# CLIMATE CHANGE POLICY TARGETS AND THE ROLE OF TECHNOLOGICAL CHANGE

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**Abstract.** In this paper, we present results of simulation experiments with the TIME-model on the issue of mitigation strategies with regard to greenhouse gases. The TIME-model is an integrated system dynamics world energy model that takes into account the fact that the system has an inbuilt inertia and endogenous learning-by-doing dynamics, besides the more common elements of price-induced demand response and fuel substitution. First, we present four scenarios to highlight the importance of assumptions on innovations in energy technology in assessing the extent to which $CO_2$ emissions have to be reduced. The inertia of the energy system seems to make a rise of $CO_2$ emissions in the short term almost unavoidable. It is concluded that for the population and economic growth assumptions of the IPCC IS92a scenario, only a combination of supply- and demand-side oriented technological innovations in combination with policy measures can bring the target of $CO_2$-concentration stabilization at 550 ppmv by the year 2100 within reach. This will probably be associated with a temporary increase in the overall energy expenditures in the world economy. Postponing the policy measures will be more disadvantageous, and less innovation in energy technology will happen.

## 1. Introduction

The Framework Convention on Climate Change of the United Nations (1992) has as its stated goal the achievement of the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference of the climate system. Specific targets are not defined, but a widely used exercise is to set a ceiling for the atmospheric $CO_2$ concentration and explore the socio-economic implications of meeting such targets (e.g., Wigley et al., 1996; Azar and Rodhe, 1997). A stabilization target of 550 ppmv, a doubling of the pre-industrial level, is a widely used benchmark among climate researchers. Another approach is to use limits on the temperature change and its rate of change and on the sea level rise beyond which risks of considerable damage are expected to increase rapidly (AGGG, 1990; Alcamo and Kreileman, 1996; Berk and Janssen, 1997). For such analysis, one needs to formulate a baseline or reference scenario. The IS92a scenario of the IPCC (W. Pepper et al., unpublished) is often used for this purpose.

In this paper, we investigate how the expected energy system costs to meet climate targets depend on the assumptions of technological developments. In our

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analysis, we use a system dynamics simulation model of the energy and climate system which takes into account inertia and technological learning. A brief model description is given in Section 2. Next, we present four model-based scenarios with diverging assumptions on technological progress and orientation. We use these scenarios to address in Sections 4 and 5 the issues of timing of mitigation policies and influence of social time preference.

Most analyses of questions on timing and discount rate are based on simple academic models to illustrate different viewpoints on the cost-effectiveness of early action. Wigley et al. (1996) conclude that it would be cheaper to defer mitigation for many years and still achieve concentration targets above 450 ppmv. Grubb (1997), however, argues that it is cost-effective to begin some mitigation immediately for limits below 550 ppmv. Our model allows us to deal more explicitly with aspects of system inertia and energy technology development.

## 2. The Model

TARGETS* is an integrated assessment model for global change developed at the Dutch National Institute for Public Health and the Environment (RIVM) (Rotmans and De Vries, 1997).† The TARGETS framework consists of a population and health model, an energy model, an element cycles model, a land model, and a water model. TARGETS is meant to explore the long-term dynamics of global change and to bring into operation the notion of sustainable development at a global scale. In this paper, we focus on the energy submodel which, as a stand-alone model, is called Targets IMage‡ Energy (TIME). It consists of five submodels: Energy Demand, Electric Power Generation, and the supply of Solid (SF), Liquid (LF), and Gaseous (GF) Fuels (Figure 1). Its main objective is to analyze the long-term dynamics of energy conservation and the transition to non-fossil fuels within an integrated modeling framework. The model builds upon several sectoral system dynamics energy models (Naill, 1977; Sterman, 1981; Davidsen, 1988) and is described in detail in De Vries and van den Wijngaart (1995), Bollen et al. (1995), De Vries and Janssen (1996), and Rotmans and de Vries (1997). The model has been carefully calibrated to reproduce the major world energy trends in the period 1900–1990. Uncertainty analysis of the TIME model is reported in De Vries et al. (1999). Feedbacks and delays are an essential part of an integrated system dynamics model such as TIME. The following paragraphs give a rather comprehensive description of these incorporated system dynamics.

In the TIME-model, a combination of bottom-up engineering information and specific rules and mechanisms about investment behavior and technology is used

* Tool to Assess Regional and Global Environmental and health Targets for Sustainability.

† An interactive version of the TARGETS model is available on CD-ROM.

‡ A regionalized version of TIME is used as the energy model in IMAGE 2.2 (De Vries et al., 1998).

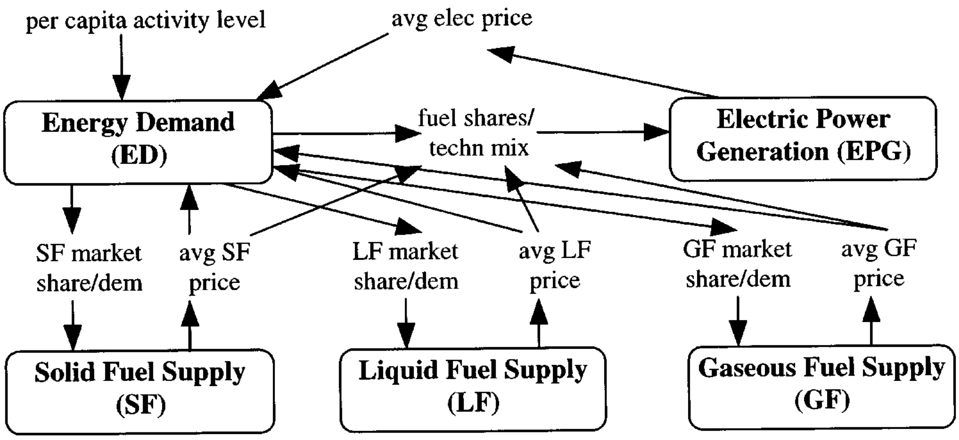



*Figure 1.* Outline of the energy model of TARGETS.

to simulate the structural dynamics of the energy system.* The output is a rather detailed picture of how energy intensity, fuel costs, and competing non-fossil supply technologies develop over time. Most macro-economic models deal with the same developments in the form of one or a few highly aggregated production functions and a single backstop technology that supplies non-fossil energy at a fixed cost level.† In our view, the two approaches are complementary: the macro-economic models provide consistent links with the rest of the economy, while the TIME-model benefits from the bottom-up process and system insights. It should be emphasized, however, that the interactions between changes in the energy system with the rest of the economy are not incorporated in the model simulations presented in this paper. In the remainder of this paragraph, we give a brief description of the various submodels.

## 2.1. THE ENERGY DEMAND (ED) SUBMODEL

In the Energy Demand submodel, we distinguish three determinants of energy-intensity changes: changing activity patterns, products, and processes ('structural change'); autonomous increases in energy productivity ('Autonomous Energy Efficiency Improvements' or AEEI); and energy productivity changes in response to changes in fuel and electricity prices ('Price-Induced Energy Efficiency Improvements' or PIEEI). First, end-use energy demand which would result without any changes in technology or prices is calculated for five different sectors: residential

* See Appendix A for a concise formulation of the model equations.

† Recently, a rather detailed and integrated energy system model was constructed using economic concepts and introducing technological change (Chakravorty et al., 1997). It has been applied to investigate the world energy system with regard to climate change and it has several similarities with the TIME-model. However, the authors focus almost exclusively on the dynamics of the solar backstop technology, which limits their conclusions.

(or households), industrial, commercial (or services), transport, and others.* The product of population and a structural change multiplier drives end-use demand, which is a function of a sectoral per capita activity indicator. The calculated end-use energy demand is multiplied by the Autonomous Energy Efficiency Increase (AEEI) multiplier to account for the historical fact that, even with falling energy prices, energy intensity has dropped in most sectors. This multiplier is assumed to decline exponentially to some lower bound and is linked to the turnover rate of sectoral capital stocks. To incorporate the effect of rising energy costs to consumers, we have opted for an approach intermediate between the bottom-up engineering analyses and the top-down macro-economic approach. Energy demand after AEEI is multiplied by a factor, referred to as the Price Induced Energy Efficiency Improvement (PIEEI), which is calculated from a sectoral energy conservation supply cost curve and end-use energy costs which in turn depend on prices and market shares of secondary fuels. It is assumed that the supply cost curve declines over time as a consequence of learning-by-doing.

A price-determined mixture of solid, liquid, and gaseous fuels satisfies heat demand after AEEI and PIEEI. We distinguish four commercial fuel types in the TIME-model: solid, liquid, and gaseous fuels, with the liquid fuels split into light (LLF: gasoline, kerosene, etc.) and heavy (HLF: fuel oil and distillates). The market shares of these four commercial fuels are calculated for each sector from their relative prices through a multinomial logit function (Bollen et al., 1995). Actual market shares are supposed to follow, with a delay, these economically indicated market shares. The change in market shares affects the end-use costs, which in turn determines the degree to which energy conservation actions are taken in subsequent years. Electricity demand after AEEI and PIEEI is met by electric power generation as described in the EPG submodel.

