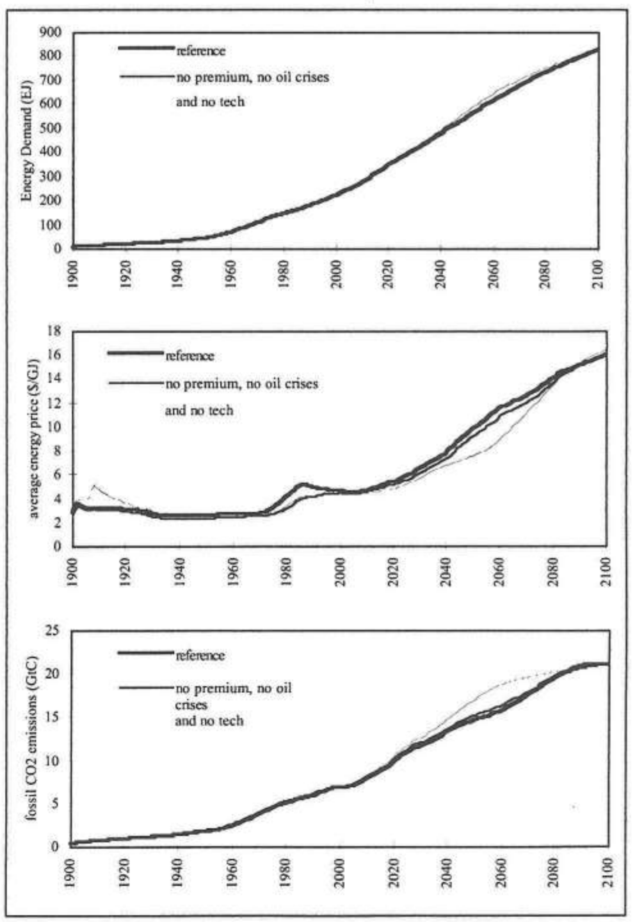


Figure 5.13a-c Simulated energy demand, average energy price and fossil fuel carbon emissions in the reference scenario and in a world with no premium factors and no 1973-1985 oil crises and with no technical constraints on market penetration as well.



Taking the experiment one step further, we also removed the technical constraints which limited the penetration of oil and gas (cf. *Figure 4.8*). As *Figure 5.12c* shows, the system now immediately switches to a situation of only slightly changing market shares during the 20th century - in fact, each of them having one third of the market for commercial fuels. This shifts the comeback of coal 20 years forward in time and it postpones the penetration of biofuels (because coal can now penetrate the transport market). Interestingly, the average energy price trajectory is significantly below those in the previous experiments - and demand is higher (*Figure 5.13a-b*). This is mainly caused by the large availability of cheap coal in the next century. One result is that carbon emissions are some 30% higher in the middle of next century (*Figure 5.13c*). Coal expansion ends rather abrupt after 2060 when commercial biofuels rapidly gain a market share of 15% between 2060 and 2100.

6. SCENARIO [RE]CONSTRUCTION: SOME OTHER GLOBAL ENERGY SCENARIOS

6.1 Introduction

In the past decades numerous energy scenarios have been developed. They differ in the level of aggregation, the degree of economy-energy interaction and the assumptions on fuel prices and resources and on cost and penetration of new technologies (energy conservation, nuclear, renewable). Appendix B gives an overview of the scenarios which are presently most representative and relevant at the global level.

An important set of scenarios in the context of the climate change issue are those presented by the IPCC, referred to as IS92a-f (Pepper et al. 1992). The IPCC has published an evaluation of these scenarios (Alcamo et al. 1994). A recent overview of population, economic growth, energy and emission (CO_2, SO_2) scenarios is given by the AIM (Asian Integrated Model) project team (Matsuoka et al. 1995). Both surveys indicate a wide spectrum of possible futures. For population and economic growth there is a divergence of a factor 10; for CO_2-emissions of a factor 60. However, there is apparently some move towards convergence - although it is hard to say whether this is because of expert consensus or expert imitation. We will briefly discuss a few scenarios which have been chosen for reproduction with the TIME-model.

In 1993 SEI published a study made for Greenpeace which explored the possibilities for a fossil-free future (Lazarus et al. 1993). It was assumed that demographic and economic developments would largely follow the conventional views of e.g. World Bank, but with more emphasis on equity. Its main aim was to show that even at high growth rates of population and economic activity, a fossil-free future can be realised in the course of the 21st century. However, preliminary simulation experiments indicate that we were not able to reproduce the fuel use and emission profiles of this scenario, especially in the short term. Hence, we leave this scenario out of our discussion.

A group of scientists has published the so-called Low CO_2-emitting Energy Supply System (LESS) scenario, the contours of which go back to the early 1980's (Goldemberg et al. 1985) and the Renewables-Intensive Global Energy Scenario (RIGES, Johansson et al. 1993). The most recent report on the LESS-scenarios is one prepared for the IPCC Second Assessment Report, Working Group IIa (Williams 1995). This study describes in numerical detail five scenario constructions. Four of these assume a high degree of decoupling of energy demand from economic growth and hence only a doubling of energy demand. These four variants comprise a biomass- and a nuclear-intensive variant of the reference case, a natural gas intensive variant and a coal-intensive variant. The fifth scenario is a high-demand scenario with a quadrupling of energy demand over the next century - similar to the IPCC-IS92a scenario.

We do not consider these scenarios in the present report because the LESS-scenarios involve a rather

The Stockholm Environment Institute (SEI) states in a report to Greenpeace (Lazarus et al. 1993) : *'Achieving a fossil free energy future will require major changes in energy policy and lifestyles. The wasteful high energy consumption path that the North has enjoyed has to end. Future energy use will have to be extremely efficient, and increasingly based on sustainable renewable energy sources such as solar, wind and biofuels. The basis of that wasteful lifestyle is of course the economic growth and development path that we have chosen...'*

The central finding of the LESS-study is *'that there are various **alternative** paths to the energy future that can be pursued for achieving deep reductions in CO2-emissions over the long term (to ~ 2 GtC/yr by 2100), at projected costs for energy services that would be plausibly comparable to the projected costs of these services provided by conventional energy systems. This finding is contingent on society's active pursuit of technological innovation in the energy sector.'* (Williams 1995 pp. 3). Technology and learning-by-doing are key elements in these scenarios. Major commitments to energy R&D-programs are assumed.

elaborate description of various supply technologies and the TIME-model can in its present form only reproduce these scenario elements in a very aggregate way.

In the course of 1994, Shell Planning Centre has published various scenarios in which the consequences of dematerialisation and energy conservation and renewable energy technologies are assessed (Kassler 1994, Shell Venster 3/4 1995). It is suggested that the IPCC-IS92a scenario cannot serve as a reference scenario with respect to future carbon emissions and climate change impacts because it underestimates the huge potential for reducing energy-intensity and for decarbonization in the form of non-carbon nuclear and/or renewable energy sources.

One of the two scenarios presented by Kassler (1994) of Shell Planning is called New Frontiers. It depicts a world with high economic growth in the developing world and in which environmental problems are resolved by market instruments. Renewable energy sources mitigate the threat of climate change. *'As they progress along their learning curve, first capturing niche markets and then gradually expanding, new energy sources may well become commercially competitive over the next decades and start to be visible around 2020. [] It is not necessary, for this argument, to determine which renewable technology has the best prospects. Technologies will compete but the market will decide. [] With this perspective in mind, the idea of 'saving hydrocarbons for future generations' is perhaps unduly conservative. [] It is also worth noting that this scenario ... would have powerful implications for the climate change debate... There is an exciting challenge lying ahead : reaching New Frontiers following a path which makes economic sense. The industry has the capability and is prepared to tackle this task, as it has demonstrated through past and recent achievements. Policy makers must also create the market conditions allowing this to happen. ' This scenario is mirrored in a second one called Barricades; it is more dystopian : 'liberalisation is resisted and restricted because people fear they might lose what they value most [] There is increasing divergence between rich and poor economies, as many poor countries become marginalized, partly by the lack of foreign investment. [] In the developed world, a number of non-governmental organisations... cause energy to be regarded as something bad and to be used sparingly, leading to an unfavourable investment climate in this sector.'*

Recently, as part of a joint IIASA-WEC project, six scenarios were presented as an extension of three previously published scenarios by the WEC (WEC 1993, IIASA/WEC 1995). As to energy demand the major conclusions are that world energy needs will increase, that primary energy used per unit of GDP will fall significantly and that energy end-use patterns will converge, even as energy system structures diverge. Quality of energy services and forms will become an increasingly important factor, as well as local environmental impacts. Resource availability is expected not to be a major constraint, whereas decarbonization will diminish environmental impacts at all scale levels. Up to 2020 the six scenarios hardly diverge because of system inertia (existing investments, lead times for new technologies). After 2020 the scenarios show an increasing divergence, especially on the supply side. Also other, sector-oriented scenarios were presented at the World Energy Conference.

The major assumptions and outcomes of some of these scenarios are given in *Table 6.1*.

In the context of the World Energy Conference Statoil (1995) states : *'Discussing transport sector energy demand towards 2020, this report is based upon the assumption that an extrapolation of current trends would be insufficient. Therefore, the bulk of the report consists of a discussion on possible 'trend-breakers' []. Energy security is not likely to become a major issue in the next few decades. [] Population growth and urbanisation inevitably mean that local pollution problems will soon reach thresholds of reaction, leading to considerable changes in current urban transport trends... as regards the potential threat of global warming due to human activities, [] the difficulties in reaching international agreement on limitations of CO2- and other greenhouse gas emissions, at a time when scientific evidence is still inconclusive. [] Even in the absence of a scientific consensus, the potential gravity of global climate change merits precautionary measures already today.'* (pp. iv-v)

Table 6.1 Key assumptions and outcomes of various global future energy scenarios.

Scenario :	IS92a	IS92a	IS92e	IS92e	IIASAa	IIASAa	IIASAc	IIASAc	Shell	Shell
Scenario variable in year :	2050	2100	2050	2100	2050	2100	2050	2050	2060	2060
GWP (10e12 1990$)	92.4	243.1	138	520.3	100	300	75	75	170	170
Population (10e9)	10	11.3	10	11.3	10.1	11.7	10.1	10.1	10	10
GWP/cap (1990$)	9.200	21.500	13.800	46.000	9.900	25.640	7425	7425	17.000	17.000
Primary energy use (EJ)	934	1453	1240	2494	1045	1885	835	585	1453	872
Prim. energy-intensity (MJ/$ 1990$)	10	6	9	5	10.45	6.3	11.1	7.8	8.6	5.2
Carbon emission (Tg)	13.2	19.77	18.6	34.9	9-15	7-22	10	5	9.0	8.0

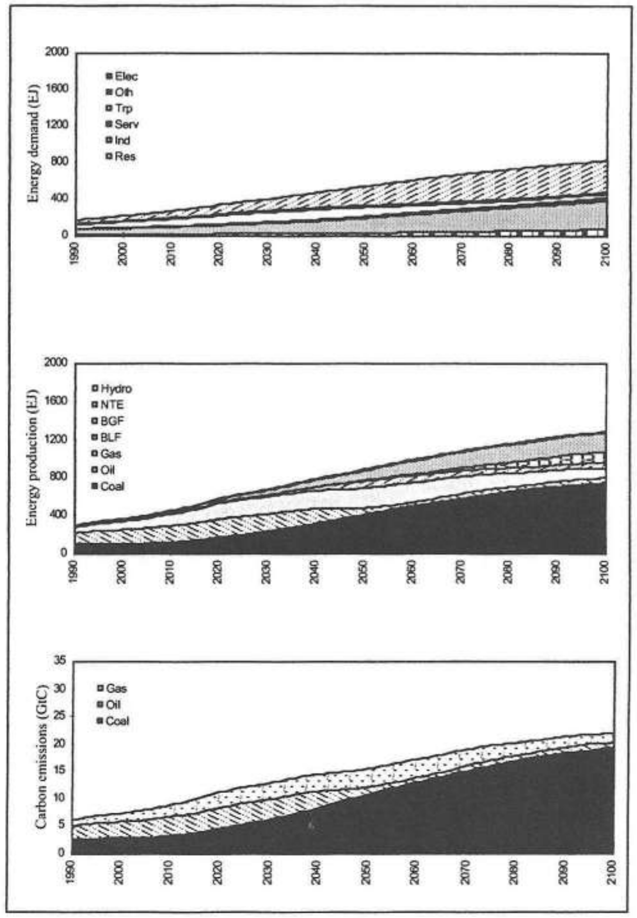
In the following paragraphs we explore two scenarios which use different assumptions with regard to energy supply systems : Supply-Oriented Technology Change (SOTC) and with regard to energy demand : Demand-Oriented Technology Change (DOTC). We also present a few results for a scenario which uses both sets of assumptions : Energy System Technology Change (ESTC). All three scenarios are also discussed in Chapter 8 as part of optimization experiments. They incorporate some key assumptions underlying the scenarios presented by IIASA/WEC and Shell.

6.2 The IS92e-scenario : 3 %/yr instead of 2.3 %/yr GWP-growth

First, we consider a different question : how would the future look if the IS92a-assumptions, as outlined in Chapter 5 are combined with the economic growth path of the IS92e-scenario and Shell-scenarios of an average 3 %/yr in the period 1990-2100. Some results are shown in *Figure 6.2* in comparison with a simulation with 2.3 %/yr GWP-growth (*Figure 6.1*). Key findings are :

- sectoral heat demand soars to almost 1250 EJ/yr, electricity demand rises to almost 500 EJ/yr, i.e. twice the IS92a-level;
- electricity production from NTE-options and coal use for electricity are by 2100 almost twice the value in IS92a;
- fuel demand is largely met by relatively cheap coal and the share of coal in the primary energy supply increases to almost 60%;
- biofuels play a relatively limited role, after 2060, because their cost levels are not competitive with coal c.q. the coal-derived liquid and gaseous fuels;
- biofuel plantations require, under these assumptions, huge areas of land;
- carbon emissions steadily grow to a level of about 32 GtC/yr;
- energy investments keep growing; as a fraction of GWP the expenditures for energy remain close to 10% and are 1-2 % point higher than in IS92a;

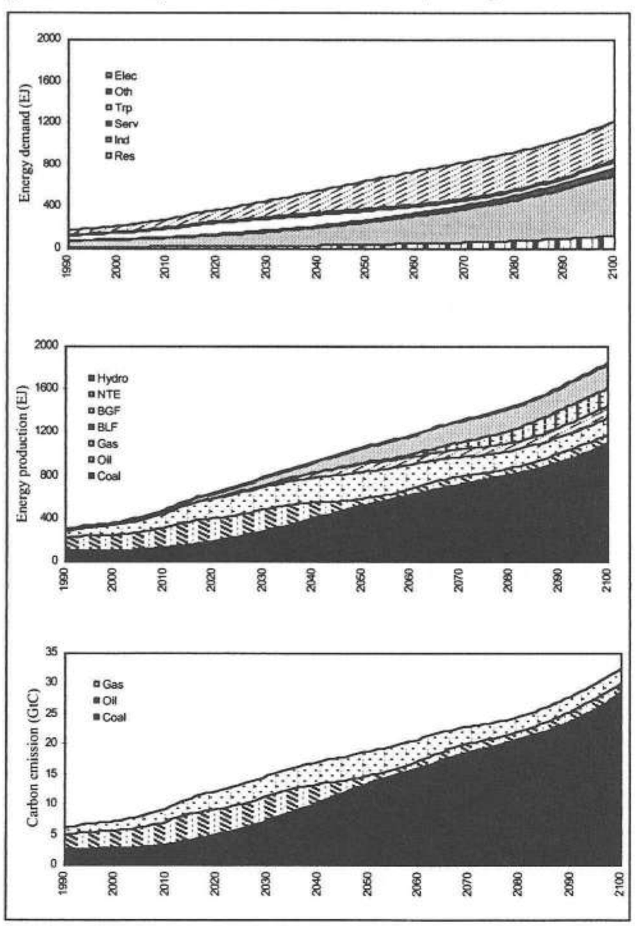
Figure 6.1: Simulation of sectoral non-electricity (heat) energy demand and of electricity demand (upper), of energy production from seven sources (middle) and the resulting carbon emissions for the IS92a scenario (lower).



- the average energy price in the economy quadruples; price-induced energy-efficiency is slightly higher than in IS92a.

Comparison with the IS92e scenario indicates that coal use is close to the IS92e-outcome while oil and gas use are too high until their precipitous decline around 2060. Coal prices are much higher than in IS92a because of further depletion but also higher per caput income and therefore higher labour costs. From this simulation experiment it can be concluded that the IPCC-IS92 scenarios are fairly well reproduced with the TIME-model on the basis of largely common assumptions.

Figure 6.2: Simulation of sectoral non-electricity (heat) energy demand and of electricity demand (upper), of energy production from seven sources (middle) and the resulting carbon emissions (lower) for the IS92a scenario with 3.0%/yr instead of 2.3%/yr growth rate of Gross World Product (GWP).



6.3 The Supply-Oriented Technology Change (SOTC) scenario

One of the two scenario's which we investigate in more detail is one in which energy supply systems are characterised by fast technological change and consequently a rapid decline in costs. This scenario contains elements of the LESS-scenario (Williams 1995) and reflects also in some ways the Sustained Growth scenario as published by Shell Planning (Kassler 1994, Shell/Venster 3/4 1995). Assuming the same growth rate as the IS92e scenario, i.e. an average 3%/yr for the period 1990-2100, its estimate of final demand is similar to IS92a but the supply side is quite different. The main argument behind this scenario is that new technology will make known and as yet unknown non-carbon energy options much cheaper and markets will ensure their subsequent introduction. Another argument is that coal, when it is correctly priced, will never be able to expand as much as in the IS92a-scenario.

To construct such a SOTC-scenario, one can of course choose from a variety of options. However, the simulation experiments showed that the following key ingredients always emerge :

- coal must be made much more expensive, which reflects either the removal of subsidies c.q. the imposition of additional costs or the assumption of a faster decline of coal grade and depth as production proceeds;
- the learning rate for NTE-generating options (solar photovoltaics, wind etc.) has to be higher so that around 2050 the cost of NTE-electricity is less than half the value in the IS92a-scenario;
- the learning rate for biofuels, both liquid and gaseous, have to be higher also, and the potential for biomass has to be made significantly higher to avoid a large cost increase as more marginal lands cause lower yields.

In our simulation, we use the IS92a-scenario assumptions and the SOTC economic growth rate of 3%/yr as discussed in Chapter 5 as the starting point. The following changes have been implemented:

a) assume that coal is effectively not used in the transport sector by keeping the premiumfactor at 6 $/GJ(instead of a decline to 0 by 2100); this is tantamount to saying that coal liquefaction/ gasification play no role in the fuel market;
b) assume that also in the other markets, coal cannot penetrate because subsidies are removed and coal liquefaction and gasification are not developing; this is done by letting the premium factor

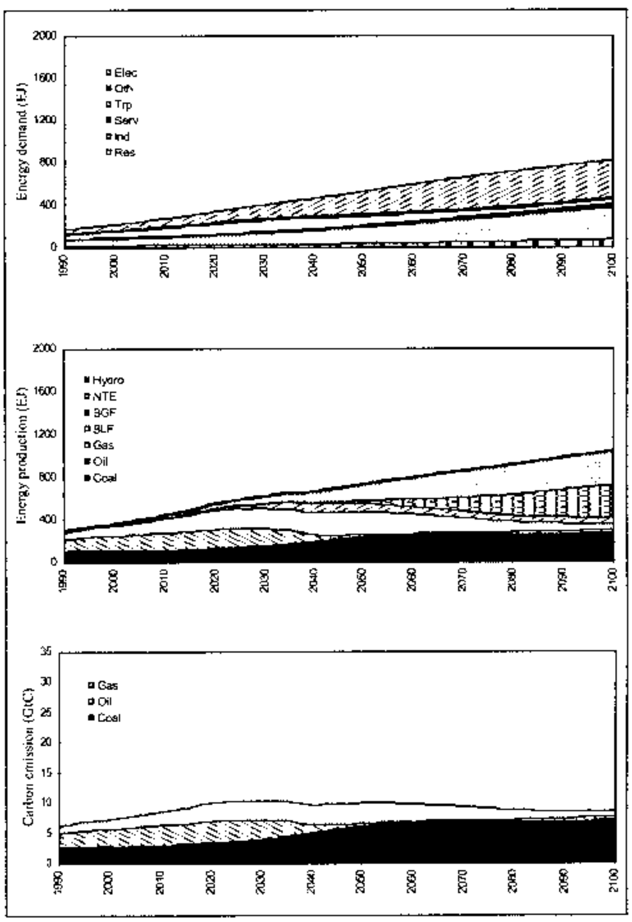
approach 3 ($/GJ) from 2050 onwards for all sectors;

c) make the effective coal price for utilities equal to 80% (instead of 30-40%) of the average coal price, i.e., the removal of allegedly hidden subsidies before 2020-2030;
d) increase the conversion efficiency of thermal electric power plants towards an average 60% by 2100; although this supports fossil-fuel based electricity, it is in line with the scenario's supply optimism.
e) assume that the production costs of surface-mined coal increase much faster because average coal seam depth increases twice as fast with cumulative production as assumed in the IS92a-scenario; this causes a tripling of the price of surface-mined coal by 2100 to a level of 5-6 $/GJ;
f) assume that despite the large share of intermittent sources, the NTE baseload factor can be maintained at 0.6; this makes NTE-electricity one third cheaper;
g) assume that learning-by-doing for NTE continues at a 10% cost reduction per doubling of cumulative output throughout the next century; this is one way of accounting for the emergence of new and very cheap non-carbon electricity generating options.
h) make biofuels more attractive which results in lower and more stable biofuel prices until at least 2080, in the following way[27] :
    - assume that the potential for both BLF and BGF at which a cost doubling occurs is three times bigger (900 EJ/yr)
    - assume faster and more learning for both BLF and BGF : a 15% yield increase (instead of 10%) for every doubling of cumulative production (learning coefficient of 0.85).
    - assume that for both BLF and BGF the relative cost of labour are 50% instead of 70% of average global per caput consumption levels.

After these changes are implemented in the 3%/yr economic growth IS92a-scenario, coal use drops from 1100 to 300 EJ/yr by 2100. The share of coal in primary fuel supply peaks at 30% in 2050 and coal use is still larger than in IS92a. Renewables have their share increasing up to 60% by 2100. Coal for electricity generation is down to 40 EJ/yr. Carbon emissions are stabilising at about 20 GtC/yr in 2080 after which they slowly increase. Energy-efficiency is about the same as in IS92a, one of the reasons being that the average electricity price is down and stable at the low level of 6-8 $/Gje. Until 2070 investments levels are at most 50% above the levels in IS92a as supply technologies are highly productive and, for biofuels, labour- and not capital-intensive. The investments in energy-efficiency are underestimated because no depreciation/replacement are considered in the present calculation. After 2070 investments in the energy system soar again as the limits for cost reductions are reached and expensive fossil fuel is again gaining market share. Due to the cheap non-fossil options total energy expenditures as a fraction of GWP do never exceed 10%. Note that we have not changed the assumptions on the long-term supply cost curves for oil and gas.

Figure 6.3-6.7 show the result of this set of assumptions. Energy demand, after autonomous and price-induced reductions, is still almost 800 EJ/yr,

Figure 6.3: Simulation of sectoral non-electricity (heat) energy demand and of electricity demand (upper), of energy production from seven sources (middle) and the resulting carbon emissions (lower) for the SOTC scenario including 3%/yr GWP-growth.



[27] that is, a learning coefficient of 0.9 (cf Chapter 4).

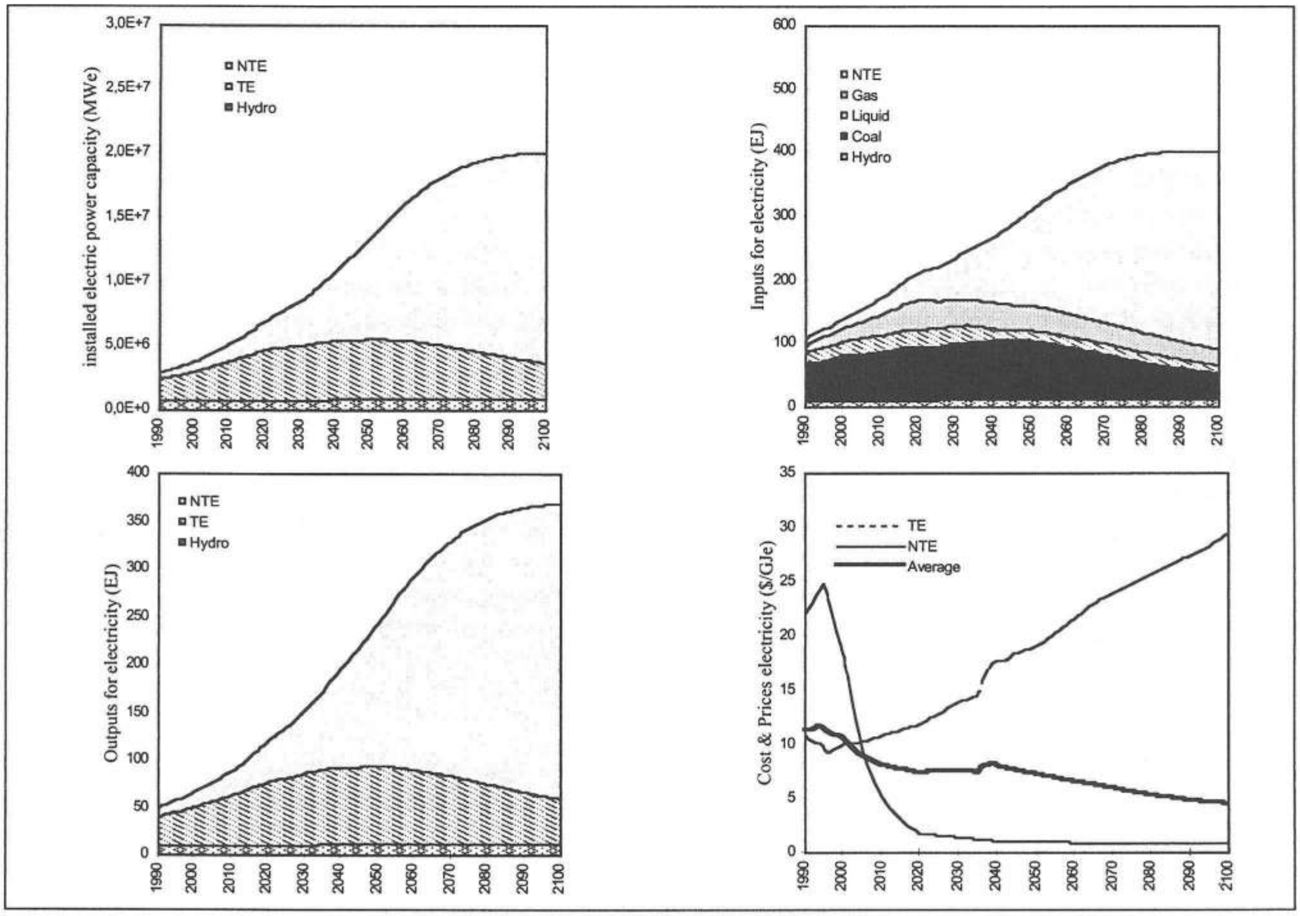


Figure 6.4: SOTC scenario with 3%/yr GWP growth. As electricity demand increases, installed capacity will expand (upper left). An increasing share of capacity and of generation (lower left) will be based on non-thermal (NTE) options. Thermal electricity (TE) will largely be generated with coal (upper right), the rising costs of which will be stabilized by the cost drops in NTE-technologies (lower right).

while primary energy supply in 2100 is about 1000 EJ/yr. The price of biofuels has dropped by 2050 to levels between 30 and 60 $/bbl. Yields on biomass plantations climb to over 3000 GJ/ha. This is implausibly high; it occurs because in the present formulation it is the only way in which we introduce learning-by-doing to lower production costs. This requires in the order of 100 Mha of land - similar to the IS92a-scenario simulation (*Figure 6.7*). Exponentially rising electricity production comes for over 50% from NTE-capacity from 2060 onwards and, because it is so cheap, average electricity price is about half the 1990-level (*Figure 6.4*). With these assumptions, carbon emissions fluctuate in the second half of next century between 10 and 12 GtC/yr and reach a level in 2100 of 8 GtC/yr down from 32 GtC/yr in the IS92a scenario with 3% growth rate (cf. *Figure 6.3*).