### 2.2. THE ELECTRIC POWER GENERATION (EPG) SUBMODEL

The EPG submodel simulates the process in which demand for electric power capacity is anticipated and new capacity is ordered. With a delay, this leads to expansion of the three electricity-producing capital stocks: hydropower, thermal, and non-thermal electric energy. Expansion of hydropower (H) capacity is an exogenous scenario, assuming increasing marginal specific investment costs. The remaining new capacity ordered is either Fossil Electric (FE) or Non-Fossil Electric (NFE) – nuclear, solar, but excluding hydro. For TE plants, conversion efficiency and specific capital costs are exogenous time paths. For the NFE option, cumulated production induces learning that shows up as decreasing specific investment costs. For FE generation, the use of fuels is based on relative prices. A premium factor is used to allow for differences between fuel costs and prices for utilities. The pene-

* Two forms of sectoral end-use energy forms, heat and electricity, are distinguished. Heat is a shorthand way of referring to all non-electric end-use applications of energy for which commercial secondary fuels are used.

tration dynamics of NFE technology is based on the difference in generation costs between FE and NFE plants using a multinomial logit function; on the penetration of NFE plants, their load factor will start to fall which tends to increase generation costs and slow down further penetration. The capital stock for transmission and distribution is considered proportional to the system's installed capacity.

### 2.3. THE FOSSIL FUEL (FF) SUBMODELS

The three fossil fuel submodels, solid, liquid, and gaseous, have several aspects in common. The life cycle of the fuel is based on the distinction between the resource base, identified reserves, and cumulated production. The resource base is explored and discovered, that is, converted into identified reserves. A depletion-multiplier and a learning-parameter govern the exploration and exploitation dynamics. The former reflects the rising cost of discovering and exploiting occurrences when cumulated production increases. The latter works to the contrary by assuming that the capital-output ratio will decline with increasing cumulated production due to learning-by-doing in the form of technical progress. An important element in the coal model is the distinction between underground and surface mining. An important element in the liquid and gaseous fuel model is the possibility of a non-carbon-based alternative fuel penetrating the market. This alternative is confined at present to a biomass-derived liquid/gaseous fuel alternative for which land will be an important input. Other conversion routes, e.g., coal liquefaction, hydrogen from biomass or solar heat or electricity, have as yet not explicitly been modeled.

In the *Solid Fuel* submodel, which deals with coal only, coal companies decide to invest in coal-producing capacity on the basis of anticipated demand. Part of the investment flow goes into underground mining, depending on the cost ratio between underground and surface-mined coal. Investments add to the coal-producing capital stocks, the output of which is determined by the capital-output ratios. In underground mining, these are assumed to increase due to depletion and rising capital-labor ratios in response to rising wages. In surface mining, capital-output ratios are also assumed to increase due to depletion but this is partly offset by economies of scale and innovations. The latter is done, as with non-fossil electric power options, by multiplication with a constant factor less than unity for every doubling of cumulated production. The coal price is the product of coal capital costs, an overhead factor, and a factor that takes supply-demand imbalances into account. It changes in response to an excess or shortage of capacity, which decreases or increases revenues and in turn generates with a delay lower and higher investments, respectively.

The *Liquid Fuel* and *Gaseous Fuel* submodels simulate the demand for Heavy Liquid Fuels (HLF) and Light Liquid Fuels (LLF), and gas, respectively. The anticipated required production of crude oil and gas is calculated using an overhead factor covering exploitation and processing/transport energy use and losses. In combination with depreciation, this leads to required investments which after some years come into operation. As with coal, the average price of crude oil and gas is the product of capital costs, an overhead factor, and a supply-demand multiplier. Identified reserves only increase if the reserve-production ratio is below a desired level and the price is sufficiently high for oil companies to invest in exploration. Biofuel penetration is simulated with a production function with capital, labor, and land as production factors both for Liquid (LBF) and Gaseous (GBF) biofuels. A fixed capital-output ratio and an exogenously increasing capital-labor ratio reflect the transition towards less labor-intensive techniques. Land requirements are derived from a land-output ratio that increases due to technology and decreases when the exogenously set supply potential is reached. The latter represents the assumption that increasingly less productive land is used for biomass plants. Given some initial estimate of the cost of BF, the penetration dynamics rests on the assumption that the market share for commercial biofuels is a function of its cost relative to the price of its fossil equivalent. At present, our formulation of biofuel technology and costs is meant only as a first, aggregate description.

### 2.4. THE CLIMATE SUBMODEL CYCLES

The global element cycles submodel of the TARGETS model is used to estimate the impact of greenhouse gas emissions on the environment (Den Elzen et al., 1997). An essential part of the submodel is the integration of the element cycles (C, N, S, and P) and the interactions between the cycles in the biosphere. Among others, simulated impacts of the perturbed cycles and chemical substances on the global environment include climate change due to changes in the concentrations of greenhouse gases and sulfate aerosols, and stratospheric ozone depletion due to atmospheric chlorine and bromine concentrations.

## 3. Global Energy Futures: Four Scenarios

For the present simulation experiments, we constructed four scenarios (De Vries and Janssen, 1996; Janssen, 1998). The first one is the baseline or reference scenario for which we have implemented the assumptions used for the IPCC IS92a scenario (Pepper et al., 1992). This scenario has been used widely as a Business-as-Usual or a Conventional Wisdom energy future. The other three scenarios differ from the baseline scenario in their assumptions on technology and subsidies. For all four scenarios, we use the same driving forces: the IS92a trajectories for world population and Global World Product (GWP).

### 3.1. THE BASELINE OR REFERENCE SCENARIO: BASE

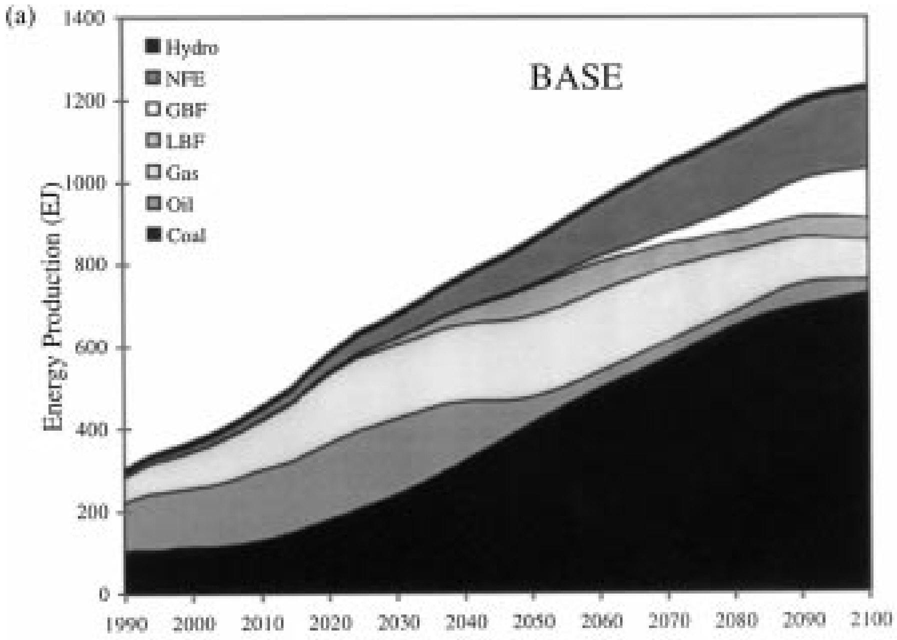
The available background documentation for the IPCC IS92a scenario (Pepper et al., 1992) does not specify all TIME input variables; hence, we had to make additional quantifications. For instance, we use literature-based estimates of more than unity for the transport fuel and electricity demand elasticities and we assume world average conversion efficiency of thermal power plants to rise from 35% in 1990 to 45% in 2100. The main features of this BASE scenario, which is our implementation of the IS92a scenario, are the following. Energy use triples to 800–850 EJ/yr and energy production soars to 1200 EJ by 2100 (Figure 2a). The depletion of cheap oil and gas causes cost increases that stimulate energy conservation and the comeback of coal and, later on, the penetration of non-fossil options. The resulting coal-intensive scenario leads to an emission level of 20 GtC at the end of the next century (Figure 3) and about 750 ppmv $CO_2$ concentration (Figure 4). Temperature increases with about 0.2 °C per decade to 2.7 °C in 2100 (Figure 5), while sea level rises by about half a meter compared with 1900. More specifically:

- the end-use of transport fuel and electricity per unit of activity keeps rising for another 2–3 decades; in other sectors, the end-use energy intensity declines; one consequence is that the share of electricity in end-use increases;
- past trends in the AEEI continue at an average 0.65%/yr for the assumed growth in activity levels (Figure 6); this is well in line with other estimates (Alcamo et al., 1995);
- in response to rising oil and gas prices, the PIEEI falls off (Figure 7); this improvement in energy efficiency slows down, however, despite the assumed decline of the supply cost curve, because the marginal costs per unit of energy saved increase and because part of the price increase is undone by coal substitution;
- non-fossil alternatives penetrate the markets for secondary fuels (Figure 8) and for electric power generation (Figure 9) as their costs decline due to learning-by-doing and relative to rising oil and gas prices; however, the low cost levels of non-fossil electricity of 0.02–0.03 $/kWhe cannot be maintained as system costs (storage etc.) rise and load factors fall.