Of course, it is possible to reduce the use of coal further. However, we feel that it is increasingly implausible to raise the assumed future costs c.q. prices of coal without at the same time discussing whether and to what extent this can be done without any reference to a carbon tax. Another way of coming closer to the SOTC estimates of fuel input is to assume large[r] RD&D-programs to stimulate new supply technologies and assume that by 2060 unknown carriers will enter the market with cost-competitive and societally acceptable but as yet unknown characteristics. We have not explored this route because it is inconsistent with the non-interventionist character of an individualist growth-oriented scenario (cf. Chapter 7) and because it introduces unknowns which are inherently escaping any means of quantitative assessment. A third option to reduce energy use is to change the energy-intensity of the [sectoral] activities - not explored here as was said in the introduction

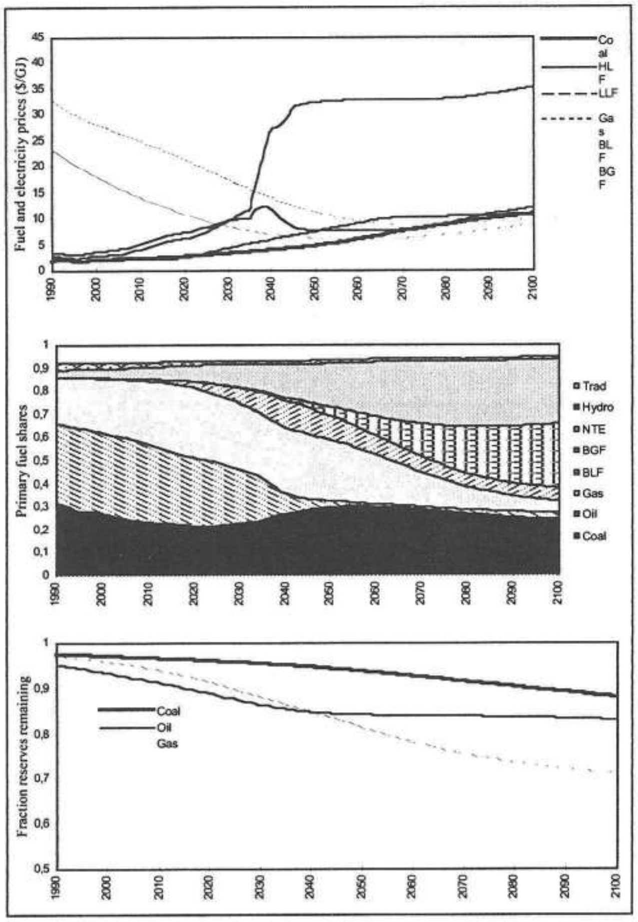


Figure 6.5: SOTC scenario with 3%/yr GWP growth. Prices of various fuels (upper) change which drives fuel substitution (middle). As fossil fuel resources are depleted (economically)(lower), fuel cost rise but the rise in liquid fuel and gaseous fuel costs are stabilised by the cost reductions in biofuels (upper).

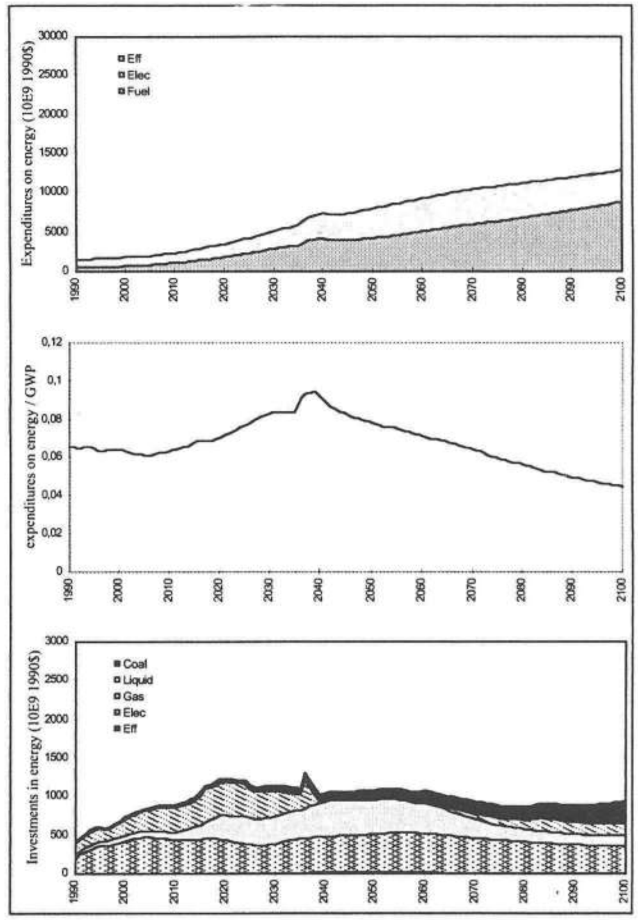


Figure 6.6: SOTC scenario with 3%/yr GWP growth. Due to rising fuel and electricity prices, the expenditures on energy will rise (upper), also as a fraction of GWP (middle). The increasing scarcity of oil and gas, the switch to alternatives and energy improvements will require large investments (lower).

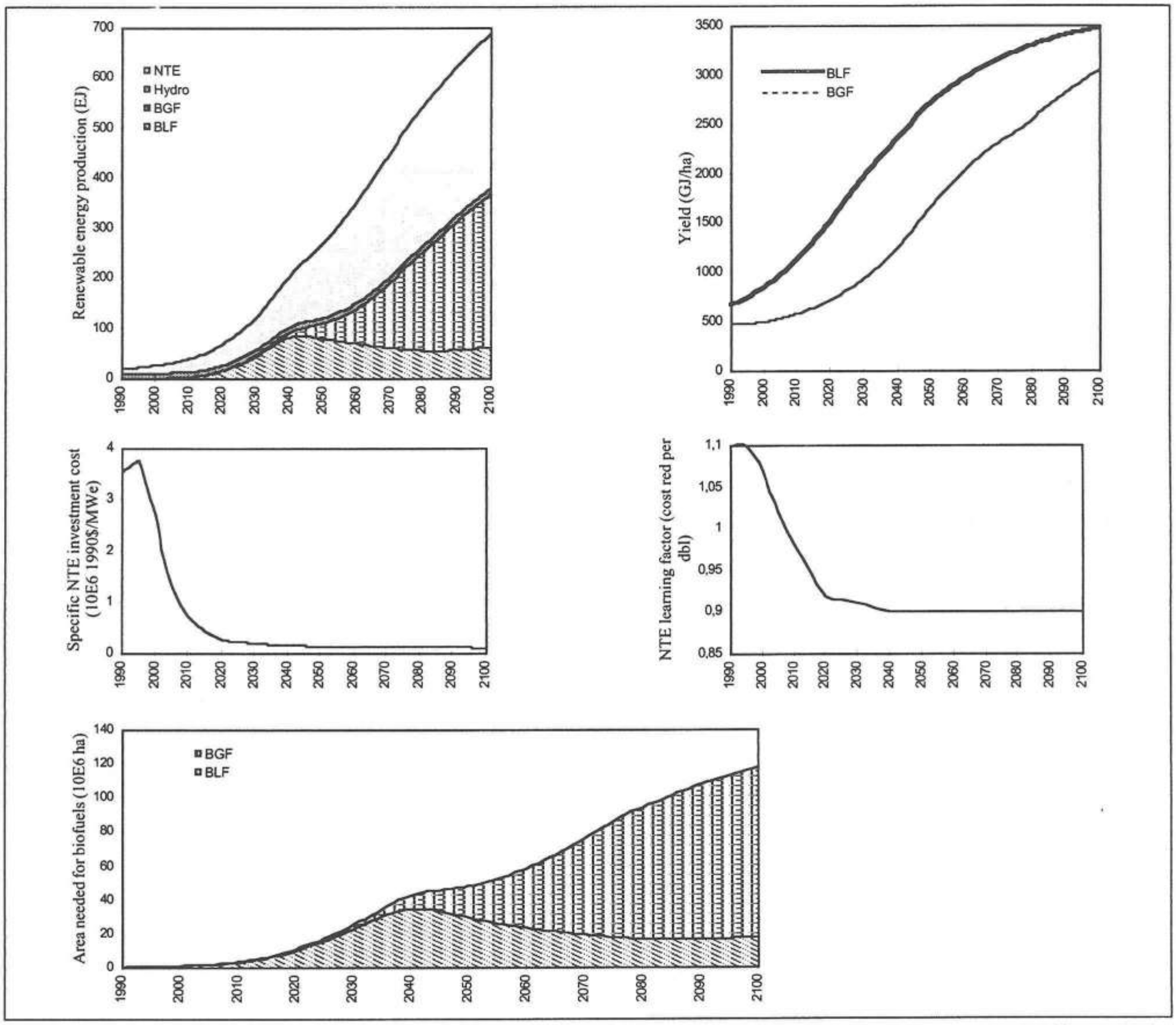


Figure 6.7: SOTC scenario with 3%/yr GWP growth. Energy production from renewable sources will reach the 1990 world energy use level in the year 2100 (upper left). This is possible because specific investments costs of non-thermal electric options are assumed to decline because of learning-by doing (middle left) and the yields of biofuels will increase (upper right).

6.4 The Demand-Oriented Technological Change (DOTC) scenario

Another scenario which could lead to low-carbon emissions is one in which the emphasis is on drastic reduction in the average energy-intensity of economic activities. This is, for example, suggested in the LESS-scenario (Williams 1995b) and in the Dematerialisation scenario of Shell Planning (Kassler 1994, Shell/Venster 3/4 1995). Its key message is that waves of innovative energy efficiency technologies in combination with shifts in economic activity patterns make it possible to sustain a 3%/yr GDP-growth at a much lower carbon emission paths. Assuming the same growth rate as the IS92e, i.e. 3%/yr, its estimate of final energy demand is much lower than IS92a but the supply side assumptions are the same as in IS92a (cf. Chapter 5).

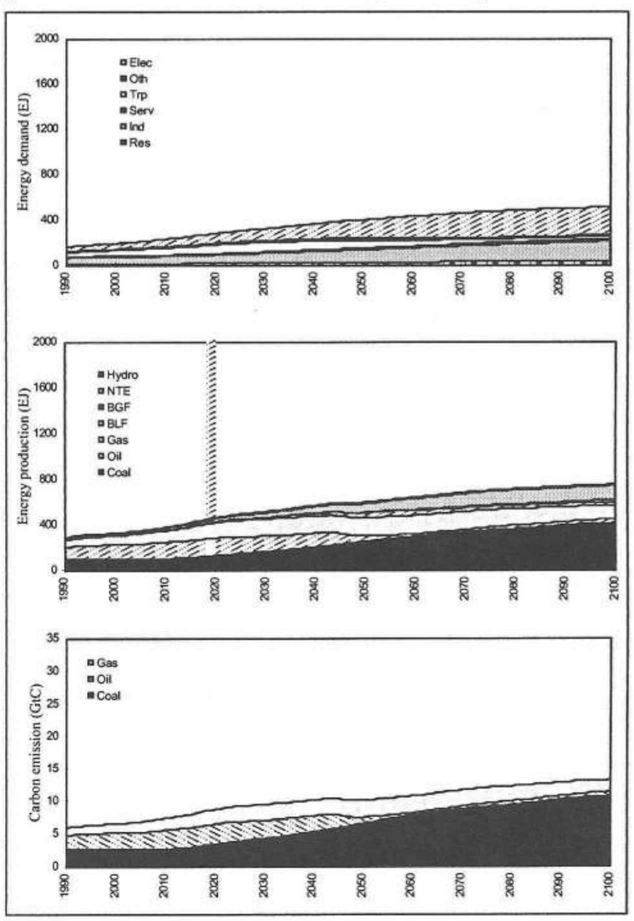
To evaluate this scenario, one has to focus on the options which induce a decline in the energy-intensity without changing the activity patterns as defined within the model. The key ingredients all have to do with either autonomous or price-induced reductions in the energy-intensity. We have chosen the following modifications with respect to the IS92a-scenario with 3 %/yr GWP-growth :

a) as in the SOTC-scenario, there is an increase in the conversion efficiency of thermal electric power plants towards an average 60% by 2100;
b) the rate of Autonomous Energy Efficiency Improvement (AEEI) increases to 1.5 %/yr (instead of 1 %/yr) in 2050 and stays at that level thereafter;
c) the lower bounds on the AEEI-based energy-intensity reductions are halved so that the effective rate is larger than in IS92a[28];
d) the steepness of the PIEEI-curve, an indication of the investment level in $/GJ at which about 60% of the energy demand can be conserved, is halved;
e) it is assumed that economies of scale, innovation etc. lead to an annual decline of the conservation investment cost curve with a rate which slowly increases to 0.5 %/yr;

The key result is that energy demand and primary energy supply are below the IS92a-path despite the higher economic growth rate (*Figure 6.8*). There is a one-third faster decline in the energy-intensity than in IS92a. Part of the reduction is due to the precipitous downward jump in the AEEI-factor between 1990 and 2000, as a result of which the primary energy supply and the carbon emission paths are significantly below the IS92a-values during the next century. The price-induced multipliers are 7-10 % point higher than in IS92a. However, because energy savings slow down the depletion of fossil fuels, the average energy price rises less quickly than in IS92a - which in turn slows down further increases in energy productivity. Overall energy-intensity drops from 18 MJ/$ in 1990 to about 2.5 MJ/$ in 2100.

Further inspection of *Figure 6.8-6.11* show that coal is still the major fuel in the larger part of next century. Use of secondary fuels and electricity is in 2100 about 500 EJ/yr above the IS92a-level in 2100; primary energy supply lags 20-40 years because of the more optimistic outlook on energy conservation.

Figure 6.8: Simulation of sectoral non-electricity (heat) energy demand and of electricity demand (upper), of energy production from seven sources (middle) and the resulting carbon emissions (lower) for the DOTC scenario with 3%/yr GWP-growth.



[28] Notice, that this causes a discontinuity because of the calibration for the period 1900-1990 (Figure 4.5)

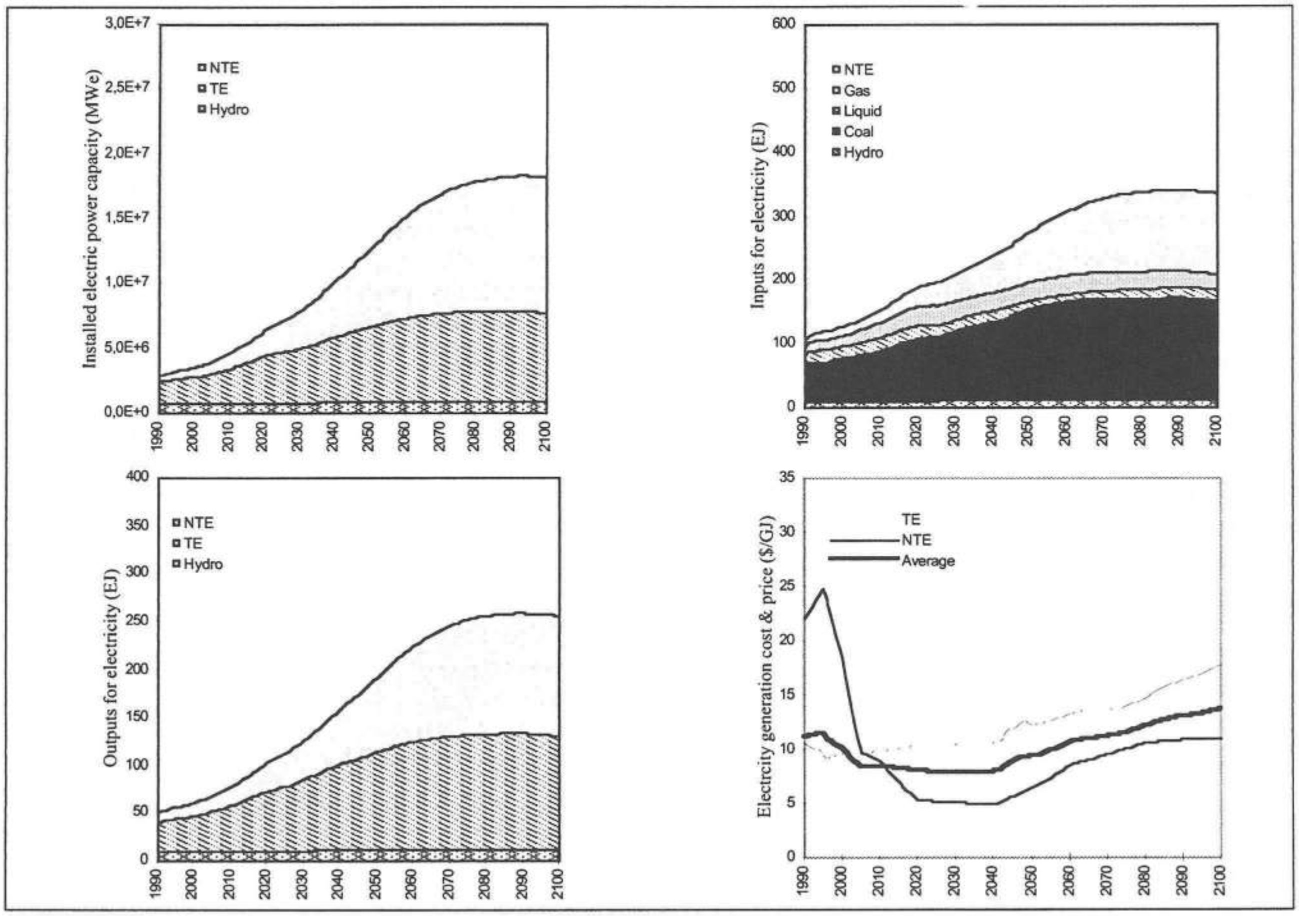


Figure 6.9: DOTC scenario with 3%/yr GWP growth. As electricity demand increases, installed capacity will expand (upper left). An increasing share of capacity and of generation (lower left) will be based on non-thermal (NTE) options. Thermal electricity (TE) will largely be generated with coal (upper right), the rising costs of which will be stabilized by the cost drops in NTE-technologies (lower right).

Because savings on non-electricity (heat) are assumed to be cheaper than on electricity - which has been the case in the past - the major reduction is in sectoral non-electricity (heat) demand and the share of electricity in total final demand rises to over 40% by the year 2100. It should be noted, however, that this is not or at best an implicit switch to an all-electric society (electric cars, electric heating etc.) because the model does not explicitly account for electricity use in the five sectors. By 2100 over 50% of electric power is generated non-thermally; coal is still the primary input (*Figure 6.9*). Because of the conventional assumptions on biofuels and the reduced demand, biofuels penetrate less rapidly. Consequently, at most 200 Mha are used for biomass plantations. Fossil fuel prices rise more slowly as depletion is retarded and biofuel price levels never drop below 80 $/bbl (*Figure 6.10*).

The comparison of the simulation experiment with the DOTC-scenario's clearly show the major difference: coal use in DOTC is almost twice coal use in SOTC. The resulting carbon emissions do not exceed 12 GtC/yr before 2050, but continue to rise afterwards as the potential for cost-effective energy conservation is depleted (*Figure 6.8*). As to the economic aspects: there is an increase in the investment flows into energy efficiency, which are underestimated in the present formulation, but the retarded use of fossil fuel leads to smaller over-all expenditures for energy (cf. *Figure 6.11*).

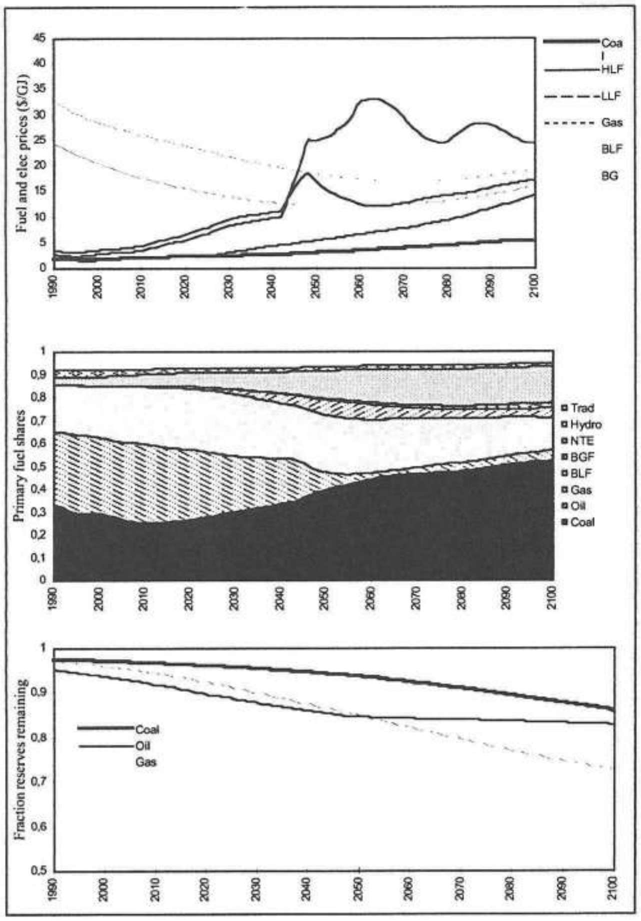


Figure 6.10: DOTC scenario with 3%/yr GWP growth. Prices of various fuels (upper) change which drives fuel substitution (middle). As fossil fuel resources are depleted (economically)(lower), fuel cost rise but the rise in liquid fuel and gaseous fuel costs are stabilised by the cost reductions in biofuels (upper).

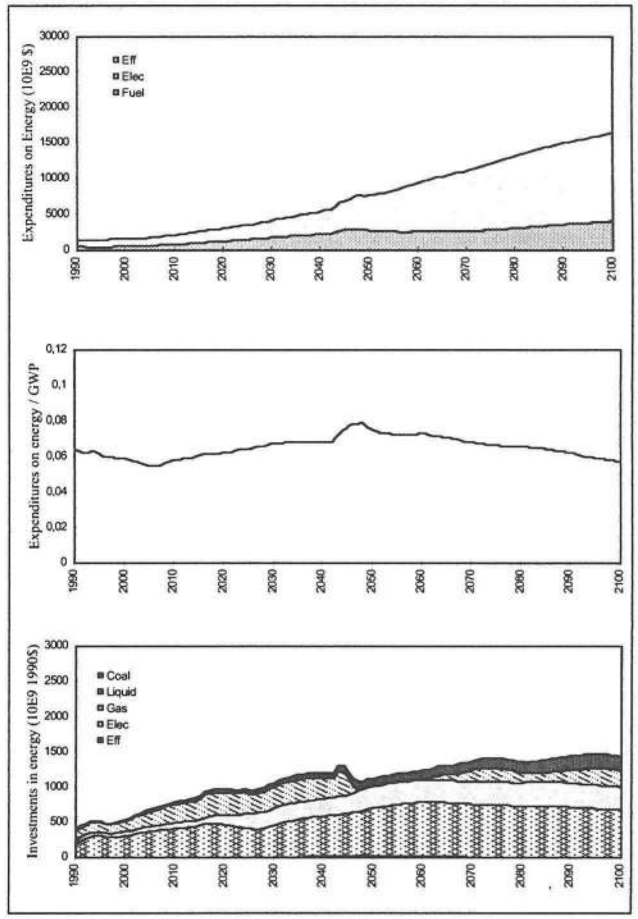


Figure 6.11: DOTC scenario with 3%/yr GWP growth. Due to rising fuel and electricity prices, the expenditures on energy will rise (upper), also as a fraction of GWP (middle). The increasing scarcity of oil and gas, the switch to alternatives and energy improvements will require large investments (lower).

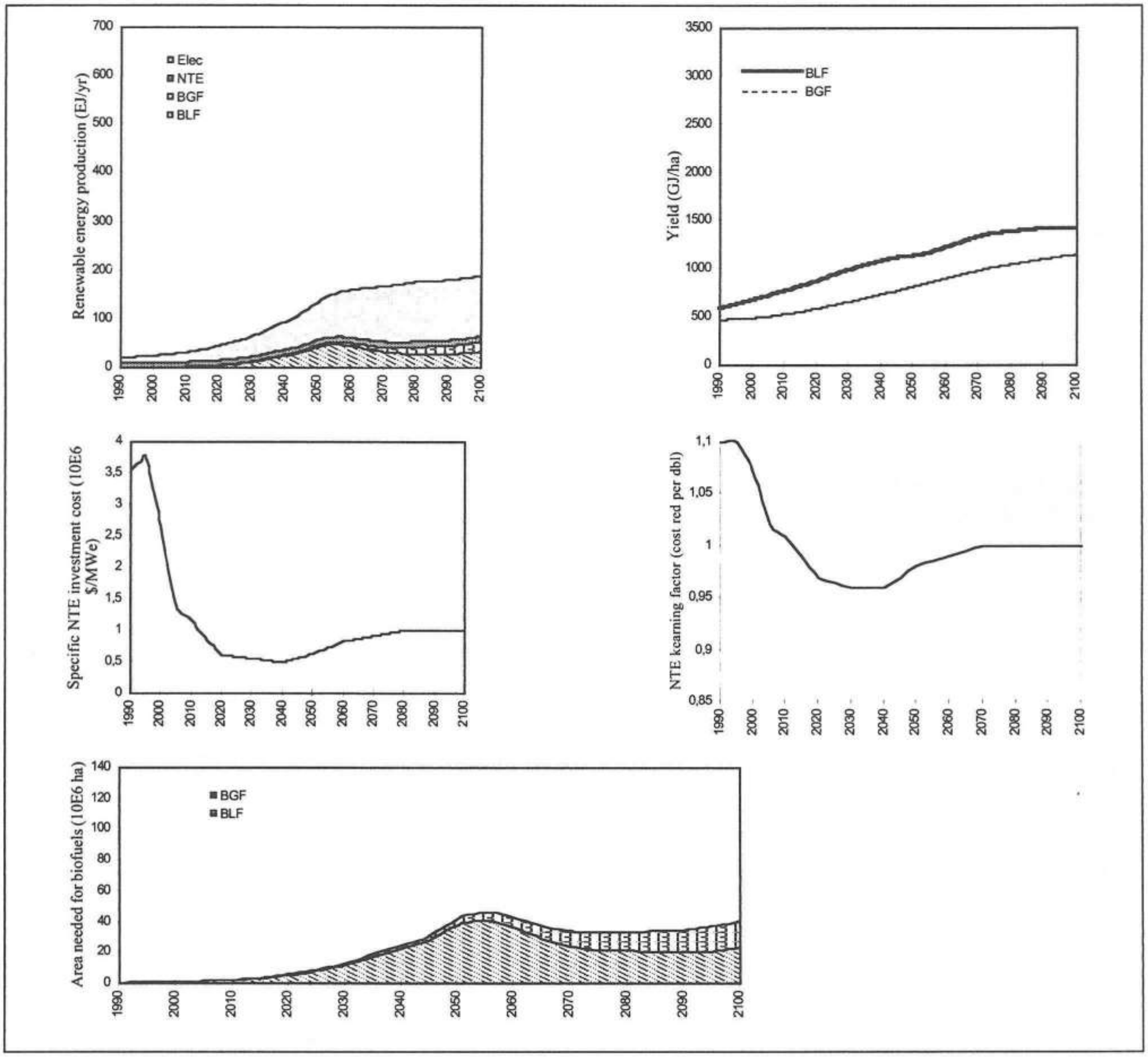


Figure 6.12: DOTC scenario with 3%/yr GWP growth. Energy production from renewable sources will reach the 1990 world energy use level in the year 2100. This is possible because specific investments costs of non-thermal electric options are assumed to decline because of learning-by doing and the yields of biofuels will increase.

6.5 Technological Change in Supply and Demand : the Energy System Technological Change (ESTC) scenario

If we combine the assumptions on the supply side technologies of the SOTC-scenario with those on the demand side developments of the DOTC-scenario, the resulting picture is shown in *Figure 6.13-6.17.* As is to be expected, energy demand for secondary fuels and electricity drops to 500 EJ/yr in 2100 and the supply side is not that much different from SOTC. Yet, there are some interesting differences due to the interactions between supply and demand. The major differences in comparison with the SOTC scenario are about 100 EJ/yr lower energy production by 2100, a delayed oil production decline and 5-6 GtC/yr lower carbon emissions by 2100 (cf. *Figure 6.13*). As compared to the DOTC-scenarios, the proportion of electricity in end-use demand is slightly higher. Coal production has almost halved, which is the main reason for the lower carbon emissions. This reduced coal use occurs largely in the electric power generation sector, where the much more competitive NTE-option captures the market for over 80% (*Figure 6.14*). The price levels are 10-20 % lower than in the SOTC-scenario because of much slower depletion (*Figure 6.15*). This is also the reason why energy demand is higher than in the DOTC scenario- but not much because most of the price-induced efficiency gains have been realized before the second half of the next century. Energy efficiency investments increase from 2020 above the levels of the SOTC-scenario, but the resulting decline in energy demand causes a downward pressure on fossil fuel prices (*Figure 6.15*). This retards the introduction of renewables and hence the constraints on land are less. These preliminary experiments suggest some of the stabilizing factors in the complex interaction between demand and supply developments.

Figure 6.13: Simulation of sectoral non-electricity (heat) energy demand and of electricity demand (upper), of energy production from seven sources (middle) and the resulting carbon emissions for the ESTC scenario including 3%/yr GWP-growth.

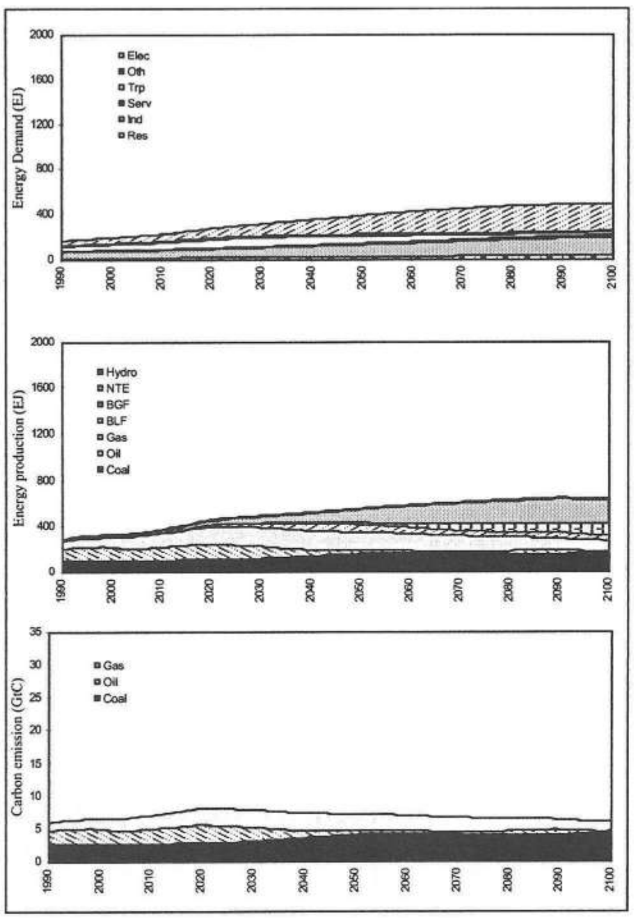
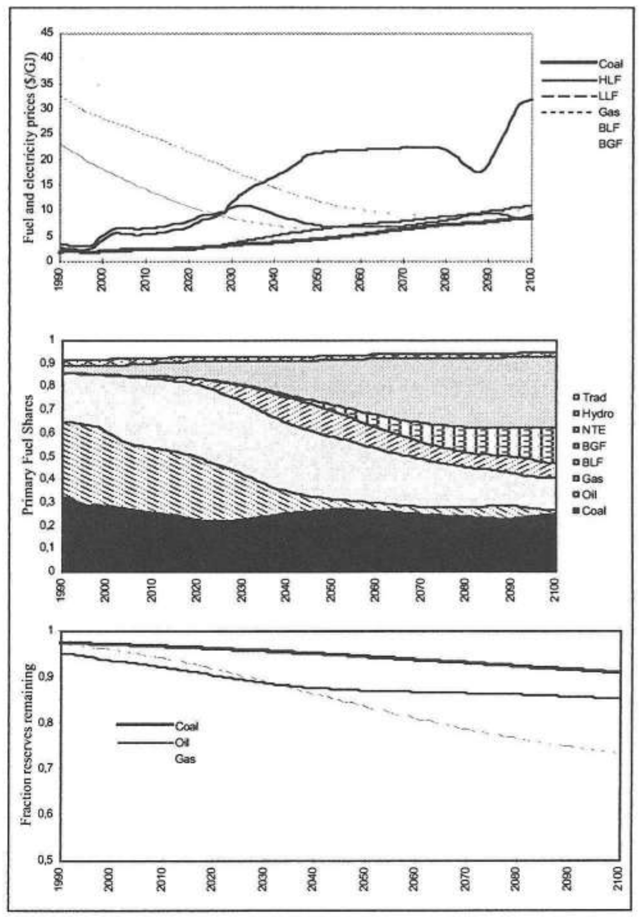


Figure 6.15: ESTC scenario with 3%/yr GWP growth. Prices of various fuels (upper) change which drives fuel substitution (middle). As fossil fuel resources are depleted (economically)(lower), fuel cost rise but the rise in liquid fuel and gaseous fuel costs are stabilised by the cost reductions in biofuels (upper).



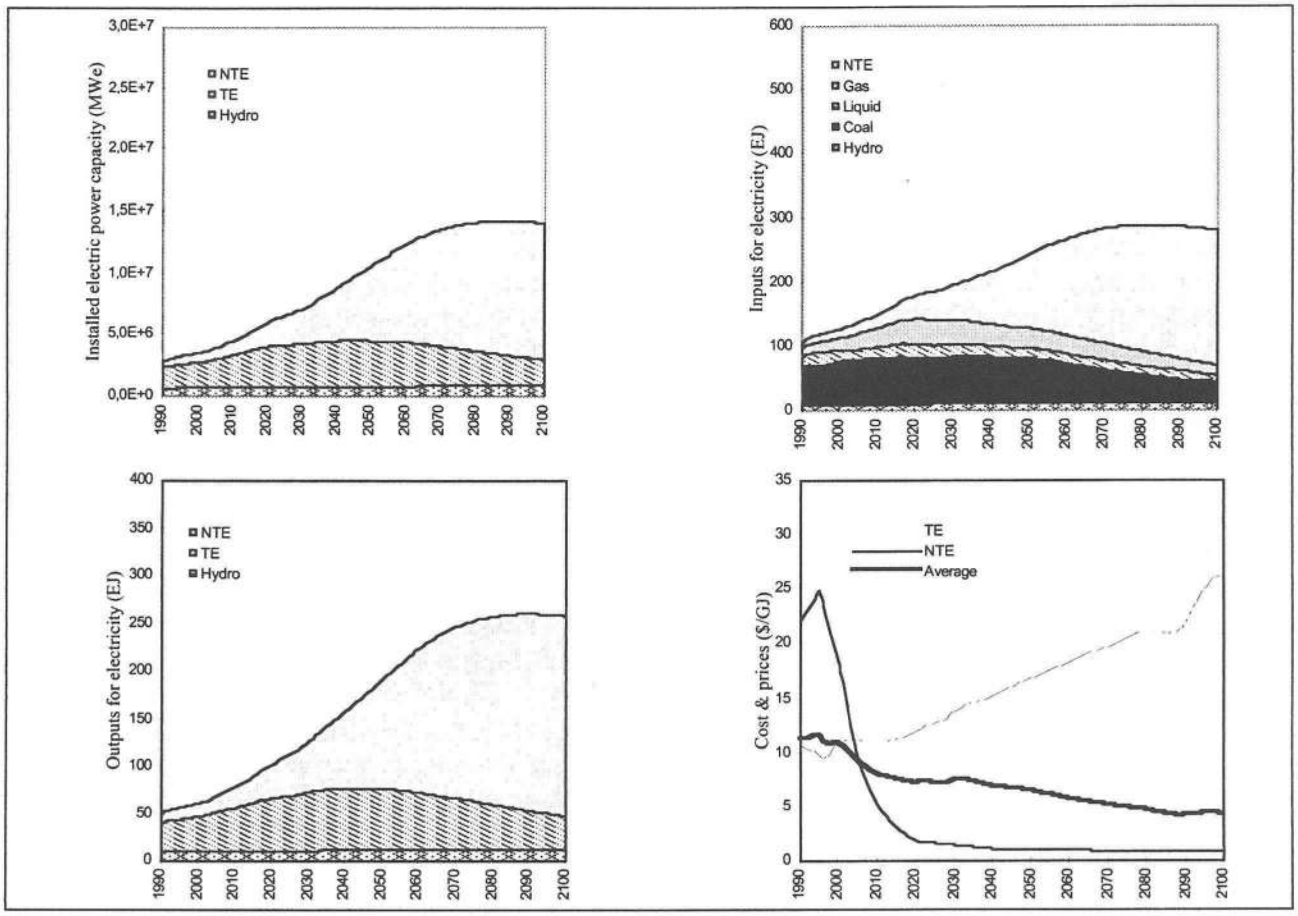


Figure 6.14: ESTC scenario with 3%/yr GWP growth. As electricity demand increases, installed capacity will expand (upper left). An increasing share of capacity and of generation (lower left) will be based on non-thermal (NTE) options. Thermal electricity (TE) will largely be generated with coal (upper right), the rising costs of which will be stabilized by the cost drops in NTE-technologies (lower right).

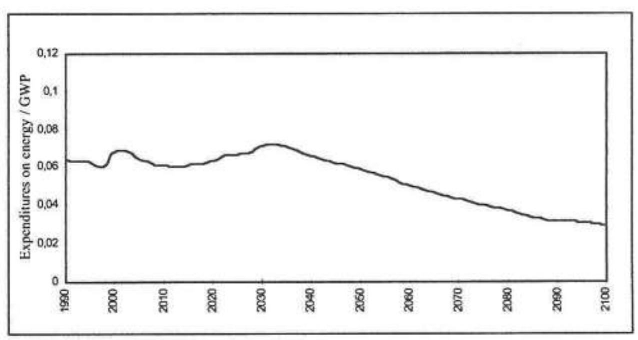
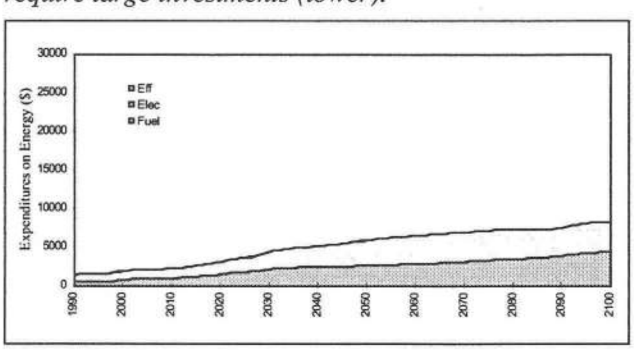
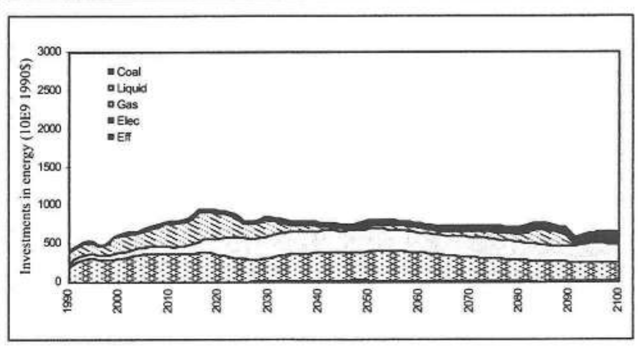


Figure 6.16: ESTC scenario with 3%/yr GWP growth. Due to rising fuel and electricity prices, the expenditures on energy will rise (upper), also as a fraction of GWP (middle). The increasing scarcity of oil and gas, the switch to alternatives and energy improvements will require large investments (lower).





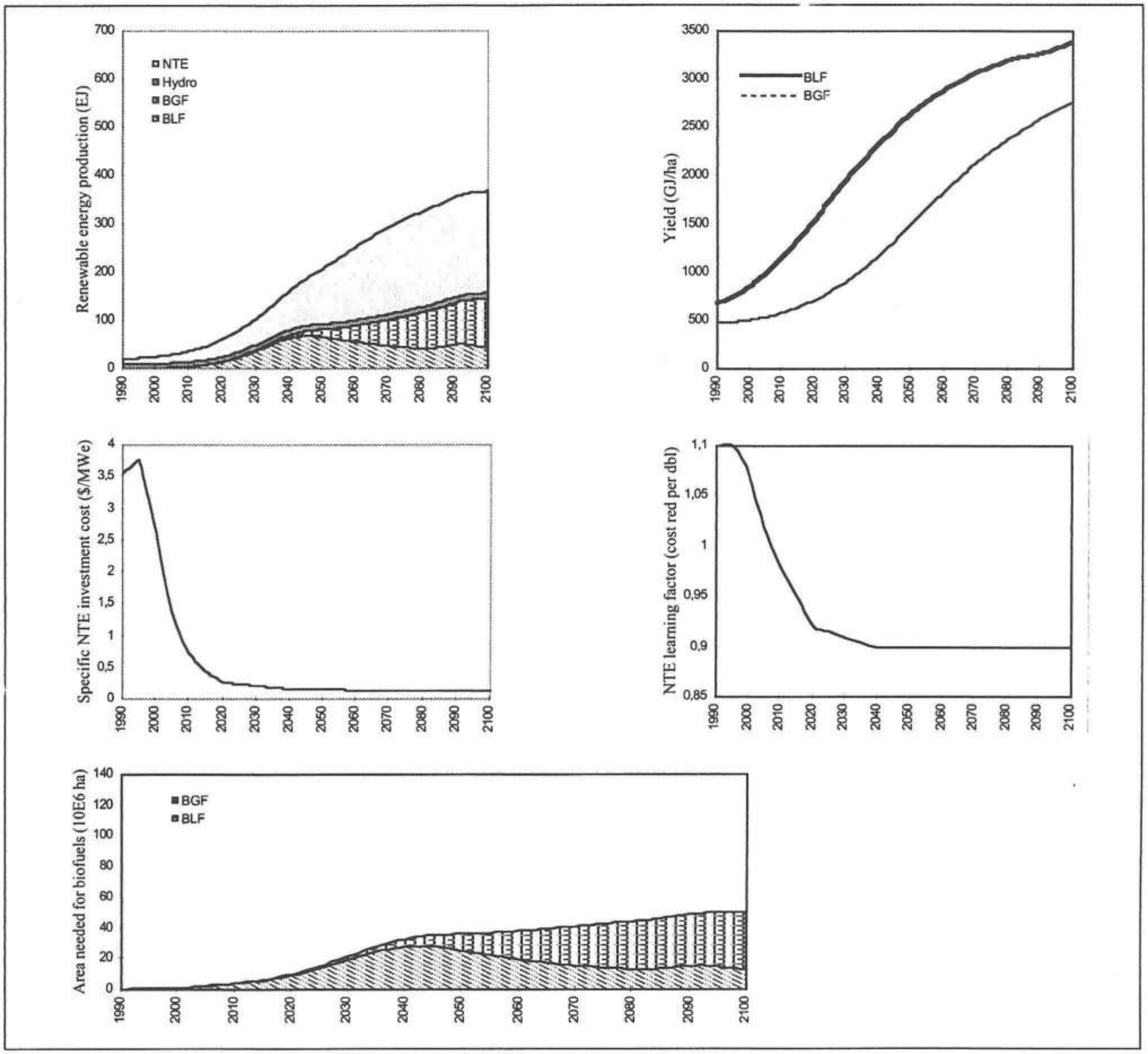


Figure 6.17: ESTC scenario with 3%/yr GWP growth. Energy production from renewable sources will reach the 1990 world energy use level in the year 2100 (upper left). This is possible because specific investments costs of non-thermal electric options are assumed to decline because of learning-by doing (middle left) and the yields of biofuels will increase (upper right).

6.6 Policy Experiments

In the following illustrative experiments we show a possible application of the TIME model: the evaluation of policy strategies. Given the IS92a scenario assumptions and a 3% growth rate for GWP, we employ a number of policies to reduce the CO_2 emissions in the long term. First we reduce the subsidies for coal. In fact, we assume a subsidy level as was used for the SOTC scenario. This policy leads to a reduction of 5 % point of coal in the fuel mix, and an emission reduction of 3 GtC in 2100.

In the previous simulations the payback times have been set at 1-3 year, based also on historical calibration. However, emerging awareness about impending fuel shortages and global environmental issues might lead to governmental support to lengthening (say a doubling) of the payback time in energy conservation investments by subsidies, information campaigns and the like. This reduces the energy demand with about 10%. The total effect of both measures is a reduction of 5.5 GtC in 2100 and an increase in energy expenditures (mainly due to less subsidies for the use of coal) (*Figure 6.18*).

The next step is to increase the thermal electricity efficiency which can be derived by successful implementation of combined-heat-and-power schemes, fuel cells and the like. This reduces the emissions slightly and the expenditures significantly.

Furthermore, we increase the R&D pulses of biofuels and NTE. The R&D pulses for biofuels are assumed to increase to 0.5 EJ for liquid as well as gaseous biofuels, whereas the R&D pulse for NTE is assumed to increase to 1200 MWe (an average 900 MWe was the nuclear power programme during the 1970's.). A carbon tax is introduced to reduce the use of fossil fuel in favour of alternatives. Starting with a 25 $/tC tax in 2000, it is assumed to rise to 700 $/tC in 2100. This can be compared with other carbon tax proposals of, for example, Nordhaus (1994).The resulting decline of emissions leads still to an emission level of 20 GtC in 2100. Cumulated emissions during the next century are markedly lower, however. The energy expenditures (excluding the carbon tax) are above the level of IS92a scenario with a 3% growth rate of GWP.

If we assume a 2.3% growth rate, the above assumptions on policy measures lead to a stabilization of CO_2 emission at a level of 10 GtC/yr, a 50% reduction with respect to the IS92a reference scenario. The relative expenditures are higher than in the previous experiments, partly because of a lower economic growth rate.

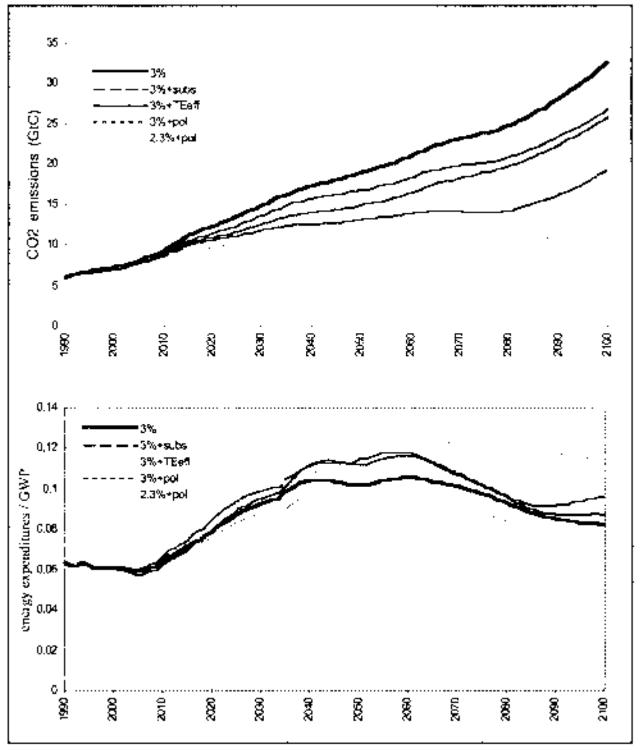


Figure 6.18: Emissions of CO_2 and relative energy expenditures for the IS92a scenario including a 3% growth rate, and the effect of subsidies (subs), plus increased efficiency for thermal electricity (TEeff), plus additional R&D programs for alternative fuels and a carbon tax policy (pol).

6.7 Evaluation

The scenarios have been presented in a convincing way by framing the future evolution of the [world] energy system in a longer term perspective. However, what is the plausibility of the five scenarios discussed in this and the previous chapter ? Without making any judgement on the economic growth path, what are the relative merits of the SOTC, DOTC and ESTC scenarios and can they replace the IS92a scenario as a new reference view on the energy future? We think not, and for two reasons:

First the assumptions we have introduced are rather extreme with respect to historical developments. Unless one presumes a trendbreak in the way society and people in the less industrialized regions develop economically, the rates of energy-intensity reduction are probably too optimistic. This is the more true as income-elasticity incorporates already a significant decline as part of the transition to a service-oriented, 'post-industrial' world. Also for the supply side, the technology related assumptions are such that major disappointment like past developments with regards to nuclear fission power and coal conversion techniques have to be excluded. Here, too, the road is too full of extraordinary technological successes to be a medium-probability scenario. Both the SOTC and the DOTC scenario and evenmore the ESTC scenario can serve, in our view as a lower bound on what probably can be achieved in a 3%/yr economic growth future without major policy interventions and trendbreaks / surprises in a technologically successful and well-managed world.

However, behind these quantitative simulation results are a set of other highly relevant issues which are not addressed. They have to with the social, political and economic aspects implicit in these scenarios, in all of them, also the IPCC-IS92a scenario. We only mention three points.

1. Market shares and absolute throughput

Measured in EJ/yr of energy supply, the throughput in the system in 2060 will be 3.8 times the 1990-value in the SOTC-scenario and 2.5 times the 1990-value in the DOTC-scenario. Similarly, our simulations suggest that in 2060 annual investments in the system are 7-8 times the 1990-value for the SOTC-scenario and the DOTC-scenario. One must presume a world society that is able to deal with such large energy and capital flows. Energy-system related expenditures become twice as important in terms of fraction of GWP.

2. The rate-of-substitution aspect

During the period 1950-1970 the world has experienced a five-fold increase in oil production, in a unique and fascinating political and economic context (see e.g. Yergin 1993). Yet in absolute terms this expansion, in which the extremely large and cheap Middle-East reserves played the major role, added only 80 EJ/yr to the global energy system's throughput. In the SOTC-scenario it is assumed that renewable energy sources (wind, modern biomass, solar, geothermal, surprise) will increase between 2040 and 2060 with a factor 2.4. However, in absolute terms, this entails an addition to the global throughput of 470 EJ/yr - almost 6 times the increment oil added between 1950 and 1970. Similarly, the assumed expansion of nuclear power in the SOTC-scenario between 2000 and 2060 is to generate an additional 90 EJ/yr, which is tantamount to building 65 nuclear reactors of 1000 MWe each year between 2000 and 2060 - and yet, the role of nuclear in this scenario is quite modest. The same questions have to be asked about the more than 2 %/yr decline in energy-intensity in the DOTC-scenario which in the past only occurred under the political pressure of real or perceived oil shortages.

A key question here is not whether these high rates of penetration and substitution are technically feasible but whether the world community as it is will be able to manage them from a political, cultural, institutional and risk point-of-view. As for most renewables, both capital and land will play a role - quite unlike the oil glut in the 1960's and 1970's. Will the capital be available in view of other often pressing needs like infrastructure and health services? How will the need for land interfere with food production? Regarding nuclear power, one wonders whether there will be public acceptance for building over 65 1000 MWe reactor annually. How can consumers who supposedly enjoy an annual income growth of 3 %/yr, be convinced that they should invest in energy-throughput reduction which they can easily afford not to?