### 3.2. THE SUPPLY-ORIENTED TECHNOLOGY CHANGE SCENARIO: SOTC

The second scenario we investigate is characterized by fast technological change and consequently a rapid decline in costs in the energy supply system. New technology will make known and as yet unknown non-carbon energy options much cheaper and markets will ensure their subsequent introduction. Coal is increasingly considered as an inconvenient fuel and becomes increasingly uncompetitive as subsidies are removed. The key assumptions are summarized in Table I. This scenario contains elements of the LESS scenario (Williams, 1995) and reflects also elements of the Sustained Growth scenario as published by Shell Planning (Kassler, 1995).

Assuming the same growth rate as the BASE scenario, the development of energy demand is quite similar but the supply side is quite different. Primary energy production is some 20% lower, due to initial high – and assumedly irreversible – energy efficiency improvements and higher conversion efficiencies of thermal


(a)
BASE
Hydro
NFE
GBF
LBF
Gas
Oil
Coal
Energy Production (EJ)
0
200
400
600
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1200
1400
1990
2000
2010
2020
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2070
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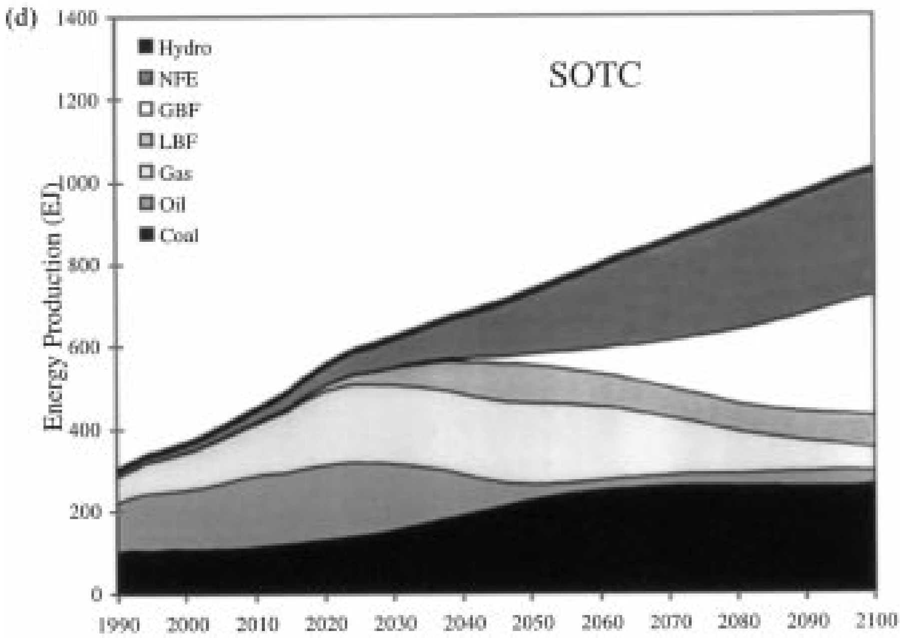
2100


(d)
SOTC
Hydro
NFE
GBF
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Gas
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Coal
Energy Production (EJ)
0
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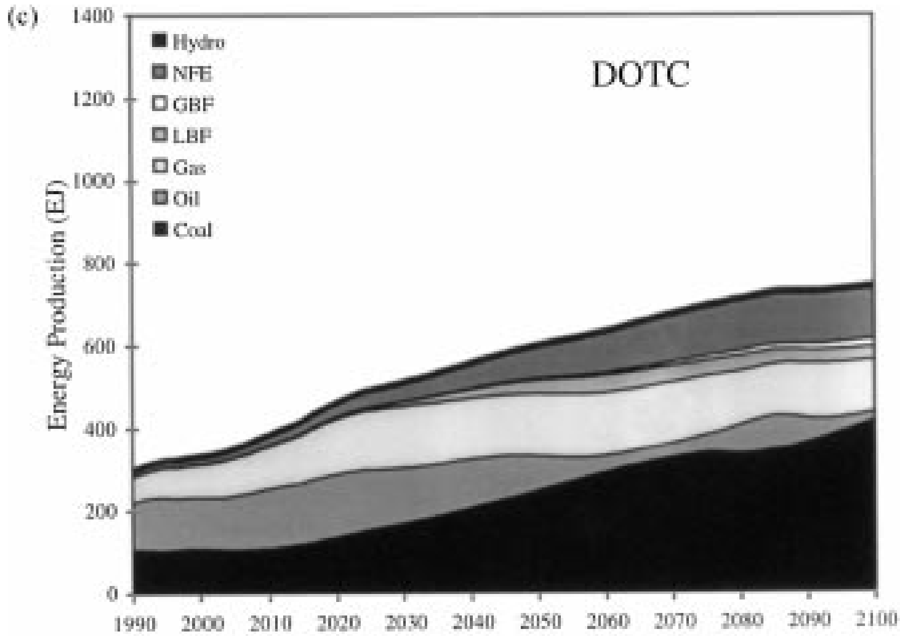
*Figure 2a,b.*



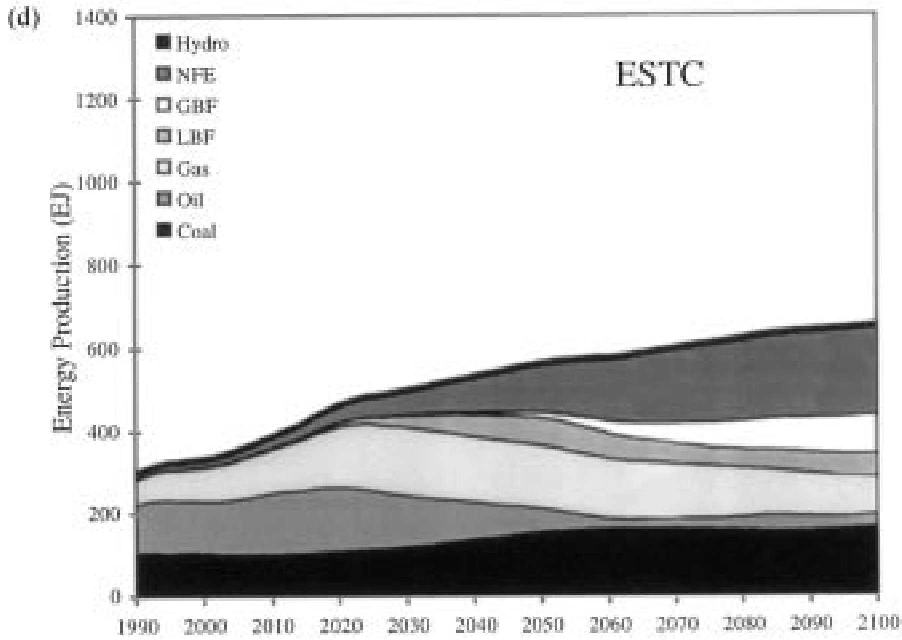




*Figure 2c,d.*

*Figure 2.* Fuel mix in primary energy production in the four scenarios: (a) BASE; (b) SOTC; (c) DOTC; (d) ESTC.

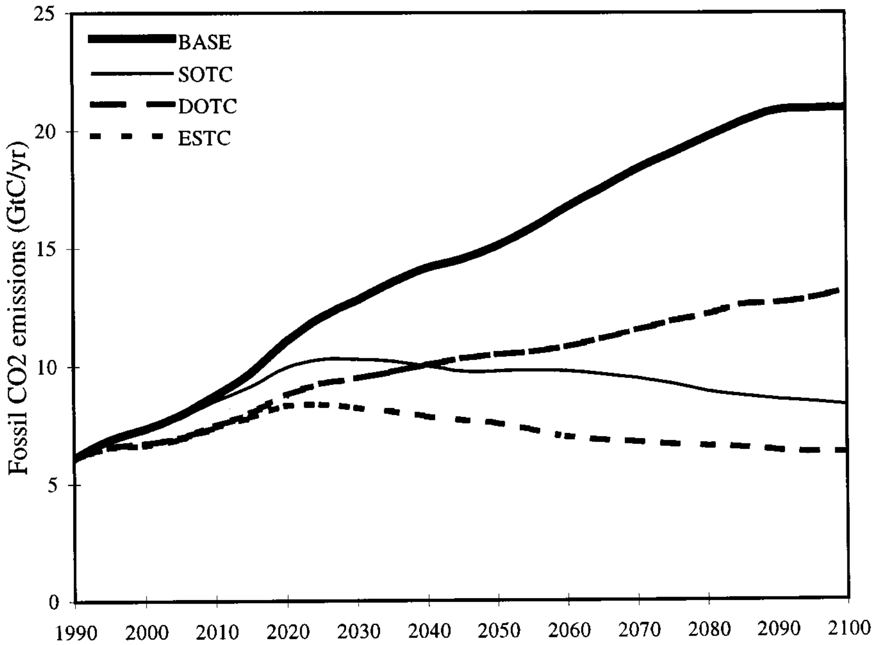



*Figure 3.* Fossil $CO_2$ emission paths for the four scenarios.