3. Consistency of scenarios in socio-cultural terms.

The TC-scenarios can be characterized as being individualist in outlook, with technological dynamism and free-market allocation mechanisms the major determinants to shape the future. To some extent, this is even a bias in our model formulation. Yet, there are some inconsistencies as to the role of government [intervention]. For example, one may argue that a free-market oriented approach will be characterized by the low payback times for energy conservation investments we found for the historical calibration - but will that be compatible with the large decline in energy-intensity of the DOTC-scenario ? Or, similarly, can one expect to have major inroads of plantation biofuels, wind and solar power and nuclear electricity without major support from governments in the form of R&D-funding, market protection and the like ? We will not discuss this aspect any further, though.

The analyses with the TIME-model as presented in this report suggest that either supply-side optimism as in the SOTC-scenario or demand-side optimism as in the DOTC-scenario could well lead to a stabilisation of carbon emissions at less than twice to thrice the 1990-level, around 2050-2060, and a decline afterwards. Key assumptions to accept such an assessment are :

- the relationship between economic activity and energy demand;
- the long-term supply cost curves for coal, oil and gas; and

- the successful mobilization of governments, firms and consumers to develop and invest in low-carbon options as part of their rising material income.

The next, and constructive, step in this debate will be to investigate plausible combinations of changes in both the supply- side and the demand-side assumptions, and assess to what extent and in which way government actions can support the acceleration of the resulting emission trajectories. Such an analysis is discussed in Chapter 8.

7. GLOBAL ENERGY SCENARIOS WITHIN THE FRAMEWORK OF CULTURAL PERSPECTIVES

7.1 Background : cultural perspectives

One of the intended uses of the TARGETS1.0-model is to explore the ways in which model outcomes are affected by differences in model assumptions and by uncertainties in model parameters and relationships. This goes beyond the conventional sensitivity analysis in the sense that it attempts to formulate coherent sets of assumptions within cultural perspectives as formulated by Thompson et al. (1990) and using parameter domains derived from a variety of scientific and policy assessments. In previous work this has been applied to the allocation of CO_2-emission rights (Janssen and Rotmans 1995) and the formulation of population scenarios (Van Vianen et al. 1995, Van Asselt and Rotmans 1995) and climate change scenarios (Janssen 1996, 1997; Van Asselt and Rotmans 1995). In this chapter we will present a number of simulation experiments in which this methodology is used for the TIME-model. In these experiments we use the IS92a-scenario assumptions as discussed in Chapter 5 and also in Chapter 8, and two new sets of scenario assumptions. As more elaborate discussion of scenarios inspired by the cultural perspectives applied in the TARGETS model can be found in Rotmans and De Vries (1997).

The cultural theory is a rather refined way of looking at social dynamics. In our present work it is used to stimulate a more differentiated approach c.q. exploration of possible, model-based futures. The essence of the cultural theory is that people's perception and behaviour with regard to certain issues can be understood in terms of their inclination to be a member of a group and of their preference for structured relationships. Using the two corresponding axes of 'group' and 'grid', the theory distinguishes four different cultural perspectives: the hierarchist, the egalitarian, the individualist and the fatalist. These four perspectives are in constant dynamic interplay. For a more detailed exposition on the cultural theory, we refer to Thompson et al. (1990), Thompson and Trisoglio (1993) and De Vries (1994).

In an elaboration of the theory, it has been proposed that the cultural perspectives can be made operational by distinguishing between the way in which reality is believed to be ('worldview') and the way in which it is acted upon ('management style'). In this way, a 3x3 matrix representation can be constructed (*Figure 7.1*).

We will now first give a brief characterisation of three of the four perspectives in the context of future energy demand and supply developments. Of course, there are many actors in the energy field with widely varying interests: coal, oil and gas producers; transport and port operators; gasoline distributors; electric power utilities; government agencies - energy, industry, environment; and a large variety of consumers. The following is only meant to describe with keywords the three cultural perspectives as expressed by some of the more outspoken representatives of certain groups.

Characteristic features of the adherents of one of the three 'active' cultural perspectives with regard to energy issues :

a) Hierarchist (H) :
   - maintain established order and respond to c.q. anticipate the threats on the basis of knowledge and governance structures
   - as such keen to suppress or incorporate egalitarian and individualist counterforces (Greens, markets)
   - preference for technologies which can be planned and controlled and require a 'scientific priesthood' - often centralised
   - people c.q. energy consumers can and should be confronted with 'The Facts' to guide them towards what is good for them

Figure 7.1: Matrix of perspectives: world view and management style.

	world-as-is: World View			
I	pioneer utopia	dystopia	dystopia	world-as-perceived and managed. Management Style
H	dystopia	bureaucratic utopia	dystopia	
E	dystopia	dystopia	eco utopia	
	I	H	E	

- feels secure if decisions are supported by [mathematical] tools like cost minimisation, cost-benefit analysis etc.
- likes to think of climate change issue in terms of 'acceptable risks', including strategic and societal risks (e.g. OPEC-oil oligopoly, nationalism, fundamentalism).

b) Egalitarian (E)
- precautionary principle with regard to sources ([cheap] fossil fuels) and sinks (CO_2 a.o.), that is, one should use a safe low value for exploitation
- attention for the long-term and for the next generations : one should preserve sources and sinks for later use
- attention for distributive aspects and ecological impacts of human activities incl. technologies
- preference for decentralised and clean technologies.

c) Individualist (I)
- entrepreneurial freedom [of energy supply companies] is important as it reflects freedom and efficiency and, though sometimes in the long run, justice
- people c.q. [energy] consumers can hardly be influenced; only prices really matter for their decisions
- human skills generate science and technology, and these are the real resource for the future; hence, enormous [energy-]productivity increases are to be expected
- in fact, because of this dynamic, not much can be said about the distant future anyway as we are in a great adventure - biotechnology, information-society ?
- the Earth itself is far more resilient than we tend to think, so climate change impacts are probably exaggerated by those advocating strict measures.

For a more elaborate description of the perspective on energy, we refer to Rotmans and De Vries (1997) and Van Vuuren (1996).

Using the distinction between worldview and management style (cf. *Figure 7.1*), there are nine combinations. Based on observations, a social construct is made of how the world 'works' ([world]view, perspective). Those in power will manage the world according to this perspective (management style). As long as the world responds to these actions in agreement with this perspective, view and management style are mutually reinforcing: utopia. If the view of the world can no longer be sustained in the face of contrary evidence, a dystopia evolves until the ones in power change their worldview or are replaced [28]. We now discuss the three utopias briefly within the context of the energy controversies and uncertainties. This is not to say of anything about their plausibility. Utopias are constructed on the hypothesis that the world is 'managed' in agreement with how it actually 'works'. Although this gives interesting insights in what kind of outcomes are generated, it is based on the assumption that there is no socio-culturas dynamics involved. One remedy is to switch the management style somewhere along the trajectory, to represent some response [29].

7.2 Implementation of the cultural perspectives in the TIME-model

We use exogenous scenarios for Gross World Product (GWP) and population. The GWP scenarios used are depicted in *Figure 7.2*, while the population size is following the projection of *Figure 3.1a* for all three (energy) utopias. The two are not related because no coherent, widely accepted theory exists which links population and economic growth together. Having introduced the three so-called 'active perspectives', we have to convert the qualitative characterisations of perspectives and management styles into a set of model parameter assumptions. The associated utopias are indicated in the diagonal elements of *Table 7.1*.

The next step is to specify the perspectives c.q. worldviews and management styles for the energy model. This is an ambiguous task in itself: one cannot claim any clearcut correspondence between a [stylized] worldview c.q. management style on the one hand and certain model structures and parameter values on the other hand. In the present analysis, we have chosen to base the characterisation of the perspectives on:

- the existing controversies in the energy debate and the corresponding uncertainties;
- a limited set of model parameters.

[28] This scheme is highly simplified. Those in power support a management style (M) in agreement with a worldview (V).There is also a world-as-is, reality (R), which unites the strong knowledge we have of the world and unfolds over time. In a real utopia, V, R and M are coinciding. If V and M differ, adherents of V will feel frustrated; they argue that V coincides with R and expect a dystopia. Only if R turns out to be congruent with V, a real dystopia may develop.

[29] See also Janssen (1996;1997) for a more sophisticated approach.

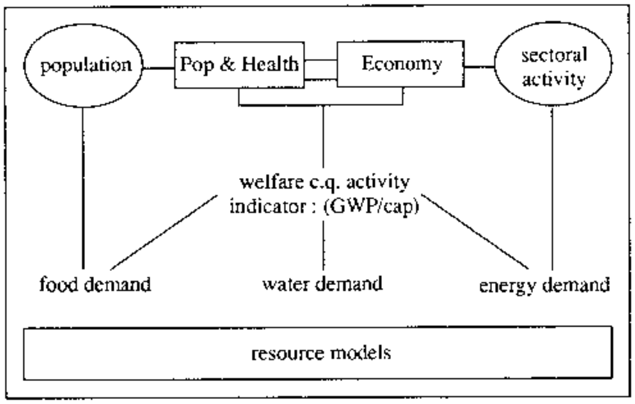


Figure 7.2: Three welfare (GWP/cap) scenarios are used as exogenous input for the TIME simulation experiments.

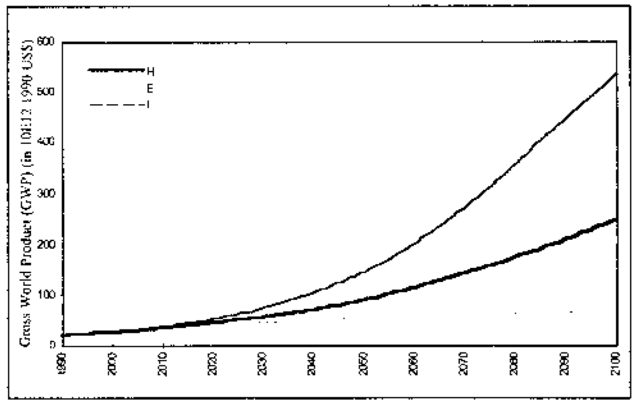


Figure 7.3: Gross World Product as simulated for the three perspective utopias.

The model structure and the historical calibration are the same for all three perspectives (cf. Chapter 3)[30]. We will now discuss the major controversies and uncertainties related to possible energy futures. Next, we present some results for the utopian energy world.

7.3 Major controversies and uncertainties

In 1886 Jevons warned in his book 'The coal question' about the rapid depletion of British coal fields, threatening the British Empire. Numerous appraisals of coal, oil and gas availability have been made since then, many of them for strategic reasons. Environmental and the two oil crises in the 1970s have intensified the debate on fossil fuel use. Later on, it has been broadened by incorporating demand side management and renewable supply options and by including macro-economic aspects. Controversies and uncertainties about the future development of the world energy system abound. Can energy demand really be influenced and to what extent are price changes the right instrument for this? How important are changes in lifestyle and in the nature of economic activities, and what is the role of technical innovation? Is the world really facing depletion of its high-quality oil and gas resources and will it show up in the form of sudden price increases and supply disruptions or will it be a smooth transition towards alternative fuels ? Are the new technologies to supply energy from non-fossil sources really as promising and competitive as their advocates claim?

The major controversies all hover around the question: *How can energy demand be met in an adequate and reliable way within the constraints set by socio-economic developments and goals, available energy supply options and environmental integrity*? This formulation emphasizes a few key characteristics of energy in society. First, energy is, in a variety of ways, a necessity of life which has to be satisfied at such levels of costs and reliability that it does not disturb the mainstream of human activities. In rural areas of non-industrialized regions, this refers to activities like cooking, food preservation and water supply. In urbanised regions of industrialized countries, it is about operating factories, heating dwellings and offices, transporting people and goods etc. Secondly, energy has to be supplied from a variety of resources; this involves a whole spectrum of technologies and requires capital and skilled labour for its operation. As such, the energy supply system is a major part of an industrialized nation's economy. Its dynamics are governed by a complex interplay between resource endowments, prices, technologies and strategic aspects. Thirdly, energy supply, conversion and use as we know it today has numerous impacts on the natural environment. Some of these have led to serious environmental damage but can be dealt with by a combination of technology, capital and political will. Other impacts, first and foremost the contribution to the enhanced greenhouse effect due to CO_2 emissions from fossil fuel combustion, are likely to be more serious and probably less easily mitigated.

The above-mentioned question can be reduced to a couple of major controversies and uncertainties

[30] It would be interesting to explore different explanations of what happened in the past, as there is room for ambiguity. For example, a higher AEEI-rate would allow a larger structural change impact.

around the following questions:

- how will energy demand - in whatever form - develop in relation to population, economic production and consumption patterns ?
- how will technical innovations in combination with changing fuel prices affect the relation between end-use energy demand and secondary fuel use?
- how much energy from fossil fuels will be available and at what costs?
- which alternatives - for all energy forms - will be available and at what costs, and at what rate can they be expected to penetrate the market?
- should the combustion of fossil fuels be constrained because of the enhanced greenhouse effect?

Of special interest is the question which transition pathways from finite fossil fuel resources to non-fossil resources and technologies can be envisaged, and what are the expected requirements for capital, labour and land for such transitions. In the present chapter we will focus on these questions by constructing perspective-based sets of assumptions which are then explored within the TIME model.

7.4 Simulation results for the three utopias

In the previous section we have introduced the three 'active perspectives' on world energy futures. The qualitative characterisations of perspectives and management styles have been translated into a set of model parameter assumptions (see Appendix; Van Vuuren, 1996). Here, we discuss the hierarchist, the egalitarian and individualist utopias. These are not 'full' utopias because only the driving forces (population and GWP) and the energy model assumptions are changed while the water, land and cycles submodels are run according to the hierarchist utopia. The description of the population/health scenarios is given in Rotmans and De Vries (1997).

Within the energy submodel a number of parameters has been chosen the same for all three perspectives. As to structural change we assume a further decline in average end-use energy intensity for the residential, services and other sector. For transport and electricity, however, it is assumed to keep growing in the next few decades[31]. The lower bound on the AEEI-factor is set at 0.2 for heat and 0.4 for electricity. For another set of parameters we have made perspective-based assumptions, which are a reflection of the controversies and uncertainties outlined above. Some of these are related to expectations on energy intensity, and on end-use and conversion technology: the AEEI factor, the energy conservation cost curve and its rate of decline, thermal electric conversion efficiency and the learning coefficients for non-thermal electric power generation (NTE). As to energy efficiency, desired payback times for energy conservation measures and premium factors for coal have been varied. For NTE, the base load factor has also been differentiated. A second group has to do with the fossil fuel resource base and its exploitation: the long-term supply cost curves for coal, oil and gas, labour costs in underground mining and the learning coefficient for surface coal. A third group is related to biofuels (BLF/BGF): learning coefficients, labour and land costs, and the influence of land scarcity on biofuel yields. The management style is implemented on the basis of three policy variables: a carbon tax on secondary fuels, an R&D programme for NTE and R&D programmes for biofuels. The assumptions made for the present simulation experiments are based on a mixture of simulation experiments and literature estimates, and they are summarised in the Appendix to this Chapter. We have endeavoured to implement three quite divergent views on the energy system into a single model structure. However, the model itself is biased too, for example because of the importance given to relative prices in driving substitution processes.

The hierarchist utopia: simulation results

In the hierarchist scenario the AEEI factor is an average 1% per year towards the lower limit. The premium factors for coal and gas are kept at their rather low 1990 levels as derived from historical calibration. Coal for electric power generation remains relatively cheap because governments support their coal industries for strategic and employment reasons. For NTE options a learning coefficient of 0.9 is used but cost reductions are counteracted by a declining base load factor (storage, transport). The ultimately recoverable oil and gas resource base is rather large (72000 and 60000 EJ, respectively) but only 60% and 30%, respectively, are recoverable at cost levels less than 20 times the 1900 level. This reflects the rather conservative attitude of hierarchist resource estimates. The learning coefficient for surface coal is kept at 0.9. Labour costs rise for underground coal

[31] For transport, this is a widely held assumption. For example, Statoil uses for air transport an income elasticity for all regions of 1.8-2 except in the Green Drivers scenario. For electricity it may fall in the industrialised regions (EC, 1995) but this will probably be compensated for by the high growth in the less industrialised countries.

but this is partly offset by a doubling of capital - labour ratios. Commercial biofuels are also assumed to have a learning coefficient of 0.9, which increases yields and bring costs down to the level of 10-15 US$/GJ. Only for BLF is a modest R&D programme assumed; no carbon or energy taxes are applied. The assumptions are chosen in such a way that they reproduce important parts of the IPCC-IS92a-scenario (Leggett, 1992).

Cost-based market prices and modest expectations for energy efficiency and supply technologies determine fuel use. In combination with medium economic and population growth, carbon emissions rise throughout the next century up to about 20 Gt per year by 2100 compared to about 6 Gt per year in 1990 (*Figure 7.4; cf. Figure 5.2*).

Use of secondary fuels and electricity increases from the present 220 EJ per year to over 800 EJ per year by 2100 (*Figure 7.12*). The largest growth is in electricity and the industrial sector. The share of electricity in final demand climbs from the present 16 % to over 40 % - a level which has almost been reached now for the US residential sector. About 40-45% of demand reduction between 1990 and 2100 is from autonomous improvements (AEEI). There is an additional reduction in the energy intensity of 3% for electricity up to some 40% for the transport sector since rising energy costs induce energy efficiency investments [32].

By 2100 over 50% of the electricity is generated in non-thermal electric (NTE) power plants. Installed capacity increases from some 3000 GWe in 1990 to about 25000 GWe by 2100; about two-thirds of it is NTE capacity. Of the thermal electricity, 90% is generated by burning coal (*Figure 7.9/7.13*). The costs of coal-fired electricity will rise significantly over the next century, but the declining costs of NTE electricity tends to stabilise its average price. Coal prices show a smooth and small increase, partly because surface-mined coal emerges as a cost-stabilising option which counteracts the rather steep increase in the cost of underground coal caused by depletion and rising labour costs[33]. Coal production in the scenario increases almost fivefold to about 700 EJ per year, about the level in the IPCC-IS92a scenario. The proportion of coal decreases until 2010 after which it starts rising; oil and gas will be depleted by the end of next century and biofuel-based substitutes have largely taken (*Figure 7.6*).

Energy demand and fuel supply are influenced by secondary fuel and electricity prices, which, in turn, depend on depletion and learning dynamics. The rise in oil and gas prices induces the penetration of biomass-derived fuels, which, in turn, stabilises the price of Light Liquid Fuel (LLF) and of Gaseous Fuel (GF) after 2060 at a level of about 15 US$ /GJ or about 100 US$/ barrel [34]. This is five times the current price of North Sea oil which is much higher than expert estimates. One interpretation for this is that it includes non-price barriers and that in the present model formulation it is primarily an indication of the price differential needed to let commercial biofuels penetrate the market[35]. Later on, the use of less productive lands and the ebbing away of learning-by-doing tends to increase biofuel costs. The simulations suggest that biofuel technologies with the hierarchist characteristics would penetrate without the need for major demonstration projects to stimulate the necessary cost reductions. Of course, this hinges on the assumptions on the long-term supply - cost curves for conventional oil and natural gas.

Two important system characteristics are the over-all energy intensity and the average energy price. The latter gradually increases to about three times the 1990 level by 2100. Although energy use per capita doubles, there is a continuous decline in the energy intensity calculated as the ratio of primary fuel supply and GWP, from the present 14 to 5 MJ/US$. Another system characteristic are the investments in the energy system. They rise from about US$ 400 $*10^9$ in 1990 to a plateau of US$ 2500 $*10^9$ per year after 2060. Almost half of these investments go into the electricity system. due to the capital-intensive nature of the NTE options. Overall cumulative investments in the 1990-2020 period are in the order of US$ $18*10^{12}$ (1990). This compares reasonably well with the recent estimates of cumulative capital requirements of US$ 16 $*10^{12}$ (1990) for a medium-growth scenario [IIASA/WEC, 1995]. The overall energy costs, defined as the product of secondary fuel use and prices, rise as a percentage of GWP from about 6% at present to 10% for the second half

[32] It should be recalled that a switch to electric transport is not (explicitly) included.

[33] It should be noted that coal liquefaction and gasification are not explicitly taken into account.

[34] In the model biofuels only penetrate the markets for Light Liquid Fuel (gasoline, kerosene etc.) and natural gas.

[35] A better researched production function for biofuels and more insight into the substitution dynamics is needed to refine this analysis.

of next century, which is comparable to the high level in the 1980s (*Figure 7.5; cf. Figure 5.8c*). The slow rise in the next 40 years reflects the increasing costs to produce oil. Whether or not the economy can afford these investment levels is discussed in Rotmans and De Vries (1997).

The egalitarian utopia: simulation results
If the world is managed by egalitarians, there will be more incentive to develop energy efficiency-oriented technology and stimulate its penetration[36]. We assume that with active government support the AEEI rate can be raised to 1.5% per year and that the decline in the PIEEI cost curve is twice as fast as in the hierarchist scenario. Moreover, consumers are willing to use longer payback times because of information campaigns and concern about impending climate change. It is also assumed that coal use is actively discouraged in both the end-use and the electricity generation market due to its environmental disadvantages. The major policy instrument is a world-wide carbon tax increasing to US$ 500/tC (about 12,5 $/GJ) in 2020 and constant thereafter. This would go with successful negotiations, which would convince regions like China and India to revise their coal expansion plans and to focus instead on oil and gas, the availability of which increases because of energy conservation efforts in the industrialised regions. Later on, their economies will be strong enough to introduce the renewables, by then significantly cheaper.

In the egalitarian [semi-]utopia the population is only 8 $*10^9$ at 7000 US$/cap in 2100 (see Rotmans and De Vries 1997). Mainly as a result of this and of a carbon tax, the trajectory of secondary fuel use is almost 70% below the hierarchist scenario (Figure 7.14/7.15). The proportion of electricity grows towards 50%. The AEEI factor runs about 10% point below the hierarchist scenario values. The price-induced energy conservation increases to 35% (services) - 55% (transport) by 2100 as compared to 5-10% in 1990; for electricity it is still a low 5%. Electricity generation in an egalitarian utopia will use less coal because it is more costly. Moreover, efficient combined-cycle and fuel-cell power plants lead to a higher average thermal electric conversion efficiency and NTE options are vigorously supported (*Figure 7.10*). As a result, fossil fuel use is down with a factor of almost four compared to the hierarchist utopia. Installed electric power generation capacity increases to about 7.500 GWe - the equivalent of some 18.000 large power plants less than in the hierarchist scenario.

With regard to fossil fuel supply, the more conservative estimate of low-cost natural gas availability - reflecting also the attitude that such valuable non-renewable resources should be saved for future generations - allows for an earlier and faster penetration of modern biomass-based fuels. The result is that primary fuel production peaks at 400 EJ per year in 2025 and coal production remains at the 1990 level, while its proportion drops to 20-25% (*Figure 7.15*). Renewable sources increase their contribution to almost 50% by 2100 (*Figure 7.7*). This is reflected in CO_2 emissions peaking at about 7 GtC/yr between 2000 and 2030, after which they decline to 3-4 GtC/yr.

The carbon tax discourages the use of fossil fuels and especially coal: its price increases fourfold between 2000 and 2020. Investments flow into energy efficiency and non-fossil fuel-based electricity generation to the extent that in the second half of next century over two-thirds of total investments go to these two options [37]. The absolute investment level is modest, at most twice the present one, but as a fraction of GWP, it rises over 10% around 2040 after which it slowly declines to about 9% (*Figure 7.5*). In the egalitarian utopia the present generation indeed makes a sacrifice for the next.

The individualist utopia: simulation results
For the individualist, a utopian world will be driven by markets and prices, and technological innovation. Because we use a single model framework for the three perspectives, the differentiation has been introduced by higher rates of energy efficiency improvements (both AEEI and decrease of PIEEI cost curve) and fast learning for non-fossil supply options once the prices signal their competitiveness. The consumer will tend to use a short-term horizon, hence short desired payback times. Like the egalitarian, the individualist supposes that the price of coal will go up because it is inconvenient and subsidies are removed (Kassler, 1994; IIASA/WEC,

[36] We have not changed the structural change multiplier, as such changes would require more research. There are good arguments for an egalitarian world to have a lower growth elasticity because of changing lifestyles, more public transport and the like. On the other hand, the lower GWP growth rate slows down the rate at which structural change contributes to a lower energy intensity.

[37] Without the - high - carbon tax, CO2 emissions are about 5.4 GtC/yr by 2100. The investments in energy efficiency are underestimated because we do not consider replacement costs.

1995). For surface coal mining no net future learning is assumed because environmental impacts absorb the cost reductions. The assessment of natural gas resources is optimistic: the same amount as for the hierarchist is available at half the cost. Options for high-efficiency thermal conversion will fulfill their promise: by 2100 thermal efficiency reaches an average 60%. The learning coefficient for NTE is a high 0.9 throughout next century and it can be operated at a high base-load factor. Biofuels become fairly cheap because of strong, fast learning and relatively cheap labour.

All this technological optimism offers an individualist utopia in which energy use does not exceed the hierarchist level of about 800 EJ per year by 2100, 40% of which is in the form of electricity (*Figure 7.16*). This is possible with the high economic growth rate because the energy intensity declines to 2.5 MJ/US$ due to 50-70% autonomous efficiency improvements and 20-30% price-induced efficiency improvements with respect to 1990. NTE rapidly penetrates the electricity generation market up to 50% by 2050 and 80% by 2100. Biofuels grow towards a rather small 10% by 2050 as they have to compete with cheap natural gas. However, by 2100 they contribute is in the order of 25%, when both oil and gas have become scarce and expensive. Coal use increases to some 250 EJ/yr by 2100 as compared to over 700 EJ/yr in the hierarchist scenario (*Figure 7.17*). These changes together lead to a stabilisation of CO_2 emissions at 10-12 GtC/yr from 2030 onwards (see *Figure 7.4*).

The absolute investments in the energy system rise steeply in the first part of next century, to 1.500-2.000 $*10^9$ US$/yr after 2030, when fossil fuel depletion starts to play a role. As a fraction of GWP, these investments are in the same order of magnitude as in the egalitarian utopia (*Figure 7.5*). This reflects the technological optimism of the individualist borne out in the form of cheap and abundant non-fossil fuel options to supply highly efficient energy consumers. Exploitation of gas, and its transport and distribution, requires one third to one half of total investments. Prices of oil-based fuels increase and are successfully stabilised by cheap biofuels, but after 2060 biofuels start to face land-related constraints and prices go up. Coal prices go up only slightly faster than in the hierarchist scenario because the slower depletion rate partly compensates the cost increasing factors. One consequence is a continuous increase in the price of electricity from fossil-fired power plants - despite the increase in efficiency, which accelerates the introduction of the cheap NTE options.