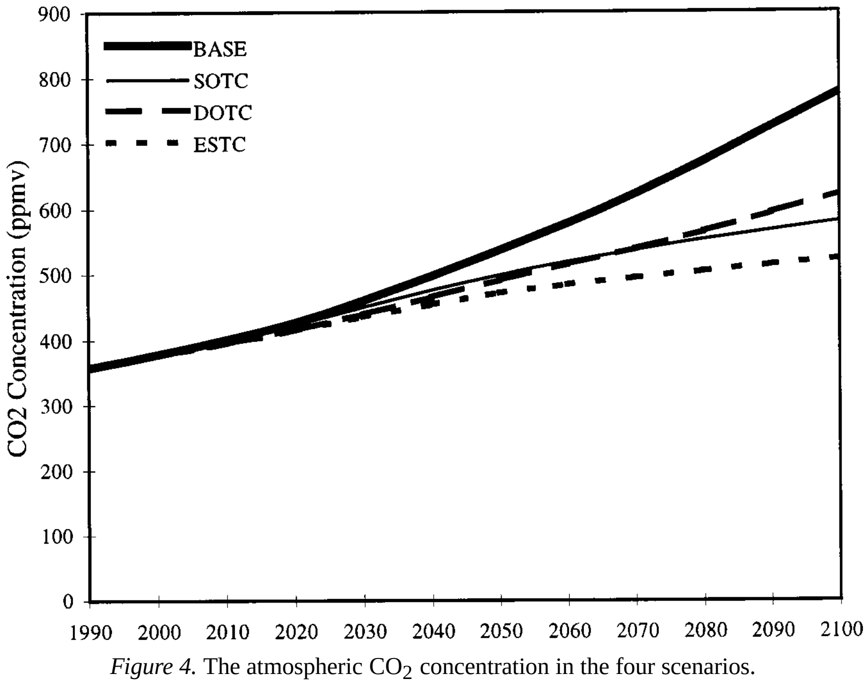



*Figure 4.* The atmospheric $CO_2$ concentration in the four scenarios.

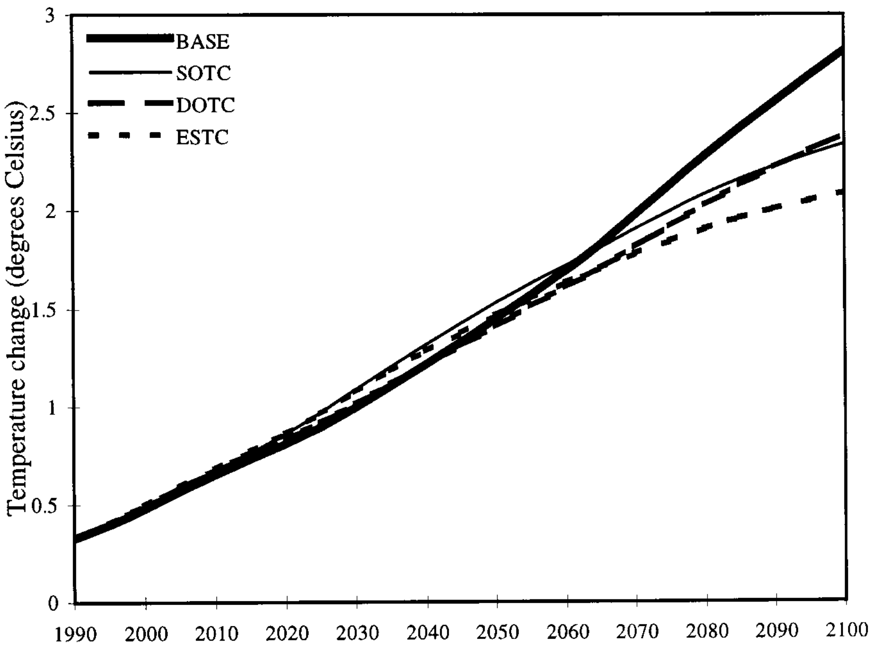



*Figure 5.* The global mean temperature increase compared with the 1900 level in the four scenarios.

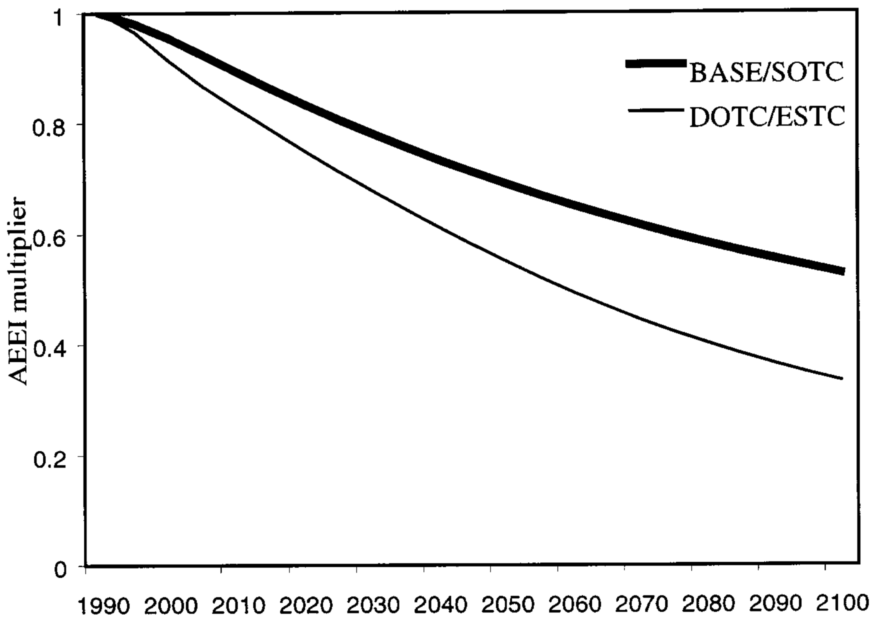



*Figure 6.* Simulated pathways for autonomous energy efficiency improvement (AEEI) in two scenarios; for the SOTC it equals BASE and for ESTC it equals DOTC.

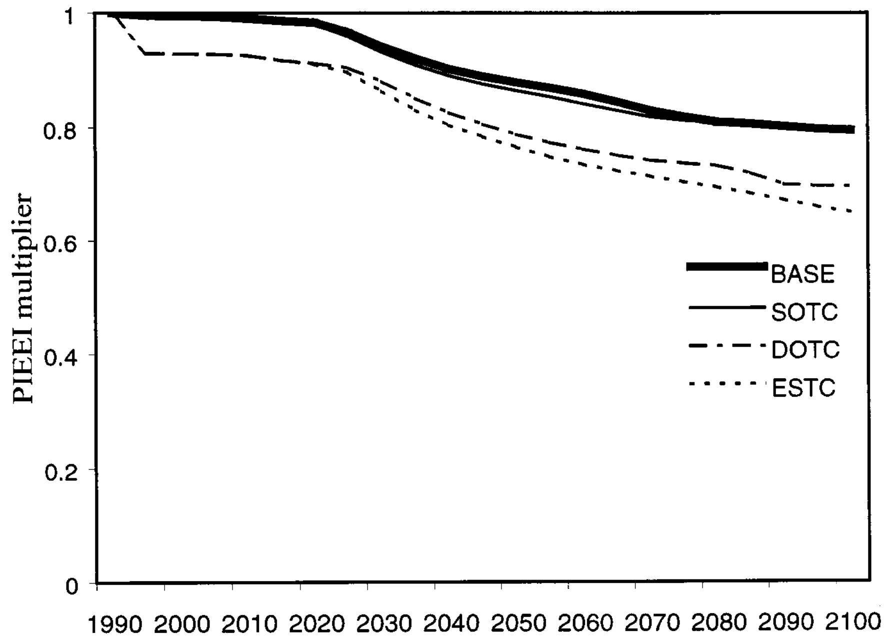



*Figure 7.* Simulated pathways for the price-induced energy efficiency improvement (PIEEI) in the four scenarios. A reduction of the PIEEI factor means that price increase leads to a lower energy demand.

power plants (Figures 2b and 6). Breakthroughs in non-fossil options to generate electricity cause rapidly declining costs (Figure 9). Coal use drops from 700 to 300 EJ/yr, the largest fall being in electricity generation, and the share of non-fossil options increases to 60% by 2100. Carbon emissions stabilize at about 10 GtC/yr in 2020, after which they slowly decrease (Figure 3). By the year 2100, the $CO_2$ concentration has increased to 560 ppmv (Figure 4), temperature has risen by 2.4 °C (Figure 5), and the sea level rises 40 cm.

### 3.3. A DEMAND-ORIENTED TECHNOLOGICAL CHANGE (DOTC) SCENARIO

A third scenario we have constructed focuses on the demand side. It assumes a drastic reduction in the average energy intensity of economic activities. Waves of innovative, partly price-induced, energy efficiency technologies in combination with shifts in economic activity patterns make it possible to effectively decouple economic growth and energy use. This is another ingredient of the LESS scenario (Williams, 1995) and is also the key feature of the Dematerialization scenario of Shell Planning (Kassler, 1995). The key assumptions are summarized in Table I.