Figure 7.4: Fossil CO2 emissions for the three simulated perspective utopias.

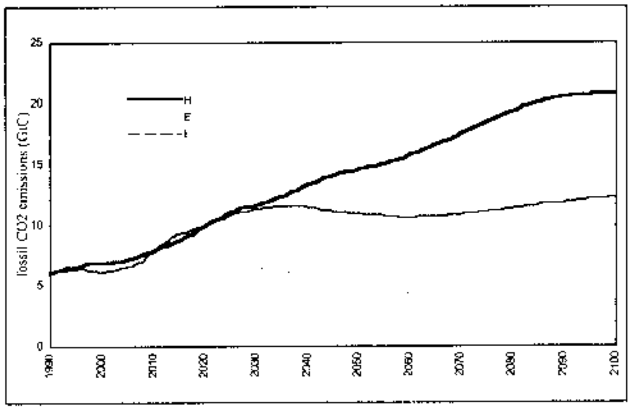
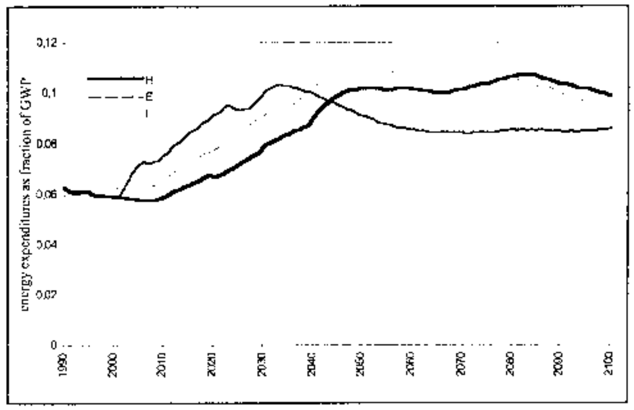


Figure 7.5: Energy expenditures as a fraction of GWP for the three simulated perspective utopias.



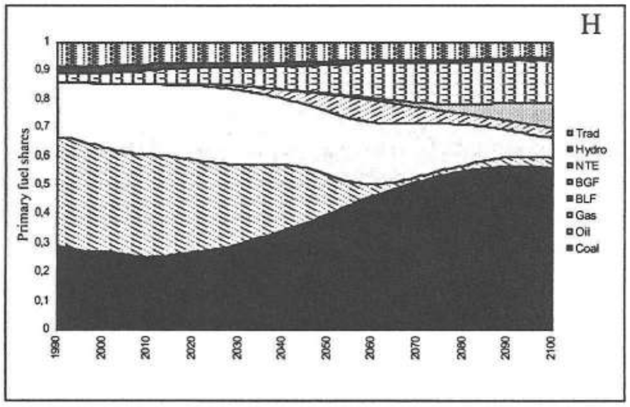


Figure 7.6 Shares of fossil fuels and non-fossil alternatives in the primary energy supply in the hierarchist scenario.

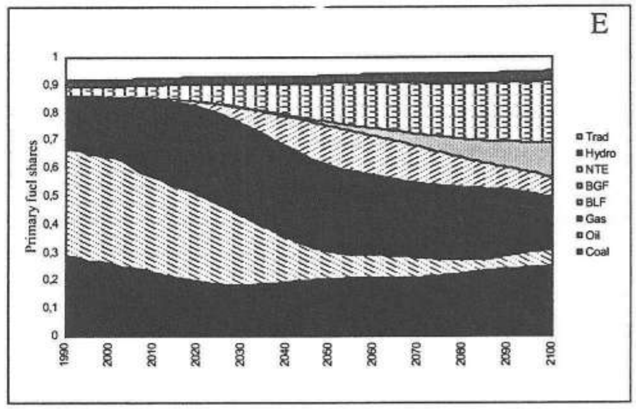


Figure 7.7 Shares of fossil fuels and non-fossil alternatives in the primary energy supply in the egalitarian scenario.

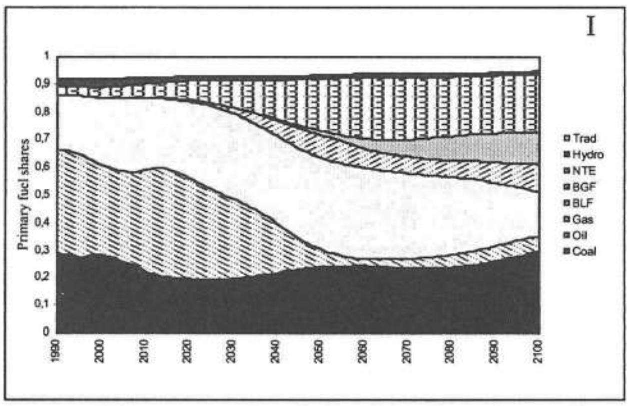


Figure 7.8 Proportion of fossil fuels and non-fossil alternatives in primary energy supply in the individualist utopia. It is similar to the egalitarian scenario but the absolute level is almost three times higher.

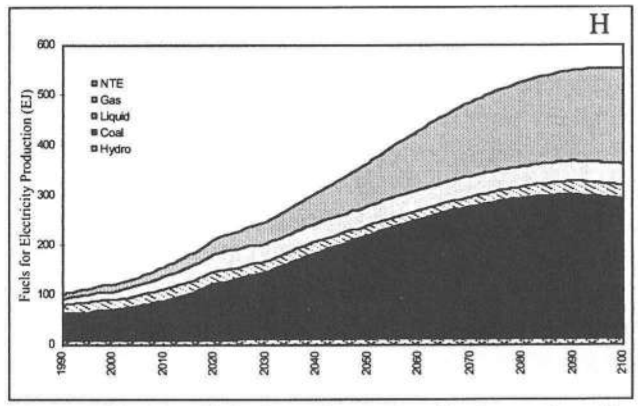


Figure 7.9: Fossil fuels and non-fossil alternatives for the production of electricity in the hierarchist utopia.

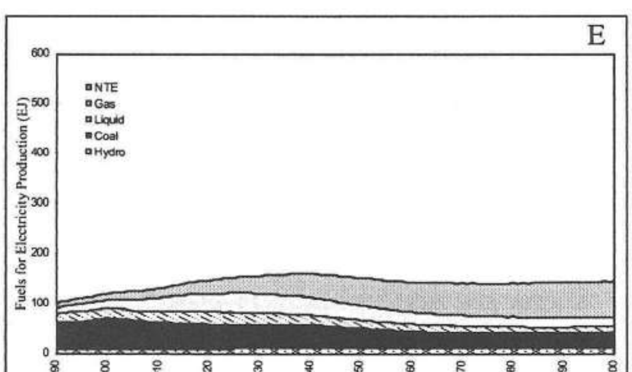


Figure 7.10: Fossil fuels and non-fossil alternatives for the production of electricity in the egalitarian utopia.

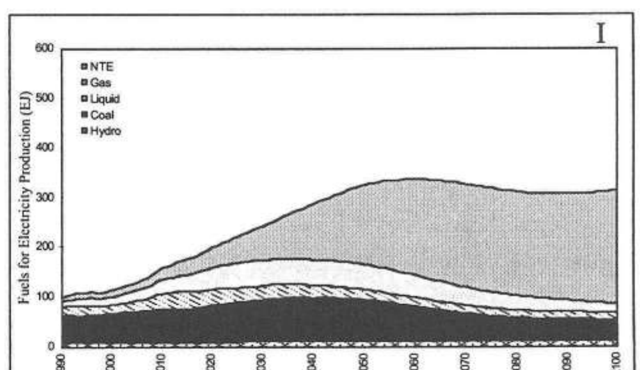


Figure 7.11: Fossil fuels and non-fossil alternatives for the production of electricity in the individualist utopia.

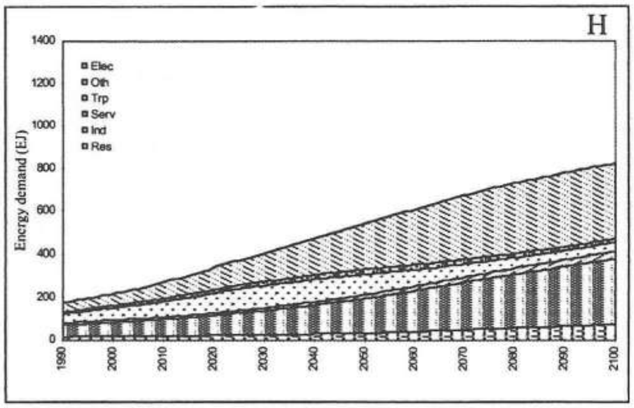


Figure 7.12: Energy demand for the different sectors in the hierarchist utopia.

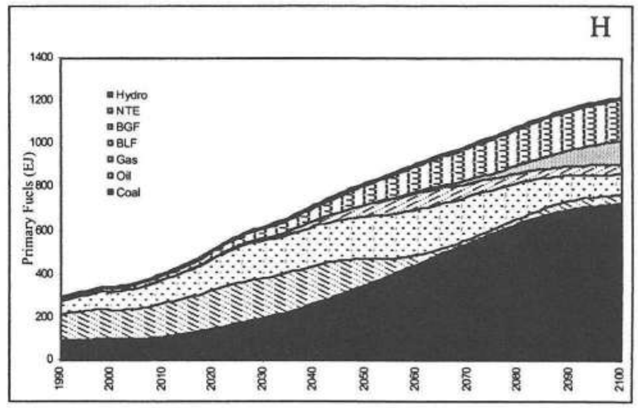


Figure 7.13: Supply of energy in the hierarchist utopia.

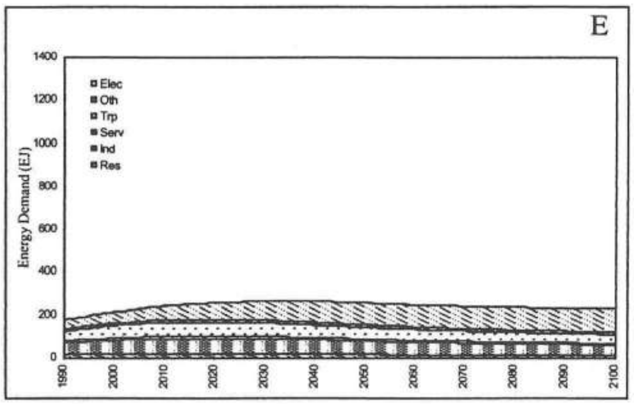


Figure 7.14: Energy demand for the different sectors in the egalitarian utopia.

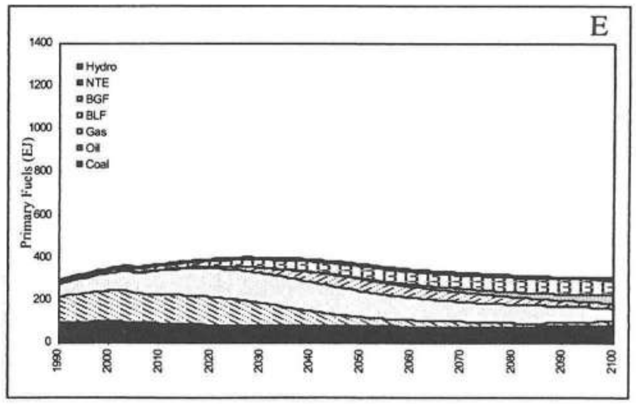


Figure 7.15: Supply of energy in the egalitarian utopia.

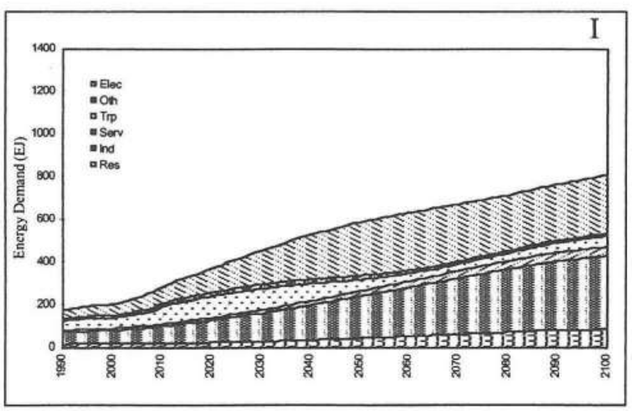


Figure 7.16: Energy demand for the different sectors in the individualist utopia

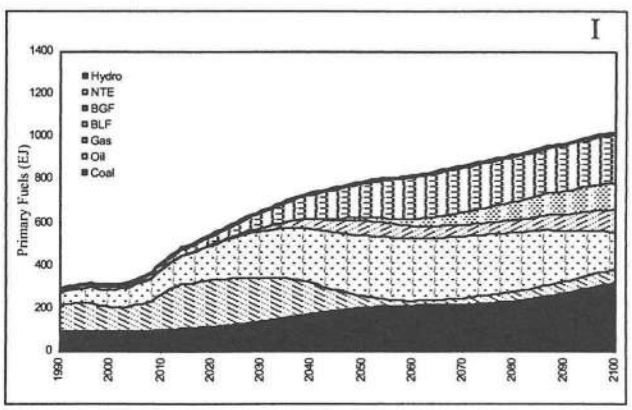


Figure 7.17: Supply of energy in the individualist utopia.

Appendix 7A

Variable/Parameter:	Hierarchist	Egalitarian	Individualist
Lower limit on AEEI factor	0.2, elec 0.3	= Hierarchist	0.1, trp & oth 0.15, elec 0.2
AEEI rate of decline	0.01	0.01 (2000) towards 0.015 (2060), then 0.015	= Egalitarian
PIEEI autonomous decrease rate	from 0.001 (2000) to 0.002 (2020), then 0.002	from 0.001 (2000) to 0.004 (2040), then 0.004	from 0.001(2000) to 0.006 (2060), then 0.006
Desired Payback Time (yr)	1.1 (2000) - 1.5 (2050) * Individualist	1.5 (2000) - 2 (2050) * Individualist	[2,1.5,1,3,1,1]
Premiumfactor SolidFuel (US$ per GJ)	from [4,0,4,5.7,7.6] (2000) to [0,0,0,0,0] in 2100	from [4,0,4,5.7,7.6](2000) to [3,3,3,6,3] in 2100	= Egalitarian
Thermal Electricity Efficiency	from 0.38 (2000) to 0.50 (2100)	from 0.38 (2000) to 0.52 (2100)	from 0.38 (2000) to 0.6 (2100)
Learning coefficient NTE	from 1.07 (2000) to 0.96 (2040) to 1 (2080)	= Hierarchist	from 1.07 (2000) to 0.9 (2040), then 0.9
Premiumfactor SolidFuel for ElecGen	0.35	from 0.35 (2000) to 0.8 (2060) then 0.8	= Egalitarian
Base Loadfactor NTE	from 0.65 (2000) to 0.40 (2100)	= Hierarchist	0.6

* Model assumptions for the three perspectives - demand and electricity generation

Variable/Parameter:	Hierarchist	Egalitarian	Individualist
Labour cost UndCoal as fraction of per capita consumption	1	1	from 1.05 (2000) to 2.5 (2100)
Surface Coal cost as function of depth	50 m (10% depletion) 400 m (40% depletion) 1000 m (80% depletion)	= Hierarchist	1.1 (10% depletion) to 2.5 (40% depletion) * Hierarchist
Learning coefficient SurfCoal	0.9	0.9	1
Gas Production cost factor (GP) as function of resources depletion (RS)	RS, GP 0.2, 8.7 0.3, 22.0 0.4, 61.0 0.5, 100.0	RS, GP 0.2, 8.7 0.3, 33.0 0.4, 91.0 0.5, 100.0	RS, GP 0.2, 6.2 0.3, 10.2 0.4, 16.2 0.5, 50.0 0.6, 100.0
Labour cost BLF/BGF as fraction of per capita consumption	0.7	0.9	0.5
Learning coefficient BLF/BGF	0.9	0.9	0.85
Max potential BLF/BGF (GJ/yr)	5e11	3e11	9e11

* Model assumptions for the three perspectives - supply

8. GLOBAL ENERGY POLICY STRATEGIES

8.1 Introduction

The Framework Convention on Climate Change of the United Nations (1992) has as its stated goal to achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference of the climate system. Concrete goals are not defined, but a widely used exercise is to examine the implications of establishing various ceilings for atmospheric CO_2 concentration (e.g. Edmonds and Wise, 1995; Wigley *et al.*, 1996). A stabilization target of 550 ppmv, a doubling of the pre-industrial level, is a widely used benchmark among climate researchers. Another widely used, but weakly underpinned, climate target is an absolute temperature limit of 2°C above pre-industrial level. This temperature limit can be viewed as an upper limit beyond which risks of considerable damage are expected to increase rapidly (AGGG, 1990; Alcamo and Kreileman, 1996).

Despite the many uncertainties surrounding the topic of climate change, there is a need to derive more insight in balancing the risks of a possible climate change and the efforts of reducing greenhouse emissions. A dominating framework among economists is to balance the costs and benefits in monetary terms (Nordhaus 1994; Manne and Richels, 1992; Peck and Teisberg, 1992). The climate system descriptions used in those studies do not represent our current knowledge of the climate system (Price, 1995; Janssen, 1996). Furthermore, the chosen top-down analysis of the energy-economy models as used in those studies are biased in favour of a (kind of) wait-and-see policy (Wilson and Swicher, 1993).

This Chapter describes a number of illustrative optimization oriented experiments performed with the TIME model. We included the global CYCLES module of the TARGETS model (Den Elzen *et al.*, 1995) to assess the impacts of the use of energy. Different sets of assumptions on technological developments are used to explore (global) energy policies which would meet climate change targets. The impact of uncertainties in economic and technological development on possibilities to meet the targets are investigated. Furthermore, the consequences of differences in the timing-pattern of mitigating policies are investigated to illustrate the risks of doing too little or doing too much. This leads to the construction of several hedging strategies which take explicitly account of the possibility of different technology developments on the long run and balance short term actions given those long term uncertainties. Finally, we broaden the discussion by including the acidification problem which is related to climate change by a common cause, SO_2 emissions. But first we briefly consider some methodological questions.

8.2 Methodology

The problem we address in this Chapter is to find out which strategies for CO_2 reduction can meet certain targets at the lowest (relative) energy costs for a given economic growth trajectory. As an indicator of costs we use energy expenditures defined as the sum of prices for fuels times the production of each fuel, plus the annuatized cost of efficiency investments. We then use energy expenditures as a fraction of Gross World Product (GWP) as the objective for the optimization problem. That is, we minimize the energy costs relative to aggregated over the period 1995 until 2100. Given this objective, additional constraints on environmental quality can be investigated, like CO_2 concentration and global mean temperature increase constraints.

The decision variables for which the time trajectory is varied to find the minimum-cost solution consist of a carbon policy and RD&D programmes in non-thermal electric and biomass fuels. The carbon tax increases prices of fossil fuels and will stimulate energy conservation and penetration of alternative fuels. The RD&D programs stimulate the learning process, so that the production costs decline and the alternative options become more competitive in the energy market.
Because rule-based investment decisions with non-linearity's and delays characterize the TIME model and hence no standard optimization technique can be used, we use a genetic algorithm to search for (sub) optimal solutions to the previously defined problem. By simulating a competition between scenarios to derive cost effective ways to meet the policy targets, the algorithm generates new scenarios, leading to a family of scenarios of which the performance increases over time (Goldberg, 1989). Such an

Problem Formulation:
Minimize energy expenditures as percentage of GWP aggregated for the period 1995-2100.
Decision variables:
- *carbon tax ($/tC),*
- *non-thermal electric demonstration program (MWe/yr),*
- *bioliquid and biogas demonstration programs (EJ/yr).*

Constraints:
- *CO_2 Concentration or Temperature Increase.*

algorithm does not lead to better results in sound mathematical search spaces, but outperforms most of its cousins in noisy search spaces (Goldberg, 1989). Another important aspect is the fact that the genetic algorithm treats the model as a black box, so that it can be used in the original appearance, which is attractive in evolving model versions in integrated assessment modelling. Finally, it is not the primary purpose to find *the* optimal solution, but to find, with help of an advanced simulation model, a suitable strategy which is as good as can be found in a limited amount of time. The optimization algorithm is, therefore, not more than a tool to search for specific scenarios.

8.3 Four Global Energy Scenarios

In recent years, a number of global long-term energy scenarios have been published, primarily to support the development of policies with respect to climate change. In general, these scenarios can be characterized as either 'business-as-usual' (or 'no-intervention', 'reference' or 'Conventional Wisdom') scenarios or 'policy' scenarios. The scenarios usually capture a wide range of outcomes with respect to the main reported variables: energy supply and associated greenhouse gas emissions. The differences between high and low emission scenarios are either caused by divergent assumptions about economic and population growth or by assumed changes in energy efficiency and fuel mix or both. Further differences emanate from the assumptions about new technologies, fuel prices and policy measures.

In Chapters 5 and 6 of this report four scenarios are described which have been constructed with TIME and are briefly summerized here.

Using the characteristics of the IS92a scenario, assumptions within the energy model are constructed in such a way that it simulates the main aspects of IS92a, which we call Conventional Wisdom scenario (CW) (*Figure 8.1*). The continued use of fossil fuels in the next decades initially leads to a relative decrease in energy expenditures (*Figure 8.2*), due to efficiency improvements in the use and production of energy. Given the assumptions on oil and gas reserves in the IS92a scenario, the CW scenario shows an increase of energy expenditures as a fraction of GWP from 2010 onwards. A difficult transition period follows in which even more expensive oil and gas are replaced by still costly alternatives (biofuels, NTE). By 2040 this transition is largely over. Energy efficiency improvements lead to a stabilization of the relative expenditures in the period thereafter. The fossil CO_2 emissions in this scenario increase up to about 21 GtC in 2100 (*Figure 8.2*); the penetration of biofuels leads to a temporarily decrease of global CO_2 emission in the middle of the next century. According to our simulations with the CYCLES module, the global energy scenario leads to a CO_2 concentration increasing to about 750 ppmv in 2100 and a global mean temperature increase of about 2.7°C degrees compared to 1900.

The first alternative scenario is based on more optimistic assumptions on technological progress in the supply side of the energy system. In this Supply Oriented Technology Change scenario (SOTC) economic growth is the same as in IS92a. Final energy demand closely follows the IS92a scenario but the supply side differs significantly. New technology will be developed such that non-carbon energy options will become much cheaper and markets will ensure their subsequent introduction. Coal is assumed to be much more expensive, among other things, because subsidies are removed, and coal use is therefore much smaller. Because alternatives are in this scenario introduced at lower costs than the CW scenario, energy expenditures as fraction of GWP will decrease earlier during the transition to alternatives (*Figure 8.2*). Fossil CO_2 emissions steadily decline, leading to a CO_2 concentration of 570 ppmv and a temperature increase of 2.3°C in 2100. Due to the reduction of the fossil fuel burning the cooling effect of sulphate aerosols is lower in the SOTC scenario compared with the CW scenario, leading to a higher increase of the global mean temperature in the short term. This scenario is akin to the Sustained Growth scenario presented by Kassler (1995).

Using other assumptions on the demand side of

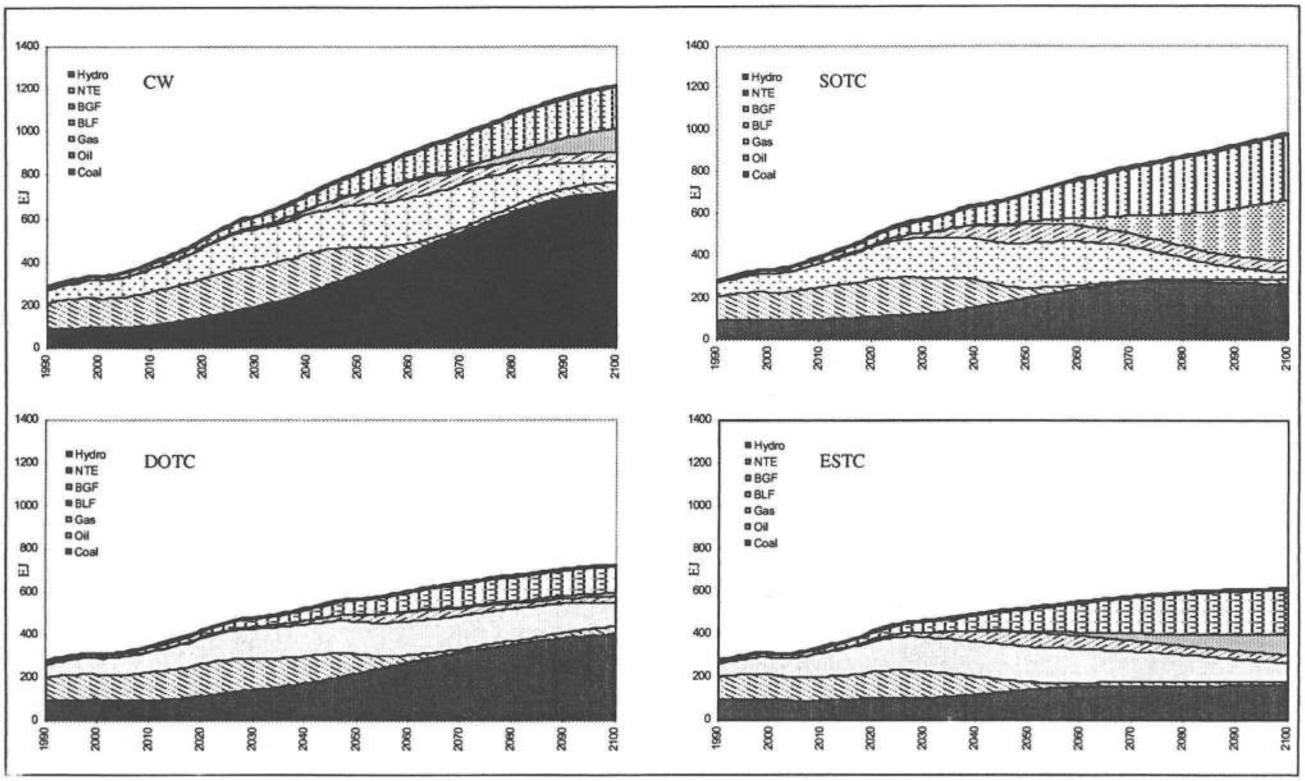
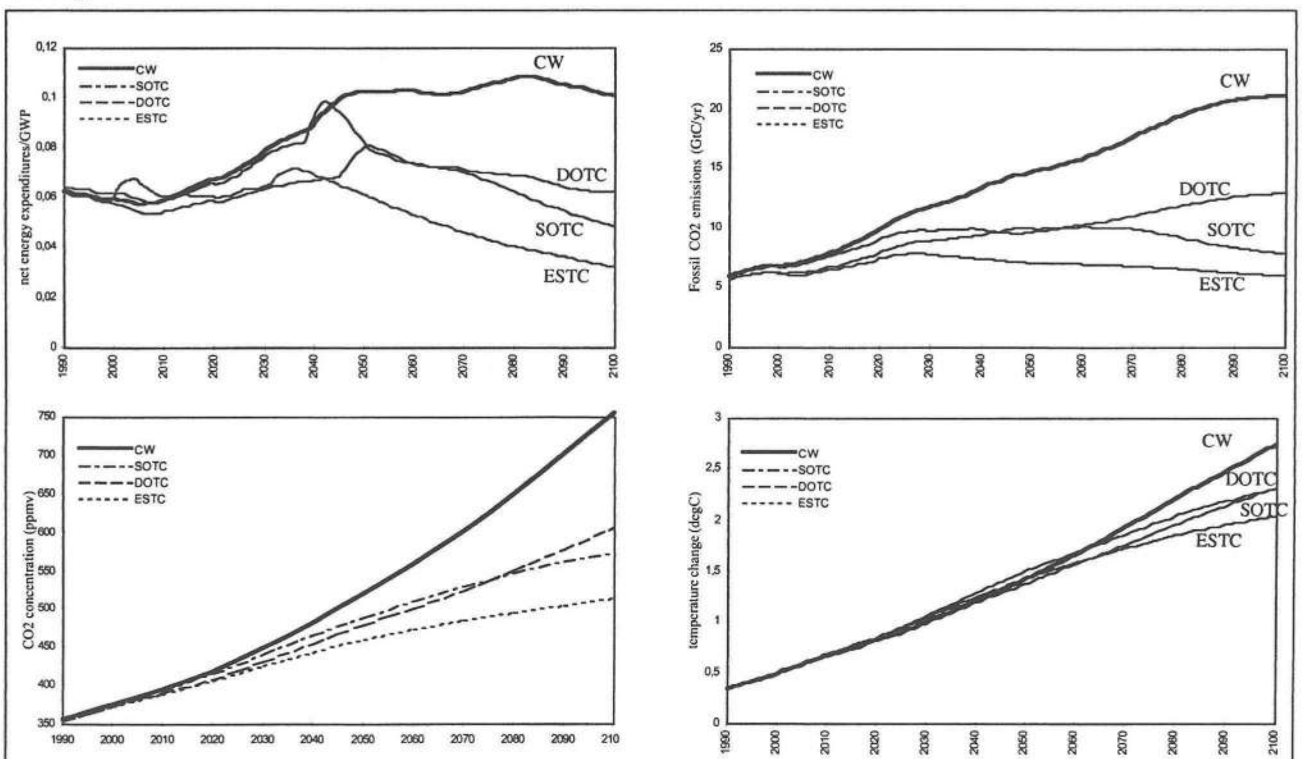


Figure 8.1: Energy production for the four scenarios discussed in Chapter 5 and 6 (cf. Figure 5.2) but with 2.3%/yr GWP-growth.

Figure 8.2: Projections for the net energy expenditures per GWP, fossil CO_2 emissions, CO_2 concentration and global mean temperature for the four scenarios discussed in Chapter 5 and 6 (cf. Figure 5.8b) but with 2.3%/yr GWP-growth.



the energy system leads to the third scenario: Demand Oriented Technology Change (DOTC) (*Figure 8.1*). Its key message is that waves of innovative energy efficiency technologies in combination with shifts in economic activity patterns make it possible to sustain a 2.3%/yr GDP-growth at much lower energy use, and, hence, a lower carbon emission path. Estimated final energy demand is much lower than IS92a but the supply side assumptions are the same as used for the IS92a scenario. Due to a lower energy demand, the pressure on fossil fuel resources is lower, leading to a lower increase of relative energy expenditures. In this scenario, CO_2 emission trajectory is until 2060 lower than in the SOTC scenario. After 2060 the lack of cheap alternatives causes an increase of CO_2 emissions, leading to a CO_2 concentration of 610 ppmv and a temperature increase of 2.3°C in 2100.

Finally, by combining assumptions of SOTC and DOTC scenarios we constructed the fourth scenario which we call Energy System Technological Change (ESTC) (*Figure 8.1*). Energy production stabilizes at 50% above the present level. Together with the successful introduction of alternatives, fossil fuel use decreases during the next century. Because alternatives can be introduced at low cost and because of large short-term efficiency improvements, relative energy expenditures in this scenario are the lowest of all four scenarios. The CO_2 concentration stabilizes at 510 ppmv resulting in a global mean temperature increase of 2.0°C in 2100.

8.4 Climate Change Constraints

We used the assumptions for the CW scenario to scan the decision space for CO_2 emission reduction strategies which meet a range of possible climate change targets. Thereafter, we will analyze the consequences of the uncertainties in technological and economic developments. We define an 'optimal' path as a scenario of R&D programs and carbon tax which meet the climate change constraints at the lowest possible costs for the next century, using energy expenditures as a fraction of GWP as a measure for costs.

CO_2 Concentration Target

We considered a range of CO_2 concentration upper levels (not necessarily stabilization before 2100) from 700 ppmv to 500 ppmv for the next century. A lower CO_2 concentration than 500 ppmv by 2100 was not found in our model exercises using conventional wisdom assumptions for the energy system. Lower concentration ceilings can according to our model exercises only be met if technology development accelerates (see below *Technological Transition*). The cost-effectiveness of the target strategies is illustrated by plotting the average net energy expenditures as fraction of GWP as a function of the CO_2 concentration in 2100 (*Figure 8.3a*). The results suggest that the first steps in reducing the CO_2 concentration can be made with relatively few extra investments in agreement with most bottom-up analyses. Meeting the 550 ppmv concentration targets requires in the CW-scenario an increase of 50% in energy expenditures. In the latter experiment an immediate carbon tax policy of the fossil energy prices triples in the coming years.

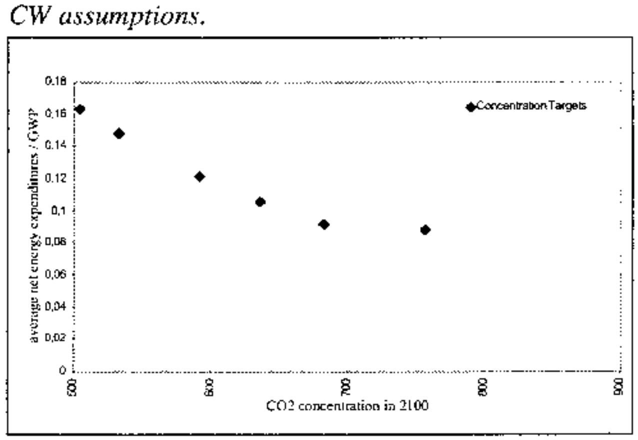
Temperature Target

We have also explored emission reduction strategies to meet a set of global mean temperature constraints. Due to the reductions of both cooling and warming effects if fossil fuel use decreases, relative costs rise rather strongly for relative small reductions of the global mean temperature increase (*Figure 8.3b*). Due to the dependence on SO_2 reduction policies, which are taken to be exogenous, and the SO_2 impact on radiative forcing, this result is highly uncertain (see also Section 8.6)

Technological Transition

The possibilities to meet environmental constraints in an efficient way greatly depends on the technological development of the energy system as discussed in the previous paragraphs. *Figure 8.3c* illustrates this by including the three other scenarios SOTC, DOTC and ESTC within the cost-effectiveness representation. The kind of technolo-

Figure 8.3a: Average net energy expenditures divided by GWP versus the CO_2 concentration in 2100 for the case that CO_2 concentration targets will be met using CW assumptions.



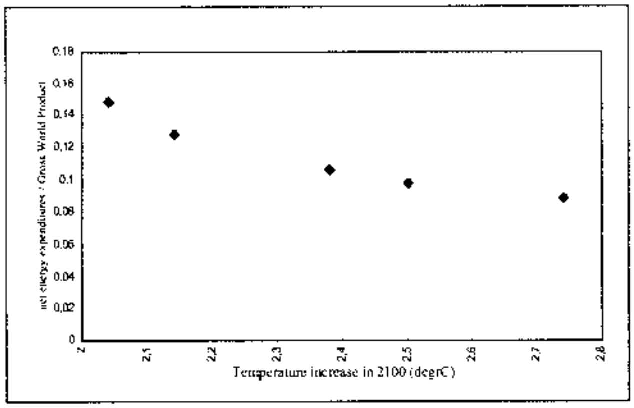


Figure 8.3b: Average net energy expenditures divided by GWP versus the global mean temperature in 2100 for the strategies meeting the global mean temperature targets.

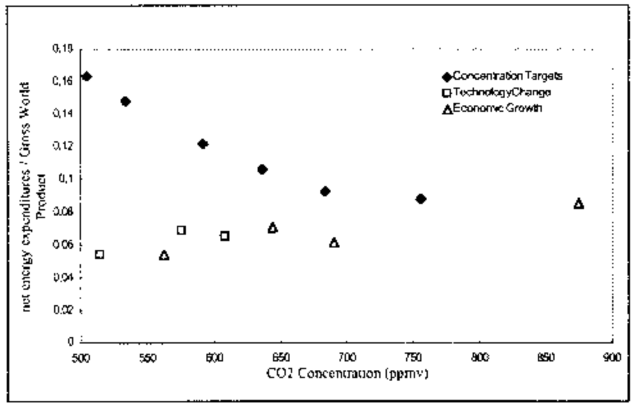


Figure 8.3c: Average net energy expenditures divided by GWP versus the CO_2 concentration in 2100 for the cases: different assumptions on technological development and different assumption on economic growth.

gical transitions assumed for these scenarios could reduce the CO_2 concentrations in 2100 at much lower relative costs. Still, meeting the 550 ppmv CO_2 concentration constraint requires additional policy measures except for ESTC. The probability of a technological transition is an important element for energy policy in the short-term, an issue discussed in more detail in the coming paragraphs. First, we discuss another highly uncertain and important energy policy issue: long term economic growth.

Economic Growth
In the four scenarios we have assumed an average 2.3 %/yr GWP growth between 1990 and 2100 and sectoral activity levels are derived from this fixed GWP-growth. An annual growth rate of 3.0%/yr would lead to an average GWP per capita of about 50,000 US90$ in 2100, about twice as high as in the CW scenario. The resulting increase in the use of fossil fuels leads to CO_2 emissions of 35 GtC in 2100. Because of high SO_2 emissions, the projected global mean temperature increase is only slightly higher. The impact on relative energy expenditures is shown in *Figure 8.3c*. Higher energy demand leads to higher use of fossil fuels and higher energy prices, which is only partly offset by more energy conservation and greater penetration of renewable energy sources. Hence, higher economic growth reduces the impact of technology improvement on the CO_2 emission reduction goals as the arrows show in *Figure 8.3c*. Because we did not model the interactions between energy policy, economic developments, and technological innovation, it is speculative to discuss the consequences for abatement in greater detail.

8.5 Delayed Response

What are the risks of implementing abatement policies at a later date? As an illustration we explore a delayed response strategy in which we assume that no active energy policy is implemented till 2010. We use the CW scenario and look for an optimal strategy thereafter to meet the 550 ppmv constraint. Such an experiment explores the situation in which governments initially assume a low impact of emissions on the climate system and/or a rapid technological transition to a non-fossil energy system. After 15 years (1995-2010) a change in insights and facts leads to a new energy policy. In our model such a delayed response leads to higher costs (*Figure 8.4a* wait and see) because of extra investments together with rising oil prices as oil is assumed to become economically depleted in the CW scenario. However, the additional cost of a delay might be comparable with the 'act-now' cost, even with a rapid emissions reduction, due to assumed autonomous technological developments. The consequences in terms of global mean temperature change are a short term accelerated increase just after 2010 due to accelerated reduction of SO_2 (*Figure 8.4*). If the rate of temperature change is viewed rightly as one of the indicators of climate change related risks (Alcamo and Kreileman, 1996), the delayed response strategy of 'wait-and-see' is probably a risky one.

Next we look at the reverse situation: implementing strong energy policies which turn out to be unnecessary. Using ESTC scenario assumptions, what are the consequences of an active climate change policy, which is then terminated in 2010?

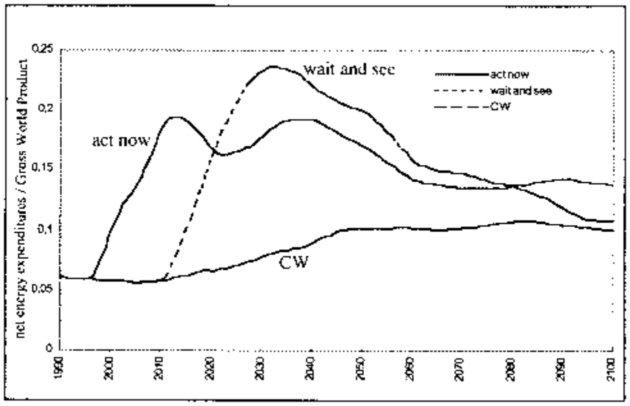


Figure 8.4a: The net energy expenditures per GWP using the CW assumptions.

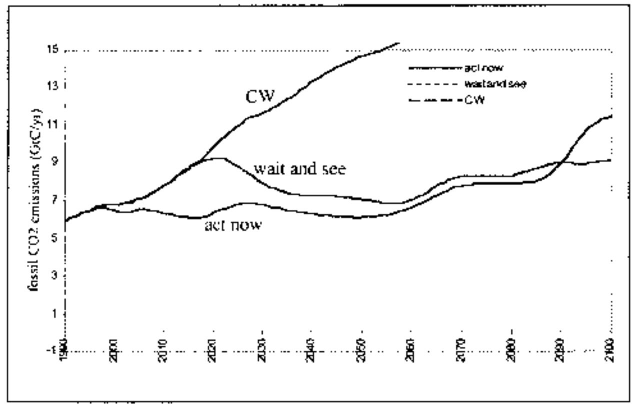


Figure 8.4b: The fossil CO_2 emissions using the CW assumptions.

In the first decades the relative net energy expenditures increase sharply if the carbon tax and R&D policies are implemented; they fall when they are terminated (*Figure 8.4c*). However, the price-induced efficiency improvements in the first decades induce large energy efficiency improvements, which leads to lower relative expenditures after 2020 than in the ESTC scenario without policy measures. As a result the aggregated net energy expenditures over the period 1995-2100 are lower in case of early intervention than without. It is not surprising that the CO_2 emissions are lower in case of a short period of active energy policy (*Figure 8.4d*). However, given reference assumptions on the climate system, a no-policy scenario was already sufficient to meet frequently used climate targets (see *Figures 8.2*).

Early emission reduction measures are found to be efficient because early taxation of fossil fuels not only stimulates alternatives but also stimulates price-induced energy conservation investments. This conclusion conflicts with the conclusions of Wigley *et al.* (1996). One reason can be that our bottom-up approach excludes macro-economic feedbacks, while Wigley *et al.* (1996) base their conclusion on macro-economic arguments neglecting the insights of bottom-up studies.

8.6 Hedging Strategies

The above exercises illustrate the important consequences of first (not) act and then learn. But the choice of a strategy is faced with uncertainties and risks. Manne and Richels (1992) introduced the concept of hedging as a method to deal with uncertainty in decision-making. Instead of assuming perfect knowledge of the system over the coming century, a period of learning is proposed. We apply this approach by optimizing the objective function $(1-\alpha)f_{CW}+\alpha f_{ESTC}$ where α is the subjective probability whether technological developments evolve as in the ESTC scenario or as in the Conventional Wisdom scenario. In fact, we optimize the decision variables for the two model implementations, given

Figure 8.4c: The net energy expenditures per GWP using ESTC assumptions.

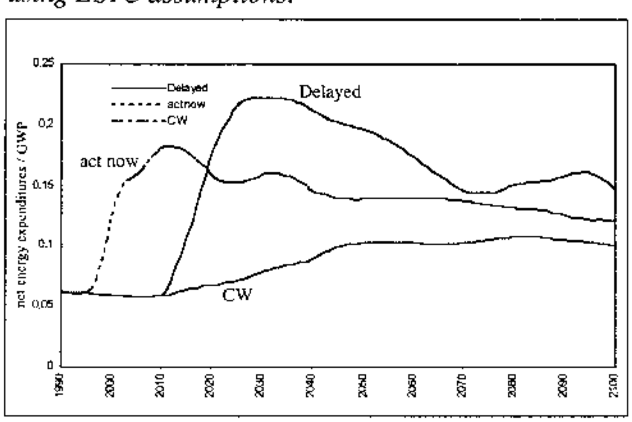
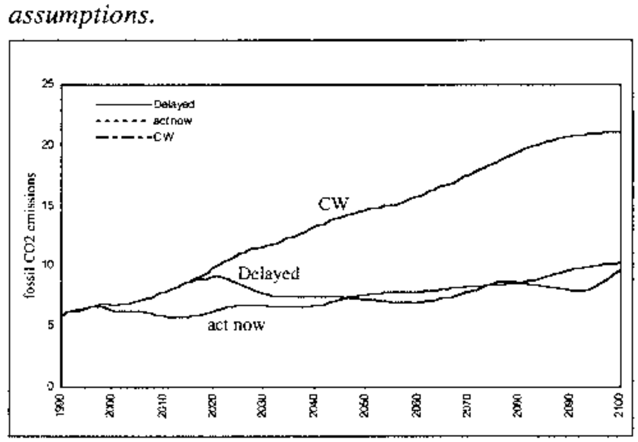


Figure 8.4d: The fossil CO_2 emissions using ESTC assumptions.



the restriction that the decision variables have the same values until 2010, and may differ thereafter.

Our illustrative experiment assumes a 50% chance on accelerated technological development as in the ESTC scenario and a 50% chance on technological development according to the Conventional Wisdom scenario. Carbon tax policy is the dominating factor in reducing emissions. In view of its global aggregation level, one cannot attach much value to the calculated carbon tax levels. Nevertheless, in *Figure 8.5a* we depict the carbon tax levels of the hedging exercise to illustrate the concept and the different kind of results compared with top-down models. The carbon tax jumps to high levels at the start of the period. The usual result of a smoothly increasing carbon tax scenario in most top-down models is depicted in the same figure. There are a number of possible explanations for the differences: (i) the system dynamics approach as adopted in our model assumes a current state of the energy system which is not necessary optimal in terms of costs. An additional policy may, therefore, lead to a more efficient energy system and lower costs. In the optimization models adopted by the top-down approach, the current state of the energy system is optimal in terms of cost, and any additional policy (like a carbon tax) will lead to extra costs; (ii) we did not include social discounting within the objective function; (iii) there is no feedback of a carbon tax on the economic activities. A carbon tax may lower economic growth and therefore energy demand, which in turn will reduce the required carbon tax levels; (iv) the inertia of the capital stocks within our model will not lead to a straightforward improved energy efficiency per US$; (v) the many non-linear relationships and feedbacks in our model instead of nice convex relationships.

In *Figure 8.5b* the relative changes, compared with the reference, in the energy mix are shown for both the CW and the ESTC scenario given a concentration target of 550 ppmv. While the short-term policy for both the CW and the ESTC scenario are the same in the hedging exercise, relative changes do not significantly differ. Because carbon intensive energy carriers become more expensive (due to a carbon tax), there will be a reduction of coal, oil and gas. Actually, there are two waves of fuel substitution. Firstly , coal is substituted for the relatively cheaper oil. Due to the increased use of oil, the price of oil increases such that oil is substituted by biofuels. The overall energy use declines relative to the CW and ESTC scenario, due to price induced efficiency improvements.

The emission profiles of the hedging strategy are depicted in *Figure 8.5c*. The reduction relative to the 'no-policy' scenario is about the same in both cases of technological development. However, due to a fast technological development in the ESTC scenario, emissions can be reduced to below the 1995 levels, while in the CW assumptions, this is less likely. The relative energy expenditures (*Figure 8.5d*) are only slightly lower in case of a fast technological development for the period 1995-2010. Not shown in the figures are the pathways after 2010; an active policy will be required to meet the 550 ppmv concentration target if the technological development follow the CW scenario, while no active policy is necessary if technological development is as in the ESTC-scenario.

Figure 8.5a: Carbon tax levels for the hedging strategy when after 2010 an optimal level is derived according to the technological developments, and a hypothetical carbon tax path for a traditional top-down approach.

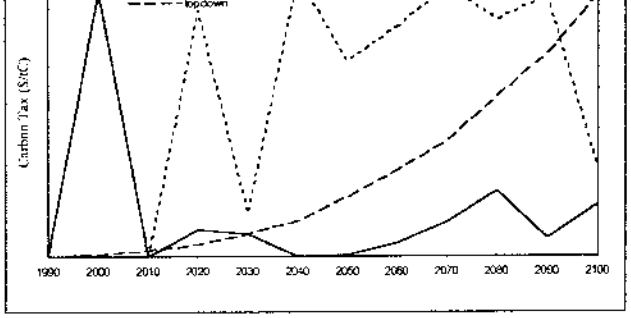
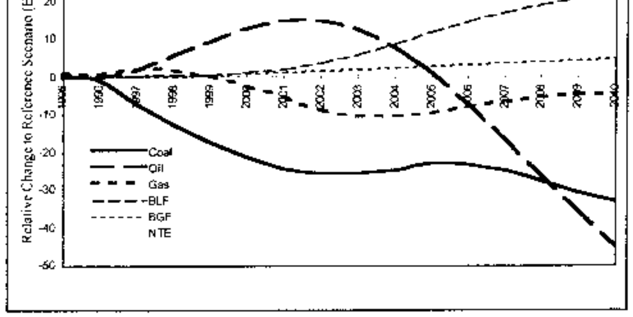


Figure 8.5b: Relative change of the fuel mix compared to the reference scenario in case of hedging uncertainties in technological development.



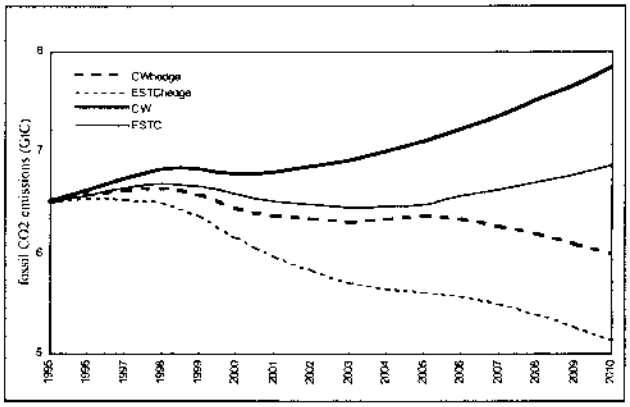


Figure 8.5c: The impact of the hedging strategy on fossil CO_2 emissions: the net relative energy expenditures for the two scenarios considered.

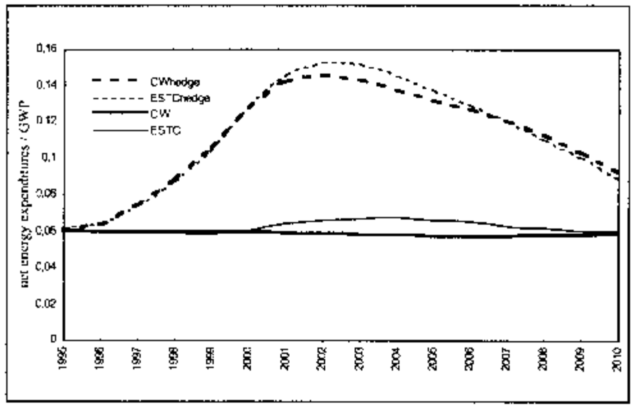


Figure 8.5d: The relative energy expenditures for the various cases.

The influence of the probability α assigned to the technological development-paths of the scenarios is analyzed by optimizing hedging strategies for a number of different values of α. It turns out that this does not have a large influence on the policy strategy. Only when it is certain that a technological transition does not occur (α=0), a strong policy is required by 2010 with high relative costs. Given the exercises discussed in Section 8.5, these findings are not surprising.

To summarize, the hedging exercise tells us that an active policy in the short term has benefits for the long term irrespective of technological developments. This is caused by the fact that efficiency improvements realized now have their benefits the decades thereafter, given an unchanged economic development. This last remark, however, denotes an important omission of this study while it does not incorporate impacts on economic development of technological development, energy policies and climate change.

8.7 Integrated Policy for Climate Change and Acidification

The recent quantification that sulphate aerosols have, in global mean terms, a cooling effect has complicated the climate change debate. Because SO_2 emissions are also an important contributor to acid deposition at the regional level, it is expected that SO_2 specific emission reduction measures will be implemented. This reduction may enhance the expected temperature increase, so that an integrated analysis is required for both CO_2 and SO_2 emission reduction strategies. Ideally the local impacts of climate change and acidification should be taken into account. Here, we only illustrate likely trade-offs between the two problems. Recent studies of Alcamo *et al.* (1995) and Posch *et al.* (1996) linked the integrated assessment model for climate change IMAGE 2 (Alcamo *et al.*, 1994) and the integrated assessment model for acid rain RAINS (Alcamo *et al.*, 1990; Foell *et al.*, 1995) to assess the combined impact of sulphate policy on ecosystems in Europe and Asia. In their analysis they conclude that in Europe the impact of sulphate reduction policies benefits ecosystems more than it harms them, while for Asia there is no clear best policy.

Our analysis focuses on the fossil fuel transition and the impact of technological change. Given different futures of the energy system, can we identify trade-offs between reduction strategies for SO_2 and CO_2? We simulate the SO_2 emissions of the IS92a scenario (IPCC, 1992) by adjusting the emissions per Joule of fossil fuel (*Figure 8.6a*; reference). We formulate two alternative SO_2-specific policies in relation to acidification policy: an acceleration and a delay of SO_2 reduction per Joule of fossil fuels. *Figure 8.6a* shows the reduction paths for SO_2 used in our experiments. *Figure 8.6b* shows the reduction paths for SO_2 used in our experiments. *Figure 8.6b* shows the calculated temperature change for the CW and ESTC scenarios for the three SO_2 - reduction paths. It is seen that, given our assumptions on the role of aerosols, an accelerated SO_2 - reduction strategy could cause a slightly higher temperature change by the year 2100.