Again using the same population and economic growth projections as in the BASE and the SOTC scenarios, the resulting Demand-Oriented Technology Change (DOTC) has, in 2100, an over 40% lower primary energy production than the BASE scenario (Figure 2c). There is a markedly faster decline in the energy

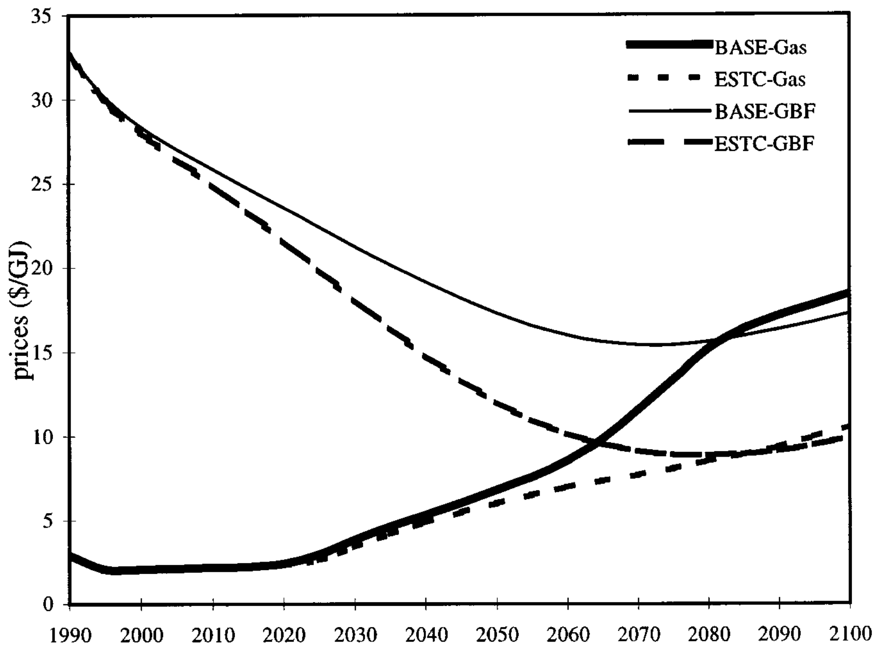



*Figure 8.* Price paths for natural gas and gaseous biofuel (GBF) in the BASE and the ESTC scenario. The lower energy demand in ESTC slows down the price increase of gas to the same degree to which technological change causes a fall in biofuel prices – hence, the penetration rates of GBF are similar in both scenarios.

intensity than in the BASE scenario – an average of 1.1%/yr (Figure 6). Assuming vigorous support for energy efficiency improvements, the PIEEI falls off rapidly (Figure 7).* The resulting low energy demand causes a slowdown in the depletion and hence in the price increase of oil and gas, which in turn slows down the penetration of coal and non-fossil options. The latter is more outspoken as we assume BASE assumptions for the supply-side technology. The resulting carbon emissions smoothly rise to about 12 GtC in 2100 (Figure 3). The $CO_2$ concentration rises to about 600 ppmv (Figure 4); temperature and sea level changes are close to the SOTC scenario (Figure 5).

### 3.4. THE ENERGY SYSTEM TECHNOLOGICAL CHANGE SCENARIO: ESTC

In the fourth scenario, we combine the assumptions on the supply side of the SOTC scenario with those on the demand side of the DOTC scenario to explore the interactions. The resulting Energy System Technological Change (ESTC) scenario has expectedly the lowest primary energy production path (Figure 2d). The major differences with the SOTC scenario are a 40% lower energy production and 2–

* The precipitous decline between 1990 and 2000 is partly a consequence of the way in which the model has been calibrated.

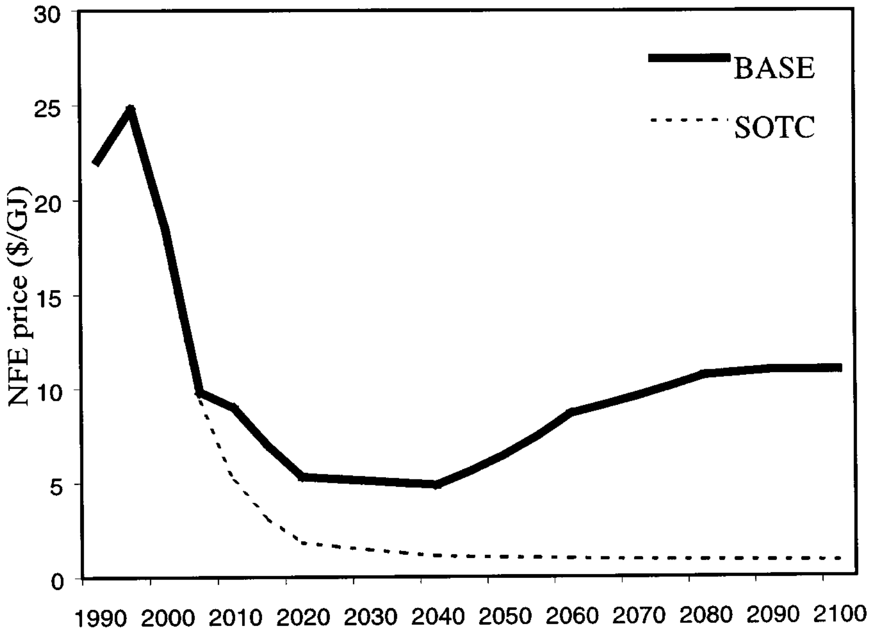



*Figure 9.* Time path of generation costs in non-fossil electricity generation (NFE) in two scenarios. In the BASE scenario, learning is offset after 2040 by additional system costs such as a decreasing load factor; in the SOTC scenario, it continues throughout the next century.

3 GtC/yr lower carbon emissions by 2100 (Figure 3). Compared to the DOTC scenario, the key difference is that non-fossil supply options seize a much larger market share at the expense of coal. Demand for secondary fuels and electricity is lower than in the DOTC scenario, but the difference is quite modest because low demand causes a downward pressure on fossil fuel prices (Figure 7). This is clearly illustrated in Figure 8: although costs of gaseous biofuels drop much faster than in the BASE scenario, there is also a much slower rise in gas prices and hence both scenarios have similar rates of penetration. The $CO_2$ concentration shows signs of leveling off at about 530 ppmv by the year 2100; the temperature increase is 0.2 °C lower than in the SOTC/DOTC scenarios (Figure 5).

An interesting feature of the ESTC scenario is the way in which the system as modeled by us is buffered by counteracting forces. This is well illustrated by another experiment that explores the effect of divergent assumptions on the supply cost curve of oil and gas, which is, next to technological change, the major uncertainty. To investigate the impact of this uncertainty on $CO_2$ emission pathways, we assume that the resource available at any given cost level is either 50% lower or 100% higher than in the BASE scenario. These two scenario variants are referred to as ‘low RB’ and ‘high RB’, respectively. The results in terms of $CO_2$ emissions are depicted in Figure 10. Although the production profiles for crude oil and natural gas significantly alter on these assumptions, it is seen from Figure 10 that the $CO_2$

TABLE I

Compared to the baseline scenario

| Cluster | SOTC | DOTC |
|---|---|---|
| Structural change | As in BASE | As in BASE |
| Energy-efficiency | – As in BASE: rate of AEEI of 0.65%/yr on average<br>– As in BASE: about 55% energy savings to be reached at marginal investments of 40 ± 20 $/GJ saved<br>– As in BASE: conservation cost curve declines at 0.1%/yr | – Rate of AEEI increases of 1.1%/yr on average<br>– Less steep conservation cost curve: about 55% energy savings to be reached at marginal investments of 20 ± 10 $/GJ saved<br>– Conservation cost curve declines at 0.2%/yr |
| Electricity generation | – Average conversion efficiency of FE power plants to 60% in 2100 (vs. BASE: 45%)<br>– Learning rate for NFE at about 10% investment cost decline per doubling of cumulated output | – Average conversion efficiency of FE power plants to 60% in 2100 (vs. BASE: 45%)<br>– As in BASE: Learning rate for NFE at about 4% investment cost decline per doubling of cumulated output |
| Fuel supply | – Negative premium on coal price in heat market (inconvenience a.o.) | – As in BASE: gradual disappearance of negative premium on coal price in heat market (new techniques a.o.) |
| | – Coal price for electricity generation from 35% towards 80% of average coal price in 2050 (subsidy removal<br>– Learning surface coal mining stops (due to environmental impacts a.o.) | – As in BASE: coal price for electricity generation 35% of average coal price a.o.)<br>– As in BASE: learning surface coal mining 10% investment cost decline per doubling of cumulated output |
| | – Learning rate for biofuels 15% cost decrease per doubling of cumulated output<br>– Biofuel supply cost curve gauged at cost doubling at 900 EJ/yr | – As in BASE: learning rate for biofuels 10% cost decrease per doubling of cumulated output<br>– As in BASE: biofuel supply cost curve gauged at cost doubling at 300 EJ/yr |

emissions remain within 10–20% of the BASE respectively ESTC scenario. If the supply cost curves are very steep, non-fossil alternatives penetrate the market at a faster rate, but part of this $CO_2$ emission reduction is lost due to the improved competitiveness of coal. If the supply cost curves are very shallow, the availability of large amounts of low-cost oil and gas push back coal but also defer the introduction of non-fossil alternatives. From this experiment, it can be seen that a slightly more

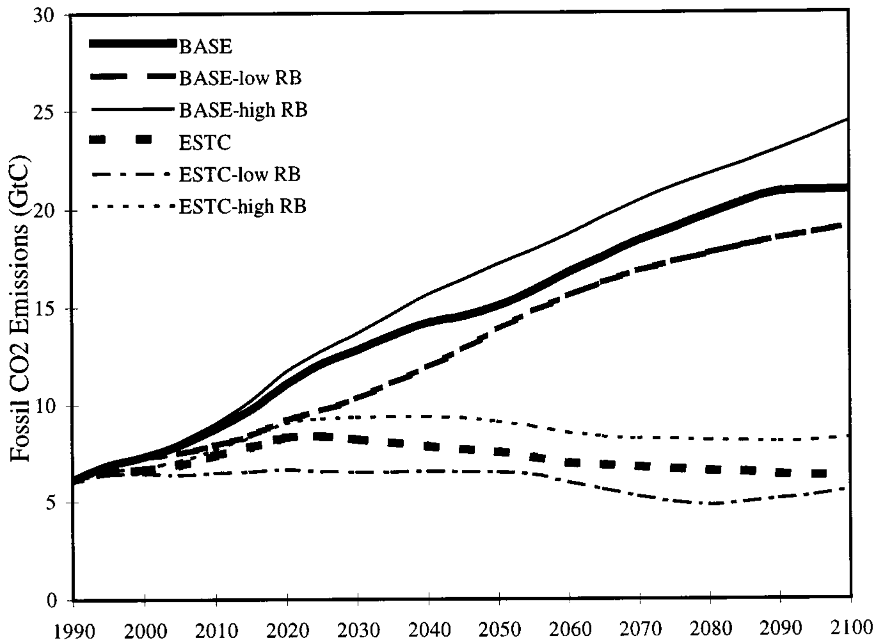



*Figure 10.* Fossil $CO_2$ emission paths for the BASE and the ESTC variants with half (low RB) and double (high RB) the BASE scenario estimate of oil and gas availability and cost.

complex system formulation can significantly effect an uncertainty assessment – in this case, it shows that the controversy on availability and cost of oil and gas may be of minor importance for the $CO_2$ emission pathway.

Finally, to conclude this paragraph on the four scenarios, it should be noted that we consider none of the above scenarios to include climate change policy measures. We do feel, however, that the SOTC, DOTC, and, *a fortiori*, the ESTC scenario sketch a future in which important technological breakthroughs occur in combination with uninterrupted economic growth, good management skills and practices, and adequate governance and infrastructure. As such, they are – for some unrealistically – optimistic pictures of the threat to climate change posed by the global energy system.

## 4. Meeting Climate Change Policy Targets

Having presented these four scenarios, we now focus on the question if and at what costs a certain climate target, notably the stabilization of the $CO_2$ concentration, can be met. To this purpose, we conduct two sets of experiments. In the first one, we design exogenous time paths for four control variables: a carbon tax and RD&D-programs for non-fossil electric (NFE), liquid biofuel (LBF), and gaseous biofuel (GBF), in such a way that the climate target is met. In the second set, we explore

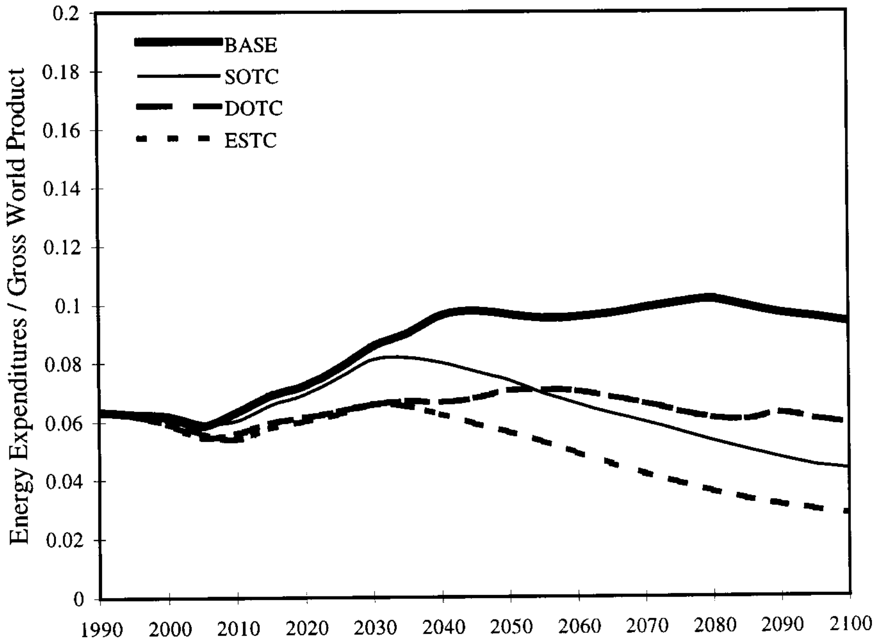



*Figure 11.* The simulated energy expenditures (excluding a carbon tax) as a fraction of the Global World Product (GWP).

the consequences of delaying climate policy measures by applying a pulse for these same four control variables in the year 2000 and in the year 2030. Before discussing the results, it is important to consider the question which measure can be used – given that the TIME-model has no macro-economic component – as a proxy for the socio-economic costs. We propose to use the fraction of energy expenditures (excluding carbon tax payments), that is, fuel and electricity use times price, in total Gross World Product (GWP). For the four scenarios, this indicator is drawn in Figure 11. It is seen from this figure that technological innovations either on the supply side or on the demand side – which are supposedly not affecting the rate of economic growth – imply a significant reduction in energy cost in the world economy. The patterns, however, differ because in the SOTC scenario the dynamics of non-fossil options cause a significant cost decline, while in the DOTC scenario the early and fast implementation of cheap energy efficiency improvements causes the cost decline. The latter, however, becomes gradually exhausted.

Of course, these results are contingent on the ‘partial equilibrium’ approach of our model in which the macro-economic effects of a carbon tax and of R&D-expenditures, for instance through changes in factor prices and re-orientation of economic activities, are not taken into account. Also, carbon tax recycling and explicit subsidies, which in our simulations are assumed to induce an accelerated switch away from carbon-containing fuels in satisfying energy end-use demand, may have macro-economic effects that are not taken into consideration. Exist-

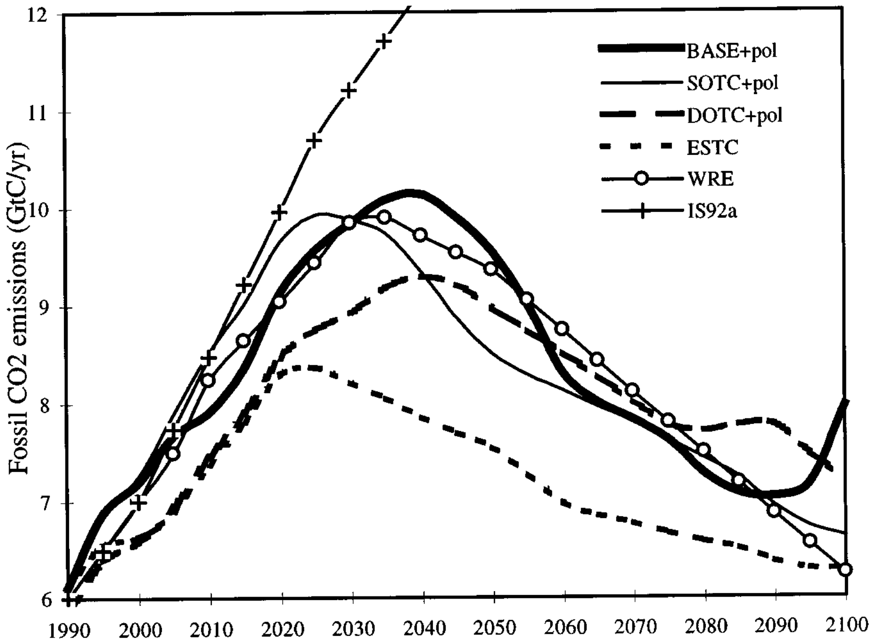



*Figure 12.* Fossil $CO_2$ emission paths with policy measures to meet the 550 ppmv $CO_2$ concentration target.

ing literature suggests a wide range of possible feedbacks of emission reduction policies on economic growth (Repetto and Austin, 1997). It all depends on the underlying assumptions of the exercise, which we have made as clear as possible for our analysis.

### 4.1. ENERGY SYSTEM COSTS TO MEET A CLIMATE TARGET

In the first simulation experiment, we select time paths for four control variables, a carbon tax and RD&D programs for non-fossil electricity generation and liquid and gaseous commercial biofuels, in such a way that the $CO_2$ concentration levels off at 550 ppmv by the year 2100. The carbon tax makes fossil fuels, and especially coal, less competitive vis-à-vis energy conservation and non-fossil options. The RD&D programs are introduced as forced capacity expansion of capital stocks, which then generate accelerated learning-by-doing. The resulting cost decline speeds up market penetration by making fossil fuels – and especially coal in electricity generation – less competitive.