In the previous paragraphs, the use of fossil fuels may decline in the coming century due to environmental policies, accelerated technological innovations or delayed economic growth. In *Figure 8.6b* the technological transition scenario (ESTC) gives

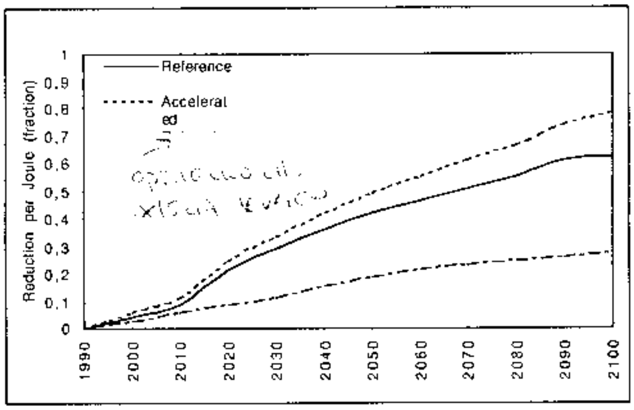


Figure 8.6a: Reduction fractions of SO_2 emissions per Joule of fossil fuel relative to 1990. The reference case meets the IS92a emissions scenario is CW assumptions are used, while accelerated and delayed policies represent alternative SO_2 policies.

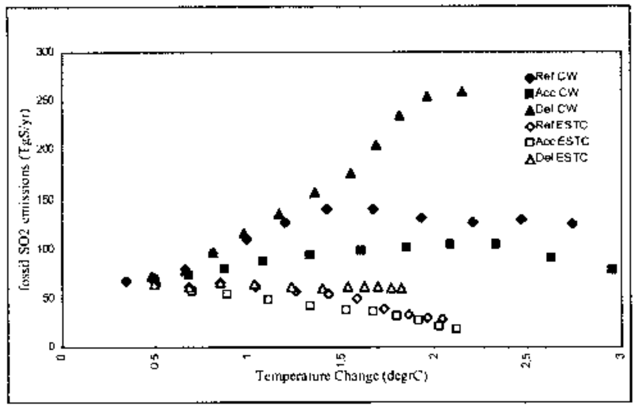


Figure 8.6b: The indicators global SO_2 emissions and global mean temperature change are used to illustrate trade-offs between acidification and climate change policies in relation to energy use.

an illustration of the integrated impact of reduced fossil fuel use. The SO_2 emissions decline for the three SO_2 policies due to an overall reduction in fossil fuel use. However, the projected global mean temperature change is not significantly lower (*Figure 8.6b*). Thus climate change impacts remain close to the higher risk area, while the impacts of acidification tend to diminish the risk at least in the short term.

8.8 Conclusions

The simulation experiments with the TIME-CYCLES part of the TARGETS model as presented in this Chapter explore ways to meet climate changes targets and the role of technological change in the energy system. Given conventional wisdom assumptions on technological developments within the energy system, an early action is cost-effective to meet long term climate change policy targets. Even with an accelerated technological change in the energy system, an early action is found to be cost effective in the long run. We did not assume an optimal functioning energy system at the present. Such an early action may accelerate the energy savings options to reduce the long term energy demand, and stimulate alternative fuels as a competitor for fossil fuels.

Important omissions in the current version of the model are the lack of feedback from the energy system to economic growth projections, the highly uncertain relation between economic growth and technological development, the impacts of climate change on the economy, absence of regional disaggregation, exclusion of a number of potentially important technical options (among them electric cars, and coal liquefaction and gasification), and the impact of required land for biomass on food production. The performed experiments are therefore a first step towards a more comprehensive integrated analysis of the global energy system and its (long term) impacts upon the global system.

Some of these shortcomings will diminish, because of a follow up of this study. The energy model will be disaggregated in the 13 IMAGE 2 regions to improve the IMAGE energy (demand) model (Bollen *et al.*, 1996) and include fuel trade. The experiments show that an optimization oriented analysis with a complex simulation model such as TARGETS can be performed. Such an approach may help to fill the gap between the complex simulation models and the simple optimization models which are both found in the integrated assessment modelling community. We hope that such an approach may help us to derive insights in the complex problem of global change and yield possible long term policy strategies.

9. CONCLUSIONS AND FUTURE WORK

In this report we have explored a number of applications of the Targets IMage Energy (TIME) model which has been described in a previous report (Vries and Van den Wijngaart 1995), in combination with the CYCLES model (Den Elzen et al. 1996). Both models are part of the integrated TARGETS1.0-model (Rotmans and de Vries 1997). On the basis of a limited set of historical data, a fairly good calibration of the world energy system between 1900 and 1990 is possible. However, such a calibration is not unambiguous in the sense that various assumptions have to be made for which, certainly at the global level, the empirical basis is rather weak. It shows up, for example, in the simulation of natural gas use in the first half of the century. An interesting case of ambiguity is the degree to which one interprets past dynamics as the result of relative prices as against an explanation in terms of autonomous technical innovations. More in general, the systems dynamics formulation gives a rather robust model behavior and appears a good approach to explore long-term structural changes.

Models can, in our view, best be seen as heuristic tools to understand real-world dynamics and to identify and communicate diverging views on the various mechanisms and forces of change. Scenario construction, in this view, is a participatory and model-supported exercise. In the present report, we first discuss scenarios from a more limited perspective : to what extent can model parameters and relationships be based on historical observations and expert views (Chapter 4) and what assumptions about model parameters have to be made to reproduce key variables of energy scenarios published by others (Chapters 5 and 6). As one would expect in the present, rather turbulent stage of various energy-related transitions, there are widely divergent views on how to interpret the past and what to expect for the future. This corresponds with our finding that one can construct with the TIME-model quite divergent long-term energy futures which reflect, either explicitly or implicitly, a whole spectrum of assumptions on such items as energy efficiency and fossil fuel supply cost curves and the learning dynamics of non-thermal electric and biomass-based options. The reproduction of published scenarios, although technically possible, neither imply a statement about their plausibility nor is it the only way in which such a reproduction can be done.

Our experiments suggest that the IPCC-IS92a scenario is rather implausible in view of the rate at which new technologies have been developed and commercialized in the past century. Especially the huge rate at which coal is assumed to expand is questionable for various reasons. On the other hand, our experiments indicate that some of the recently published low-carbon-dioxide-emission scenarios can only come true if one makes rather extreme assumptions on resource abundance and on human ingenuity, organizational skills and political will. Evidently, the threat of anthropogenic climate change can be reduced enormously and without affecting economic growth if one assumes an almost zero-cost surprise technology - like the way in which various governments have presented nuclear energy in the 1950's and 1960's.

It is against this background that we have used the Cultural Theory as a framework to make coherent sets of assumptions which then give rise to hierarchist, egalitarian and individualist utopias, that is, worlds in which the future unfolds according to a particular view on controversial issues (worldview) and a corresponding set of policy responses (management style). The resulting scenarios coincide quite well with positions which are held by certain groups in society, as Chapter 7 shows. We see this work as a first step to deal in a quantitative way with the uncertainties which arise from ignorance and the resulting social construction of the world.

Starting from the hierarchist scenario, which we in this report have associated with the coal-based Business-as-Usual IPCC-IS92a scenario, we have explored the kind of policy interference which is required to meet certain climate policy targets (Chapter 8). The additional costs resulting from having to meet stricter targets give a plausible picture of how the system might go through a transition. Further simulations in which we use assumptions which are like those for the egalitarian and the individualist utopia indicate, however, that these additional costs are an unnecessary burden if more optimistic assumptions on new energy technologies are used. Some experiments focus on the importance of divergent assumptions by exploring hedging strategies. Finally, it is shown that the future emission trajectories of sulfur-oxide emissions cannot be left out of the discussion on emission reduction strategies.

Currently, the TIME-model is being regionalized (TIMER, Targets IMage Energy model Regional), as part of the IMAGE2 model. For the 13 IMAGE-regions, the period 1970-1990 is being calibrated. Furthermore, a simple trade model will be included for the carriers oil, gas, coal and biofuels. Information about land use and land productivity from the IMAGE model will be used to improve the part on biofuels. The TIMER model will be used to construct more detailed and integrated scenarios for the European and Global Environmental Assessment done at RIVM. A similar regionalisation is planned for another TARGETS submodel, the Population and Health model (Niessen et al. 1997).

Another step is to forge closer and more systematic links between the TIME[R] model and the economic world model WorldScan developed at the Central Planning Bureau (CPB, 1995) of The Netherlands. This will lead to a further integration of energy and economic insights and allow a better comparison of results from bottom-up vs. top-down approaches. Finally, we are developing an optimization routine to estimate model parameters, given expert views on their domain, which will be used for historical calibration and scenario reproduction.

APPENDIX A: PARAMETER VALUES FOR REFERENCE SCENARIO

Energy demand (ED) model

The demand model for energy is confined to commercial fuels only. For five sectors (residential, commercial (services), industrial, transport, other) it calculates heat demand. Electricity demand is calculated for all sectors together.

We define the following input vectors (each having 6 elements : 5 sectoral for heat, 1 for electricity) :

- S structural change : the ratio of the [sectoral] energy intensity (GJ/activity) in 2100 and in 1900-level
- A autonomous decrease path 1990-2100 (%/yr)
- LA lower bound on technology , i.e., the ultimate conservation potential as fraction of the energy-intensity (GJ/activity) for infinite activity level
- P steepness of the energy conservation cost curve
- ARC annual rate of decline of the energy conservation cost curve (%/yr)
- PBT assumed pay-back time on energy conservation investments (yr)
- PF premium factor path, allowing for discrepancies between market price and perceived price (including bounds) ($/GJ)
- CPE cross-price-elasticity between LF, GF and SF.

Any scenario has to be explicit on these parameters. Table A.1 below gives the default values for the reference scenario, or reference values, for the scenario period 1990-2000.

Electric Power Generation (EPG) model

In the EPG-model there are several parts : translating electricity demand into base-load and peak-load required capacity, the charactarization of the capital stocks, and the fuel and substitution characteristics. The demand profile is characterized by a set of parameters. BF is the part of electricity demand to be supplied in base-load. BLF_i indicate the Base Load Factor of capacity stock i, i.e., the fraction of the year it is operated in base-load. PLF_{max} is the maximum Peak Load Fraction at which capacity can be run in peak-load. The value used for these parameters are:

BF	Fraction elec-demand base-load 0.9
BLF_{NTE}	0.52 (before 1980); 0.67 in 1980, 0.6 in 2000 and down to 0.38 in 2100 (>1980)
BLF_H	0.43
BLF_{TE}	0.55
PLF_{max}	0.45

We use for scenario experiments the default values of Table A.2 for the parameters for the scenario period 1990-2100.

ED-Model	S [a)]	A (%/yr)	LA	P	PBT (yr)	ARC (%/yr)	PrFac SF	PrFac GF	CPE
residential	1.7(0.65)	1	0.2	30	2	0.1	4(2000)	1.1(2000) -0.5(2010)	2
commercial	0.85(0.5)	1	0.2	40	1.5	0.1	0	0	1
industrial	0.8(0.6)	1	0.2	30	1	0.1	4	0(1985) -0.5(2010)	2
transport	8(0.7)	1	0.3	30	3	0.1	=Res	2(1990) 0(2030)	1
other	1.85(0.5)	1	0.3	30	1.0	0.1	8(2010)	1.4(1990) 1(2000)	2
electricity	36(0.65)	1	0.4	50	1	0.1	na	na	na

a) between brackets : ratio of 2100-value and 1990-value

Table A.1

Fuel (SF, LF, GF) supply models

The default values for the relevant parameters are given Table A.3 for the scenario period 1990-2100. COR is Capital-Output Ratio. The key input variables are :

- the initial resource base (ultimately technically recoverable);
- depletion multiplier, which indicates how the Capital-Output Ratio changes as a function of the fraction of resources remaining;
- learning rate, which gives the cost reduction on a doubling of cumulative production;
- characteristics of the underground coal and the biofuel production functions;
- a few additional cost parameters like the cross-price elasticity between fuels, the overhead costs (transport, distribution) and the labour costs (linked to Consumption Expenditure per caput).

EPG-Model	Thermal TE	Hydro H	NonThermal NTE	T&D
Economic LifeTime (yr)	15	15	15	40
Technical LifeTime (yr)	25	50	30	50
Interest Rate (%)	10	10	10	10
TE Thermal Efficiency (%) [e]	35(1990)[a]			
NTE Learning rate parameter [e]		d)	1.1(1995) 0.96(2040) 1.0(2080)	
Spec Investment Cost ('000 $)	2000(1900)- 595(1990)	6000[b]	1000[b]	600[c]
Premium Factor GF (relative to HLF)	1.45			
Premium Factor SF (relative to HLF) [e]	0.37(1965)- 0.35(>2000)			
Construction delay (yr)	3	5	8	na
TE-NTE cross-price-elasticity	0.65	na	(idem)	na

a) afterwards 0.3%/yr increase to about 48% by the year 2100
b) excluding depletion and learning, i.e. 1980-[initial] value
c) investment per MWe of installed peak capacity
d) for hydropower, depletion is assumed : the ultimate potential is 2430 GWe at twice the 1990-cost/MWe
e) exogenous time-series from 1960 to 2100

Table A.2

SF-Model	Underground Coal (UC)	Surface Coal (SC)
Initial resource base (1900; EJ)	230000	(idem)
Depletion : Ratio of exploitation cost final/1900 a)	3 (at 50% depletion)	
Learning rate parameter COR	na	0.9
Cross-price-elasticity UC-SC	0.4	(idem)
Overhead investm Tr&Distr factor	1.45	(idem)
Capital-Labour ratio for UC ($/my) c)	44000(1980)-100000(2100)	na
UC Ratio wage rate / per cap cons	2.5	na

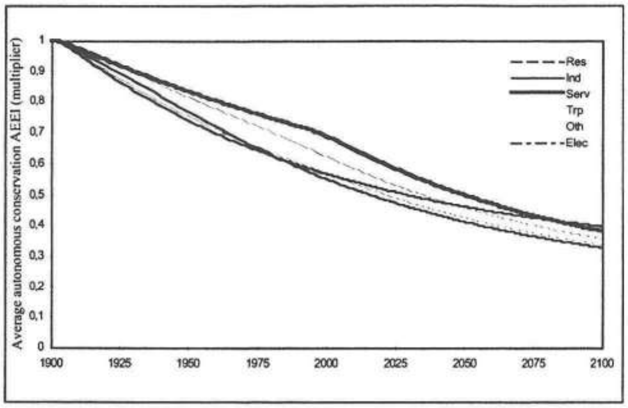
LF and GF Model : Fossil	LF (Oil, BLF)	GF (Gas, BGF)
Initial resource base (1900; in EJ)	72000	60000
Depletion : Ratio of exploration cost final/1900 a)	10	10
Depletion : Ratio of exploitation cost final/1900 a)	12	12
Learning rate parameter	0.9	0.95
Overhead investment Transport & Distribution ($/$)	0.6+LLFShare	1.1(1980)-2(2100)
Share of HLF in total LF-demand (%) c)	0.2(2000)-0(2100) [industry: 0.5(2000)-0.2(2100)]	na

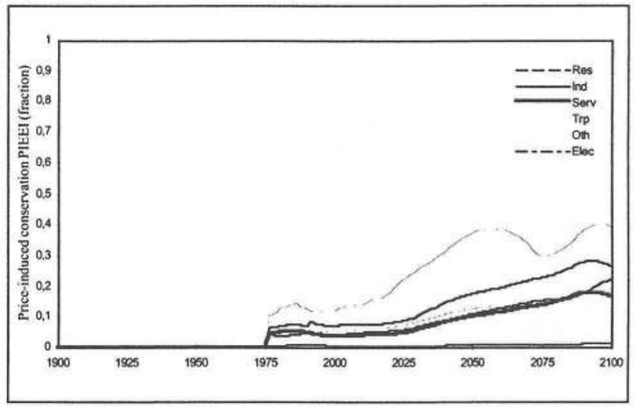
LF and GF Model : Biofuels	LF (Oil, BLF)	GF (Gas, BGF)
Initial (1970) land yield BF (GJ/ha)	470	470
Ultimate BF supply potential (EJ/yr)	300	300
Initial (1950) BF cost ($/GJ)	30	42
Depletion multiplier land yield BF b)	5	5
Learning multiplier land yield BF b)	0.9	0.9
Landprice for BF ($/ha) c)	50000	50000
BF Ratio wage rate / per cap consumption	0.7	0.7
BF Cap-Lab substitution elasticity	0.6	0.6
BF Labour productivity (ton/manday)	3	3

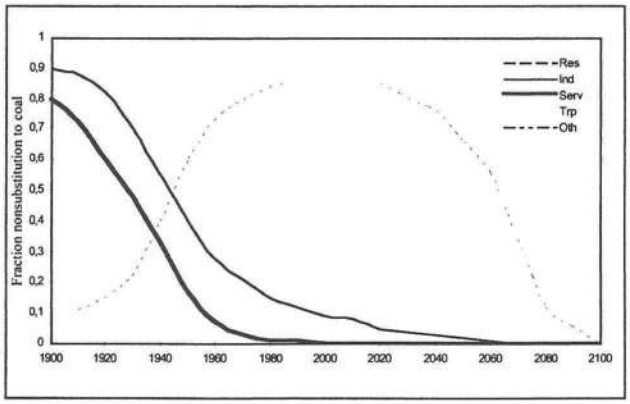
a) these are the depletion multipliers, gauged at 1 in 1980
b) defined as cost at final potential and at start, gauged at 1 in 1980
c) exogenous time-series from 1960 to 2100

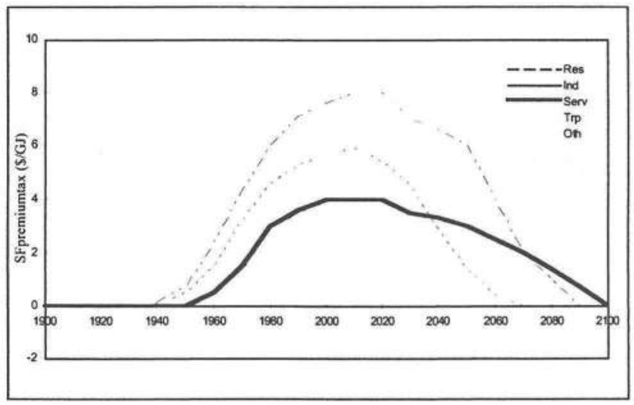
Table A.3

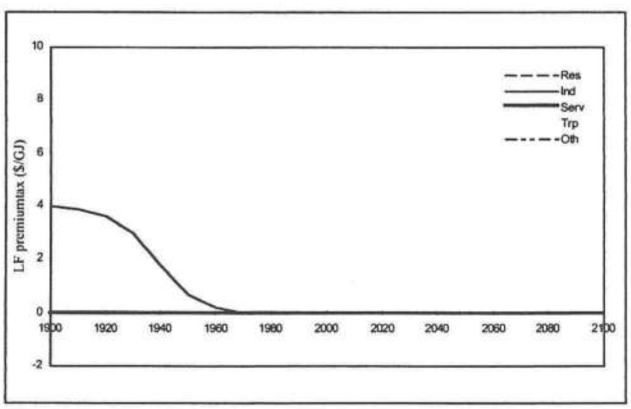
The time-dependent input variable and relationships used in the reference scenario are shown on the following three pages.

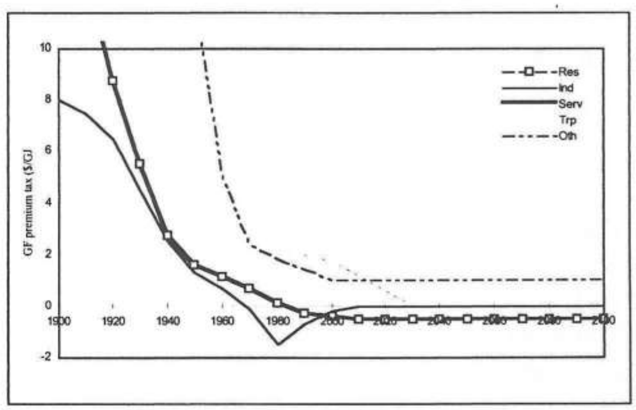

Average autonomous conservation AEEI (multiplier)
Res
Ind
Serv
Trp
Oth
Elec

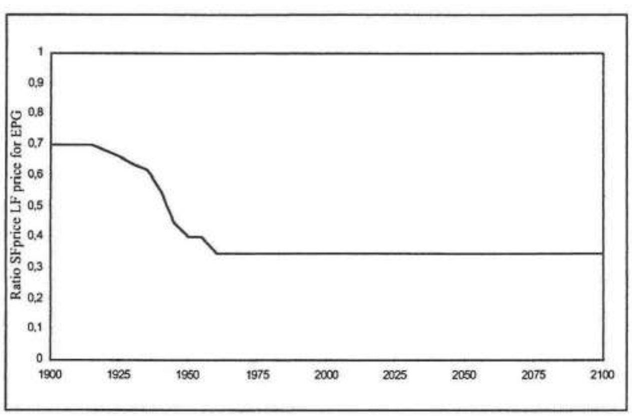

Price-induced conservation PIEEI (fraction)
Res
Ind
Serv
Trp
Oth
Elec

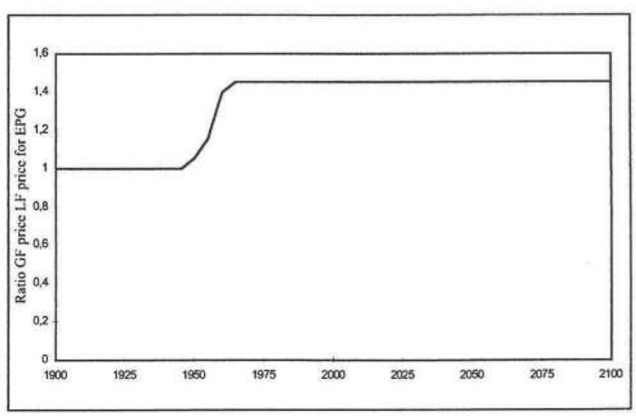

Fraction nonsubstitution to coal
Res
Ind
Serv
Trp
Oth

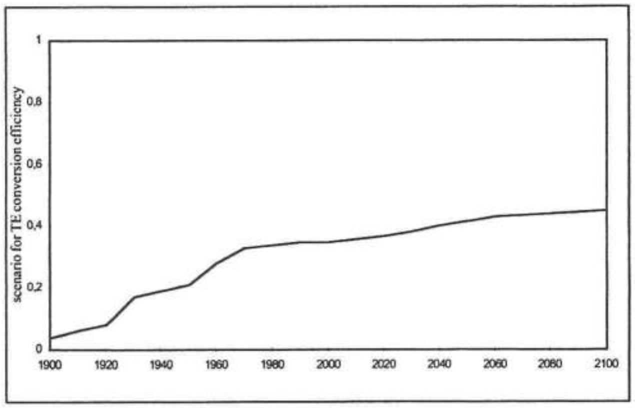

SFpremiumtax ($/GJ)
Res
Ind
Serv
Trp
Oth

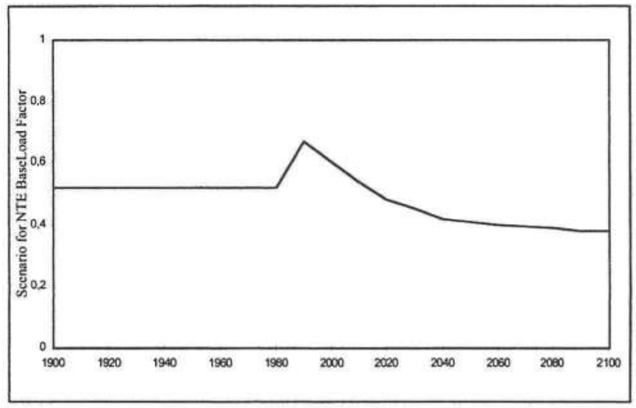

LF premiumtax ($/GJ)
Res
Ind
Serv
Trp
Oth

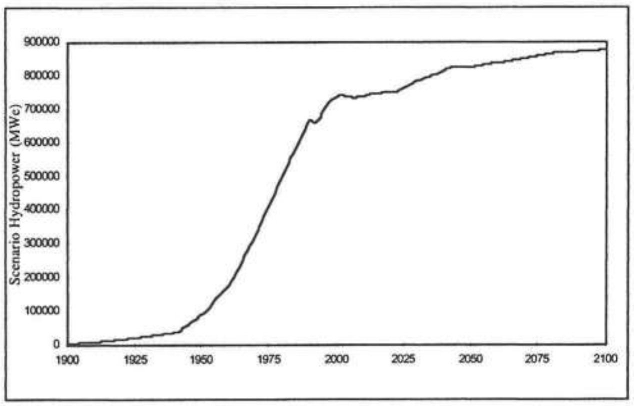

GF premium tax ($/GJ
Res
Ind
Serv
Trp
Oth

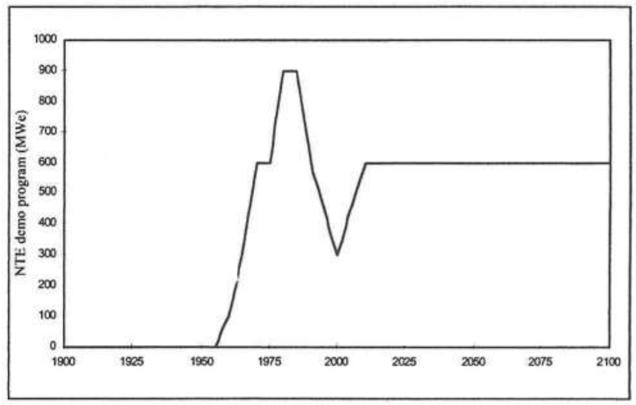

Ratio SFprice LF price for EPG

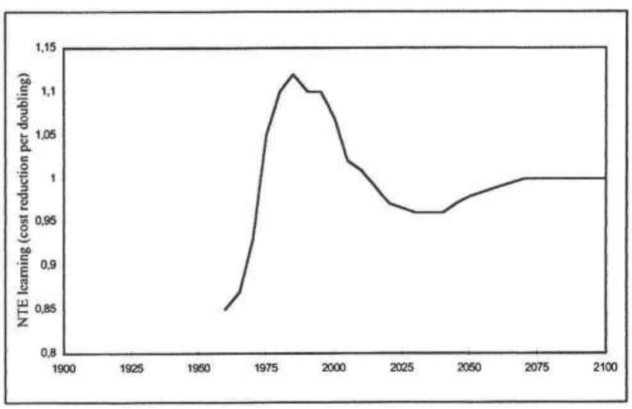

Ratio GF price LF price for EPG

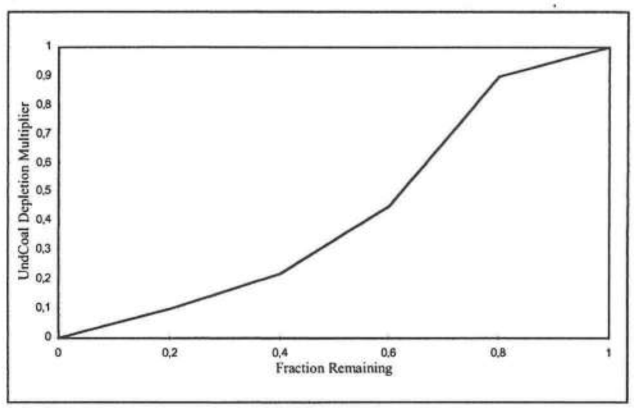

scenario for TE conversion efficiency
1
0,8
0,6
0,4
0,2
0
1900
1920
1940
1960
1980
2000
2020
2040
2060
2080
2100