The simulation has been done for all four scenarios and the results are presented in Figures 12 and 13. As Figure 12 shows, the $CO_2$-emission paths required to meet the climate target of 550 ppmv by 2100 follow fairly closely the 550-ppmv-stabilization scenario of Wigley et al. (1996) and are still significantly higher than the – assumedly ‘free-of-cost’ – emission path in the ESTC scenario. Stated dif-

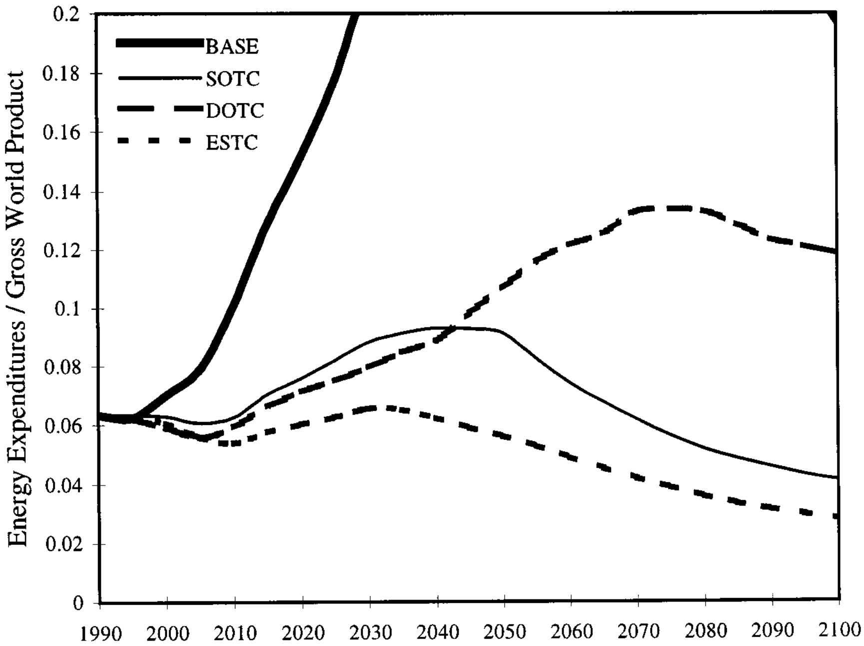



*Figure 13.* The simulated energy expenditures (excluding a carbon tax) as fraction of Global World Product (GWP) for the four scenarios with policy measures to meet the 550 ppmv $CO_2$ concentration target.

ferently, no additional climate policy is needed on the optimistic assumptions of the ESTC scenario. However, for the BASE, SOTC, and DOTC scenarios, policy measures are needed and their consequences in terms of the above-defined energy-expenditure fraction are considerable, as Figure 13 shows. In the BASE scenario, the emission reduction strategy requires a carbon tax in the range of 100–2000 $/tC which, in combination with forced non-fossil fuel expansion, drives out fossil fuels and especially coal. However, because the opportunities for cheap energy-efficiency improvements and cost-reducing innovation in non-fossil options are quite limited, the energy system costs – excluding the carbon tax – soar quickly to an unrealistically high level. In fact, the assumptions underlying the BASE scenario picture an energy system, which is so little responsive that a target of 550 ppmv can be considered unfeasible. In the SOTC scenario, the scope of action is much larger: more modest carbon taxes and non-fossil expansion programs cause an initial rise in the energy-expenditure fraction. Later on, however, it declines as the learning-by-doing-induced cost reductions in nuclear and solar (photovoltaics, biofuels, and others) continue. The DOTC scenario shows, expectedly, a different path for the energy-expenditure fraction. Initially, they rise at the same rate as in the SOTC scenario, but the energy-efficiency investments now play a larger role. Later on, after 2040, they keep rising because the cheap energy-efficiency improvements get exhausted and there are no cheap backstop alternatives in the absence of high-tech developments on the supply side. The combination of these scenarios suggests that the climate target of 550 ppmv is feasible in the limited sense of relative energy system costs if the world energy system is successful in realizing at least partly the technological and economic developments portrayed in the assumptions underlying these scenarios.

This exercise underlines the statement of Wigley et al. (1996) that the Working Group I concentration stabilization scenarios, which foresee an immediate reduction of global $CO_2$ emissions, are not likely to be cost-effective. One might even add not feasible, given the baseline scenarios for economic and population developments. The inertia of the energy system causes an unavoidable increase of emissions in the short to medium term. The simulations also underline that the degree of short-term increase and the possibility of long-term decline of $CO_2$ emissions and the corresponding costs depend largely on the extent and rate of technological change.

### 4.2. THE RELEVANCE OF TIMING: CLIMATE POLICY MEASURES IN 2000 OR 2030

In a second experiment, we investigate the question of timing: how do energy expenditures respond to a control strategy applied in the year 2000 as against 2030? For this experiment, we narrow down climate policy to a pulse consisting of a carbon tax of 100 $/tC, a 10000 MW RD&D program in non-fossil electricity options (NFE), and a 10 EJ/yr RD&D program in commercial biofuels. This pulse starts in year $t$, reaches its maximum in year $t + 10$, and returns to zero in year $t + 20$. It turns out those variations in the shape of the time pattern and in the relative role of the different policy measures does not affect the conclusions. To evaluate the outcome of such a pulse, we introduce a cost-effectiveness potential defined as the discounted amount of energy expenditures over and above the no-policy-pulse-scenario per unit of emissions reduced during the period 1995–2100. In this way, the cumulative $CO_2$ emissions during the period 1995–2100 are used in the indicator, which warrants a meaningful to important impact indicators such as absolute temperature change or sea level rise. The cost-effectiveness potential is a proxy for cost per unit of avoided effect.*

An important and interesting question is whether and how to introduce time preference. Arrow et al. (1996) distinguish two approaches for discounting within the climate change debate: the prescriptive and the descriptive approach. The first approach deals with the question how (ethically) the impacts on future generations should be valued, which leads usually to a low discount rate. The descriptive approach looks at the actual trade-offs across time and tends to generate somewhat higher discount rates. For investment decisions in the TIME-model, the latter approach is used with a discount rate of about 10% because it is about actual invest-

* It can be noted that this approach is analogous to the global warming potential formulation as introduced by Lashof and Ahuja (1990).

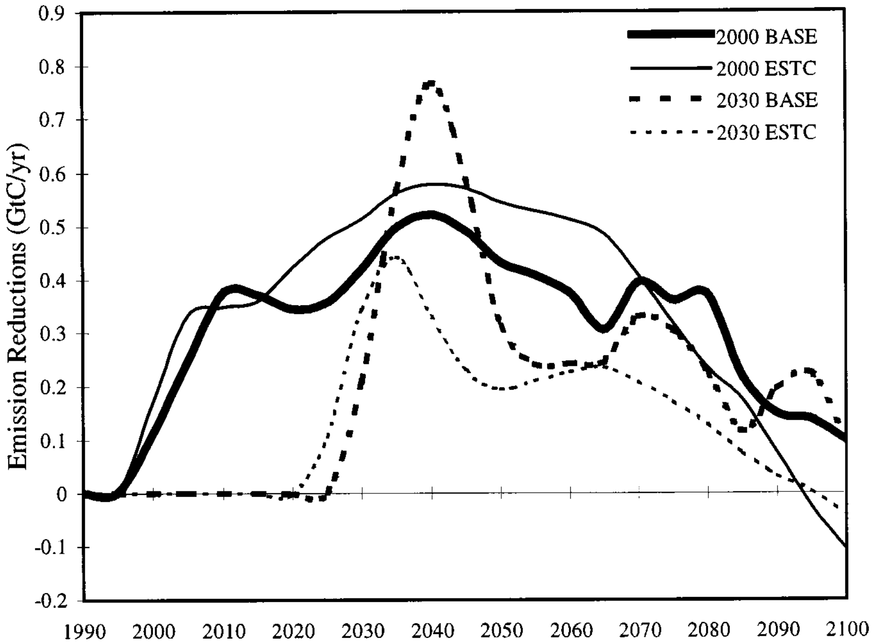



*Figure 14.* $CO_2$ emission reduction paths as a result of a policy pulse peaking in either the year 2000 or the year 2030 and for the BASE and the ESTC scenario.

ment behavior. To evaluate the energy expenditures of the policy-pulse scenario as compared to the no-policy-pulse-scenario, the lower discount rates according to the prescriptive approach should be used. We have chosen a range between 0 and 5%, which is in line with values used in other economic analyses (for example, Cline (1992) (1.5%), Nordhaus (1994) (3%), and Chakravorty et al. (1997) (2%)).