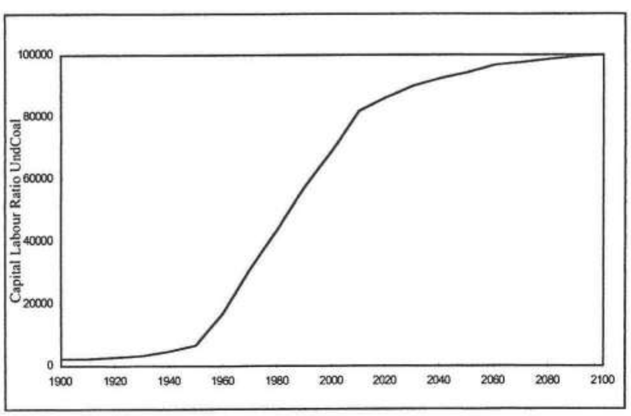

Scenario for NTE BaseLoad Factor
1
0,8
0,6
0,4
0,2
0
1900
1920
1940
1960
1980
2000
2020
2040
2060
2080
2100

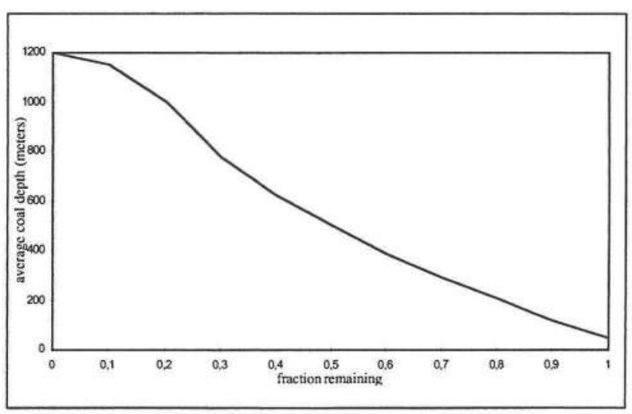

Scenario Hydropower (MWe)
900000
800000
700000
600000
500000
400000
300000
200000
100000
0
1900
1925
1950
1975
2000
2025
2050
2075
2100

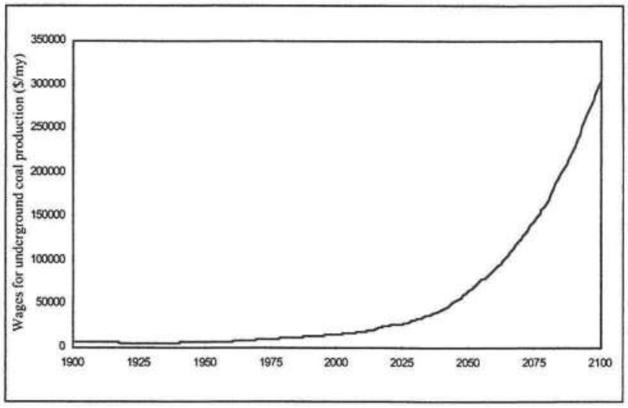

NTE demo program (MWe)
1000
900
800
700
600
500
400
300
200
100
0
1900
1925
1950
1975
2000
2025
2050
2075
2100

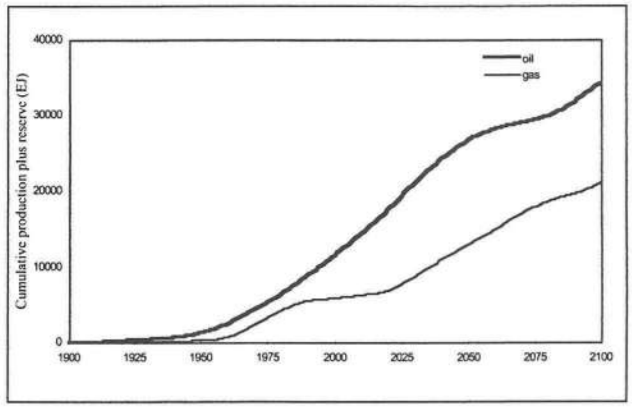

NTE learning (cost reduction per doubling)
1,15
1,1
1,05
1
0,95
0,9
0,85
0,8
1900
1925
1950
1975
2000
2025
2050
2075
2100

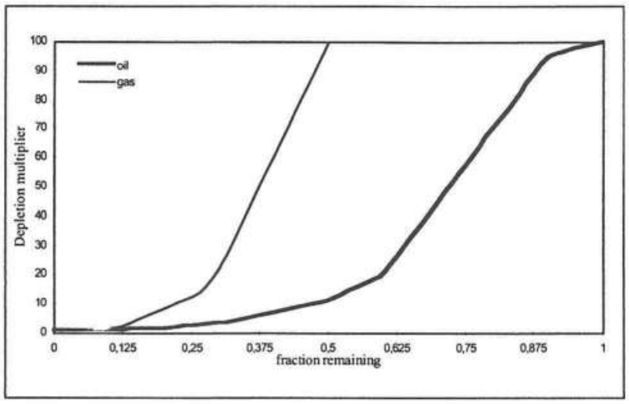

UndCoal Depletion Multiplier
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0
0,2
0,4
0,6
0,8
1
Fraction Remaining

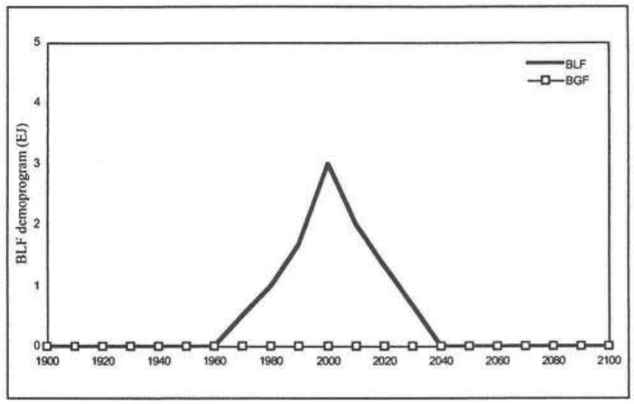

Capital Labour Ratio UndCoal
100000
80000
60000
40000
20000
0
1900
1920
1940
1960
1980
2000
2020
2040
2060
2080
2100

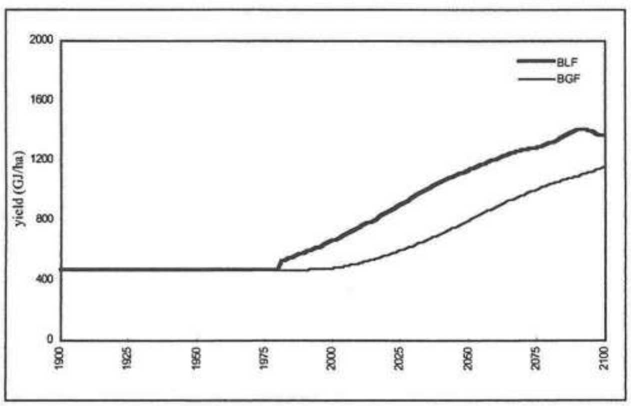

average coal depth (meters)
1200
1000
800
600
400
200
0
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
fraction remaining


Wages for underground coal production ($/my)
350000
300000
250000
200000
150000
100000
50000
0
1900
1925
1950
1975
2000
2025
2050
2075
2100


Cumulative production plus reserve (EJ)
40000
30000
20000
10000
0
oil
gas
1900
1925
1950
1975
2000
2025
2050
2075
2100


Depletion multiplier
100
90
80
70
60
50
40
30
20
10
0
oil
gas
0
0,125
0,25
0,375
0,5
0,625
0,75
0,875
1
fraction remaining


BLF demoprogram (EJ)
5
4
3
2
1
0
BLF
BGF
1900
1920
1940
1960
1980
2000
2020
2040
2060
2080
2100


yield (GJ/ha)
2000
1600
1200
800
400
0
BLF
BGF
1900
1925
1950
1975
2000
2025
2050
2075
2100

APPENDIX B: CHARACTERISATION OF SOME GLOBAL ENERGY SCENARIOS

1. Fossil Free Energy Scenario (FFES)

Main features

	1985	2000	2030	2050	2100
Population (10^9)	4,8	6.2	8.8	10.0	11.3
GNP/Cap. (in 1985-$)	3087	3757	4749	9000	18788
Energy-intensity (MJ/$)	21(1988)	17	9	-	4.6
Primary Energy Use (EJ)	338(1988)	396	384 (400 in 2010)	-	987
Primary Energy fuel shares (in EJ) :					
coal	93	93	9	-	0
oil	116	112	59	-	0
gas	65	96	57	-	0
biomass	22	38	91	-	181
nuclear	19	12	0	-	0
hydro + geo	23	26	30	-	28
other renewable (e.g. wind, solar)	0.1	20	118	-	778

* non-fossil electricity back-calculated by using averaged fossil/biomass plant efficiencies

Energy-related carbon emissions (Gt C)	5.4	5.7	2.5	2.3	

Activity and energy demand assumptions :

- economic growth: 2.3 % p.a. average 1985 - 2100 with improved equity (2100: GDP/cap(IC) : GDP/cap(DC) = 2:1)
- energy intensity *: -2.0 % p.a. average 1988 - 2030; -0.95 % p.a. average 2030 - 2100

* own calculation based on SEI-data

Sectoral energy demand (in EJ, rounded) :

	1988	2000	2010	2030	2100
Residential	53.7	1.2	47.65	46.8	53.4
Services	29.8	31.75	33.4	39.65	99.35
Industry	90.3	105.9	105.55	83.75	196.4
Transport	61.0	67.5	65.0	61.5	99.0

Sectoral activities are based on a shift in GDP-shares (pp. 27). The share of electricity in final demand is assumed to increase from 14% (1988) to 34% (2030) to 47% (2100).

Energy supply assumptions :

- oil refinery efficiency is assumed to increase from 94% (1990) to 97% (2030)
- electricity transmission and distribution losses are assumed to have fallen to 6% in 2030
- natural gas use increases up to 2010 due to fuel switching from oil and coal, especially in electric power generation

- nuclear energy is deliberately phased out by 2010
- renewable energy sources begin to dominate primary energy supply from 2030 on;
- modern biomass plays an important role in substituting fossil fuels during the first decades of the next century; later solar/wind energy become the most important source of energy
- hydrogen becomes an important secondary energy carrier to store energy from renewables and to be used in the transport sector
- fossil fuels are fully phased out by 2100; cumulative consumption of gas and oil are then 6200 EJ and 6600 EJ resp.

Price assumptions (rounded) :*

	1990	2000	2010	2020	2030
coal	1.0	1.1	1.3	1.5	1.75
crude oil	3.05	5.1	6.75	7.55	8.4
natural gas	1.75	3.1	5.4	6.0	6.7
comm. biomass	2.0	3.0	3.0	3.0	3.0

* referred energy prices (1990 $/GJ)(after 'America's Energy Choices', UCS et al, 1991):

Busbar costs of (new) electricity plants (1990 $c/kWh):

	1990	2000	2010	2020
coal-steam FDG	3.9	4.15	4.45	4.85
coal- AFBC	4.45	4.7	5.05	5.4
coal-IGCC	3.7	3.9	4.2	4.55
coal-Fuel cell/MHD			3.75	4.0
nat.gas -CC	4.45	5.6	6.45	7.1
nat. gas -fuel cell	6.05	6.2	5.45	5.95
solar PV - SW-USA	16.35	4.75	3.05	2.15
solar PV - W.-Eur	30.05	9.0	5.2	4.05
Solar thermal	6.95	5.55	4.5	3.55
wind- class 5+	3.5	2.3	1.95	1.65
wind - 4.5-5.5 m/s	4.5	2.85	2.45	2.1
biomass STIG		5.05	4.75	4.75
Geothermal	3.2	3.0	2.85	2.2

Biomass yields and land requirements :*

		Energy yield (GJ/ha)	Wood yield (Dry Tonne/ha)
Solid fuels :	Temperate wood	200	10
	Moist tropical wood	400	20
	Dry tropical wood	80	4
Liquid fuels :	Ethanol	22-150	4-63
	Methanol	150	15
Gaseous fuels :	Producer gas	201	15

* a carbon-tax in the order of $150/tonne CO^2 is applied for over 65 years

* estimated land requirement 700 Mha (at average 10 ton/ha)

Source:

- Lazarus, M. et al: Towards a fossil Free Energy Future - the next energy transition. A technical analysis for Greenpeace International, SEI, Boston, 1993

2. IPCC IS92a scenario

Main features

	1985	2000	2030	2050	2100
Population (10^9)	5.2	6.2	8.4	10.0	11.3
GNP/Cap (in 1990-$)	3800	4300	6500	9200	21500
Energy- intensity (MJ/$)	17	15	13	10	6
Primary Energy Use (EJ)	344	409	708	934	1453
Primary energy fuel shares (in EJ) :					
coal	99	117	220	342	689
oil	123	140	165	144	93
gas	80	98	140	129	42
biomass (mod.)	0	0	59	119	191
nuclear	17	23	56	82	175
hydro	24	29	44	59	72
solar/wind	1	2	25	59	191
Energy-related carbon emissions (in Gt C)	6.0	7.0	10.7	13.2	19.8

Activity and energy demand assumptions :
- economic growth: 2.9 % p.a. average 1990 - 2025; 2.3 % p.a. average 1990 - 2100
- growth primary energy use: 2.1 % p.a. average 1990 - 2025; 1.3 % p.a. average 1990 - 2100

Sectoral energy demand (in EJ, rounded) :

	1988	2000	2010	2030	2100
Residential	53.7				
Services	29.8				
Industry	90.3				
Transport	61.0				

Energy supply assumptions :
- fossil fuel use keeps growing up to 2100; coal becomes the dominant future energy source because of increases in its use for synfuels after 2025 and because of increases in the share of energy end-use supplied by electricity
- the growth in the share of non-fossil increases after 2025 due to high fossil energy prices
- modern biomass penetrates the energy market substantially after 2025, being used to make synthetic fuels (both gas and liquid) for the transport sector

Price assumptions :
- 1.6 trillion barrels of crude oil (9,300 EJ) are available at $22/bbl and an additional 0.4 trillion barrels (2,330 EJ) at higher prices. 10,800 EJ of natural gas are available at $3/GJ and an additional 2,500 EJ at higher prices (after Masters et al., 1991)
- crude oil and natural gas prices increase substantially in the first half of the next century, being more than doubled by 2025
- 29,500 EJ of coal are available for $1.30 per GJ (at the mine)(taken from WEC, 1980)
- the costs of electricity from nuclear increase modest from $ 0.067/kWh in 1990 to $0.074/kWh in 2050
- 82 EJ of primary modern biofuels are available at a crude oil price less than or equal to $55/bbl and up to 191 EJ at a crude oil price less than or equal to $70/bbl
- costs of solar energy decline to $0.075/kwh in 2050

Literature:
- Leggett, J., W. Pepper and R. Swart: 'Emission scenarios for the IPCC - an Update: Assumptions, Methodology and Results', Report prepared for IPCC -working group 1, may 1992
- Pepper. W: detailed data sheets IS92a

3. IPCC Low Emissions Energy Supply System (LESS) Reference / Low Nuclear Variant

Main features

	1985	2025	2050	2075	2100
Population (10^9)	4.9	8.2	9.5	10.2	10.4
GNP/Cap (in 1990-$)	3380	8010	14259	25600	44200
Ener-intens * (MJ/$)	20	7.6	4.1	2.4	1.4
Primary commercial energy use (EJ)	323	496	559	630	664
Primary energy mix (EJ) :					
coal	90	84	56	40	22
oil	127	78	65	50	45
gas	65	77	74	29	0
H_2 from nat.gas	-	11	25	29	35
nuclear	15	15	12	10	9
hydro/geothermal	21	32	33	32	32
modern biomass	5	152	217	300	331
intermittent renewable	-	37	63	108	166
Solar H_2	-	10	14	21	23
Energy-related carbon emissions* (in Gt C)	5.6	4.7	3.8	2.8	1.6

* own calculations based on IPCC data

Features / developments:
Demand:
- demand projections are based on IPCC-1990 Accelerated Policies (AP) Scenario - High Economic Growth Variant; however, growth in primary energy demand differs from IPCC 1990 AP:
  - economic growth: 3.5% p.a. (average) 1985 - 2025
    2.6% p.a. (average) 2025 - 2100
  - energy intensity: -2.4% p.a. (average) 1985 -2025
    -2.3% p.a. (average) 2025 -2100
- shift to very high-quality energy carriers:
  - share of electricity in global final energy use grows from 14% in 1985 to 29-36% in 2050 -2100
  - share in global final energy demand of electricity, hydrogen and methanol grows to 62 - 71% in 2100
- saturation of global demand of energy-intensive basic materials by middle of next century
- average fuel economy of cars increase from 7.4 km/l in 1985 to 17.8 km/l in 2025

Supply:
- in 2025 coal-integrated Gasifier/Gas turbine power cycles become the norm for coal use; from 2050 coal-integrated gasifier/fuel cells become the norm
- from the first decennia of the 21st century the use of coal and oil decline, while natural gas use grows substantially up to 2050 before it declines

- hydrogen becomes an important energy carrier produced from natural gas and by solar and used in fuel cells (both in transport and stationary power applications)
- expansion of nuclear is limited to 30% increase by 2000; thereafter it remain constant up to 2050 and then declines
- from the renewables, biomass makes the largest contribution to primary energy up to 2100; it plays a major role from 2025 on (31%) growing to 50% in 2100, starting from biomass residue use to predominantly plantation biomass

Price assumptions:
- fossil fuels are replaced by non-fossil alternatives as soon as available at about the same costs
- the prices of fossil fuels can be expected to rise
- long term prices in $/GJ:

natural gas	5
biomass	2-3
coal	2

- thirty-year levelized costs of electricity plants going into production in 2010 in $/GJ:

natural gas	4.4
biomass	2.4
coal	2.0

- costs of alternative sources of H2 production in $/GJ:

from natural gas	13.5
from coal	14.3
from biomass	12.9 - 14.2
from nuclear	23.6
from wind	24.3
from PV solar	21.8

Sources:

- IPCC working group II Second Assessment Report (1996)
- Williams, R.H.: Energy Demand Projections Assumed for the LESS Constructions; prepared for the IPCC Working Group IIa, Energy Supply Mitigation Options, August 1994
- Williams, R.H.: A Low carbon Dioxide Emissions Scenario for global Energy (Low-Nuclear Variant); prepared for the IPCC Working Group IIa, Energy Supply Mitigation Options, August 1994

4. Shell Dematerialisation scenario

Main features

	1990	2000	2030	2060	2100
Population (10^9)	5.2	6.2	8.5	10	12
GNP/Cap (in 1990-$)	4260	5725	8600	17000	50000
Ener-intens * (MJ/$)	23	13	8.9	5.1	2.0
Primary energy use (EJ)	393	469	654	872	1190
*Primary energy mix * (EJ) :*			(2020)	(2050)	
coal	-	-	129	144	60
oil	-	-	166	120	55
gas	-	-	141	168	75
nuclear/hydro	-	-	74	132	210
modern biomass	-	-	25	133	240
other new renewable (e.g. solar/wind)	-	-	18	119	550
Energy-related carbon emissions* (Gt C)	6.0	7.5	9.9	8.0	4.5

* own calculations / estimations on the basis of figures in Shell (1995)

Features / developments:
Demand:
- economic growth: 3% p.a. (average)
- growth primary energy use: 1.3 % up to 2030; less then 1 % therafter; 1% p.a. avg 1990-2100
- development of 3 x more efficient car ('new generation vehicle')

Supply (compared to Sustained Growth):
- less overall use of fossil fuels
- more use of gas instead of coal
- penetration of renewables slower due to slower rate of learning curves
- PV solar penetrates the market in 2050 instead of 2020; modern biomass instead of solar becomes the most prominent renewable

Price assumptions:
- slower reduction in the prices of non-fossil energy sources than in sustained growth scenario

Sources:

- P. Kassler: Energy for development, Shell Selected Paper, Shell, 1994
- Shell-venster (maart/april 1995): 'Een nieuwe eeuw vol (andere) energie', pag. 3-7.

5. Shell Sustained Growth scenario

Main features:

	1990	2000	2030	2060	2100
Population (10^9)	5.2	6.2	8.5	10	12
GNP/Cap (in 1990-$)	4260	5725	8600	17000	50000
Ener-intens * (MJ/$)	23	13	11	8.6	4.3
*Primary energy mix * (EJ) :*		(2020)	(2050)		
coal	-	-	154	180	55
oil	-	-	197	141	65
gas	-	-	135	141	105
nuclear/hydro	-	-	92	168	-
modern biomass	-	-	55	112	-
other new renewable (e.g. solar/wind)	-	-	19	393	-
Energy-related carbon emissions * (Gt C)	6.0	8.0	10.6	9.0	4.5

* own calculations / estimations on the basis of figures in Shell (1995)

Features / developments:
Demand:
- economic growth: 3% p.a (average)
- growth primary energy use: 2% p.a.(average)

Supply:
- due to progress along learning curves, renewables become fully competitive with fossil fuels by 2020 (10 % share)
- fossil fuel use reaches maximum by 2020 -2030 and then decreases
- the share of nuclear remains constant up to 2020 and grows to 10% thereafter
- after 2050 renewables have more than 50% share in primary energy supply
- after 2050 surprises possible as result of second innovation wave

Price assumptions:
- the prices of non-fossil energy sources decrease quickly
- possible developments in the prices of wind, PV solar and modern biomass (in $/kWh)):

	2000	2010	2020
wind	0.055	0.04	0.03
PV solar	0.25	0.10	0.05
biomass	0.075	0.05	0.04

* possible increase in biomass yields from 15 tdm/ha to 30 tdm/ha after 2020

Sources:
- P. Kassler: Energy for development, Shell Selected Paper, Shell, 1994
- Shell-venster (maart/april 1995): 'Een nieuwe eeuw vol (andere) energie', pag. 3-7.

6. WEC Reference Scenario (B)

Main features:

	1990	2020	2050	2100
Population (10^9)	5.2	8.1	10.1	12
GNP/Cap (in 1985-$)	3972	6884	-	-
Ener-intensity (in MJ/$)	17.8	10.2	-	-
Primary energy use (EJ)	375	569	980	1406
Primary energy mix (EJ) :				
coal	99	129		
oil	118	161	558(all fossil)	493 (all fossil)
gas	73	128		
nuclear	19	34	147	394
hydro	20	39	-	-
trad.biomass	40	56	-	-
mod.biomass	5	10		
other new renewables (solar, wind,oceans, geo-thermal, small hydro)	2	13	137 (all ren.)	366 (all ren.)
Energy-related carbon emissions (Gt C) * between brackets: incl. trad. fuels)	5.5(5.9)	7.8(8.4)	11.4(12.0)	10.8(11.4)

Features / developments:
Demand:
- economic growth: 3.3 % p.a. average 1990 - 2020
- growth primary energy use: 1.4 % p.a. average 1990 - 2020; 1.14 % p.a. average 2020 - 2100

Supply:
- fossil fuel use will increase for many decades; fossil fuels will probably remain the dominant sources of energy throughout the 21st century
- up to 2020 natural gas will gain market share compared to oil and coal; in the long run coal will be the main source of fossil energy
- nuclear energy use will expand substantially throughout the next century
- up to 2020 the penetration of new renewables will be limited due to rather slow progress because of e.g. slow introduction, inadequate energy storage systems etc.; it will take many decades before they substantially substitute for fossil fuels

Price assumptions:
- not specified; only indication that fossil fuel prices will rise over the next decades

Sources:

- World Energy Council: Energy for tomorrow's world - the realities, the real options and the agenda for achievement, London, 1993.
- WEC Study Committee on Renewable Energy Resources: Renewable energy sources - opportunities and constraints 1990 -2020, WEC -15th Congress, Madrid, 20-25 sept. 1992.

7. Some other [regional] scenarios

In 1990 both the Department of Energy and the European Commission/DGE published energy projections up to the year 2010 (IEA 1990, Deimenis 1990). The DoE-study focuses on the USA. It uses four different oil price paths : reference, low oil price, high economic growth and high oil price. With a 53% GDP-increase, the over-all energy intensity is projected to drop with 19-23% in this period. In the reference case, the price of world oil and of US coal increase with some 50% between 1990 and 2010; the price of US gas is projected to triple. The share of electricity is expected to rise in all scenarios. Coal and renewable energy are the fastest growing supply sources.

The EC-study considered three scenarios in which oil market developments were central : Conventional Wisdom, Driving into tensions and Low growth. Using the oil price developments of the Conventional Wisdom scenario (a doubling of oil prices between 1990 and 2010), world energy use is expected to increase with 62% between 1987 and 2010 (from 341 EJ to 553 EJ). The assumed GWP-growth in this period is 95%, i.e., a decline in the over-all energy-intensity with 17%. On the supply side, natural gas is projected to increase its market share from 18% in 1988 to 25% in 2010. For electricity generation, coal remains the major fuel and nuclear and hydro capacity are expected to double.

In hindsight, the greatest mistake in the scenarios is the economic growth assumption for the former USSR and Eastern Europe. It estimated a GDP-growth for the former USSR of 52% between 1990 and 2010. A recent study (Gurvich et al. 1995) expects a GDP-growth for Russia of 2% in the same period, based on the historical 49% decline of Russian GDP between 1990 and 1995. In combination with revised estimates of energy efficiency improvements due to liberalisation of energy markets, the EC-study projects for the former USSR for the year 2010 a 66% increase whereas the recently published study foresees for Russia for the year 2010 a 20-30% decline in primary energy use.

As to nuclear power, one of the latest projections is the IAEA-projection up to 2015 (IAEA 1995). Nuclear generated electricity in the world is expected to increase from the 1993-value of 2094 TWhe to 2497 - 3422 TWhe by 2015. Most of this 20-60 % increase is expected to happen in the Far East and Eastern Europe.

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