We limit our exploration to four cases: two different years in which the maximum is reached (2000 or 2030) and two different scenarios (BASE and ESTC). Figure 14 shows the resulting $CO_2$-emission reduction profile for the four cases. If the policy pulse peaks in the year 2000, emission reductions for the BASE and the ESTC scenarios are remarkably similar albeit the ESTC scenario is expectedly somewhat more responsive. The difference in energy expenditures for these two scenarios is also fairly similar, as can be seen from Figure 15. The cost-effectiveness potential is defined as the discounted integral of the curves in Figure 15 divided by the integral of the curves in Figure 14. Figure 16 shows this ratio as a function of the discount rate applied; negative values indicate a negative cost, that is, a benefit, because the decrease in (discounted) energy expenditures exceeds the increase in (discounted) energy expenditures due to the policy measures. The policy measures accelerate learning-by-doing which lower the costs of alternative non-fossil fuels, which becomes commercially attractive sooner. As one would expect, the two curves are very close and the cost-effectiveness potential – that is, the discounted cost per ton of carbon emission avoided over this period –

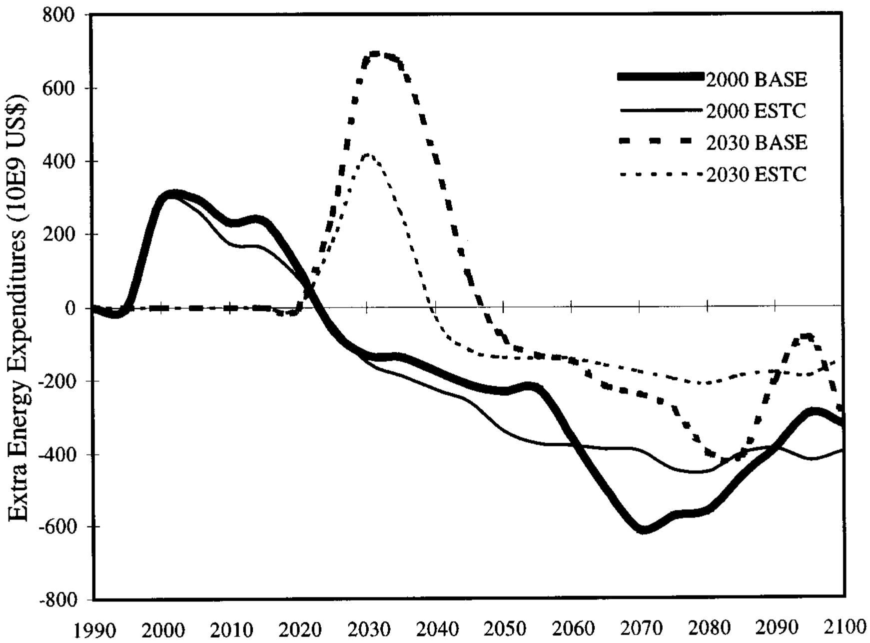



*Figure 15.* The difference in energy expenditures (excluding a carbon tax) as a fraction of Global World Product (GWP) with a policy pulse peaking in either the year 2000 or the year 2030 for the BASE and the ESTC scenarios.

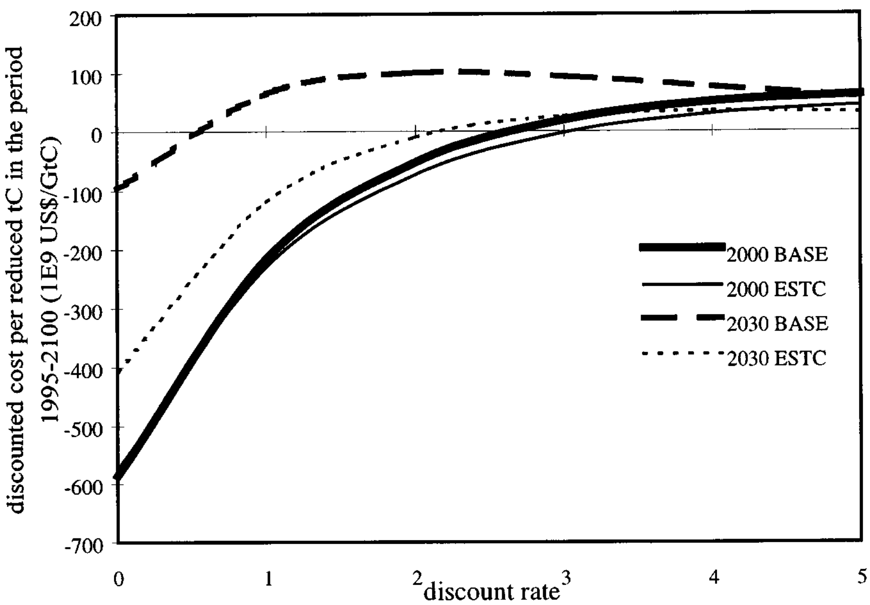



*Figure 16.* The discounted change in energy expenditures per ton of carbon emission avoided with a policy pulse peaking in either the year 2000 or the year 2030 for the BASE and the ESTC scenario, for varying discount rates.

tends towards zero or slightly positive for higher discount rates. This is obvious from the time profiles in Figure 15. It should be emphasized here that the emission reductions in Figure 14 are *not* related to a climate target: for the BASE scenario, these reductions fall far short of a 550 ppmv $CO_2$-concentration goal, whereas they are not needed in the ESTC scenario for such a goal.

Figures 14–16 also depict the results for the situation in which the policy pulse peaks in the year 2030. Apart from the obvious result that postponement will shift all costs and benefits into the future and hence reduce the cost-effectiveness potential, there are significant differences in the emission reductions and the associated costs/benefits. In the coal-based BASE scenario, the policy pulse generates a large reduction but at significant additional costs. In the ESTC scenario, on the other hand, there have been so many 'autonomous' developments towards a more efficient and less fossil-fuel-based energy system that the policy pulse generates a much lower response. Also, the associated costs are much lower. Again, it should be emphasized that these simulations make no statement about the adequacy of the policy pulse or, for that matter, about the damage and adaptation costs on the impact side. If these profiles are used for the calculation of the cost-effectiveness potential, it turns out that for low discount rates the benefits in the ESTC scenario are much larger than in the BASE scenario (Figure 16). For higher discount rates, both scenarios tend to the same value.

From this, two conclusions emerge. First, postponement of climate-policy measures in the rather conservative BASE future will be quite costly from a societal point-of-view, with discount rates below 3%. An early carbon tax policy reduces energy demand and stimulates the introduction of non-fossil fuels. Early RD&D programs support the penetration of non-fossil options by, albeit modest, cost reductions. In the more optimistic ESTC future, the differences between the pulse and no-pulse variant are small to negligible, given the large uncertainties anyway.

A second conclusion is that the use of high discount rates in evaluating the energy system costs tends to nullify any difference in the BASE-scenario and its underlying assumptions. This is rather undesirable, as it seems to legitimate a sense of laissez-faire based on a rather theoretical consideration, whereas the real-world inertia suggests large obstacles in implementing climate policy in world without major technological breakthroughs. To put it differently, conclusions on postponing climate policy measures from analyses with high discount rates are biased in favor of high-tech futures or, alternatively, play down the risks of non-high-tech futures.

These results are in line with Schneider and Goulder (1997), a model-based study for the U.S.A., and with a study by Messner (1997), which investigated the impact of endogenized technological learning in an optimization model of the energy system. Messner found that the inclusion of learning dynamics leads to early investments in new technology developments. These small extra investments in the short term are compensated by large cost reductions in the longer term. She also found the discount rate to be of great importance: the lower the discount rate, the faster the introduction of new technologies.

## 5. Conclusions

In the past few years, the threat of climate change as a consequence of large and increasing emissions of greenhouse gases, notably carbon dioxide ($CO_2$), has become widely acknowledged. The discussion increasingly focuses on mitigation strategies: which policy measures and instruments are available, how effective are they, what are the socio-economic costs and benefits, and when should they be introduced? In this paper, we present results of simulation experiments using the TIME-model, an integrated system dynamics world energy model that takes into account that the system has an inbuilt inertia and endogenous learning-by-doing dynamics, besides the more common elements of price-induced demand response and fuel substitution.

The four scenarios presented in this paper illustrate the importance of assumptions on technological change in the energy system in assessing the extent to which $CO_2$ emissions have to be reduced. Without a proper discussion on these assumptions in terms of probability and risk, a judgment on the political and socio-economic feasibility of climate targets may be strongly biased.

The first scenario, BASE, is based on the coal-based IPCC IS92a scenario. In the second scenario (SOTC), we assume a rapid decline of non-carbon alternative energy options. A drastic reduction in the average energy intensity of economic activities is assumed in the DOTC scenario. The last scenario, ESTC, combines SOTC and DOTC. Although economic growth assumptions are the same for each scenario, the $CO_2$ emissions in 2100 vary between 5 and 20 GtC and the $CO_2$ concentration between 500 and 750 ppmv.

Under the assumptions of the coal-based BASE scenario, a climate target of $CO_2$-concentration stabilization at 550 ppmv by the year 2100 is almost impossible. A combination of supply- and demand-side oriented technological innovations could bring such a target within reach, but not without the introduction of climate policy measures. One may expect a temporary increase in the overall energy expenditures in the world economy as a consequence of such policy measures. Whether postponement of such measures is beneficial or not is highly dependent on how future energy technology develops. In fact, there are two timing issues: one for policy and one for emissions reductions. Our analysis shows that immediate reductions in global $CO_2$ emissions are impossible given reasonable assumptions on technological change and expected socio-economic developments. However, the marginal cost of an immediate start of mitigation policies may be lower than delaying those policies.

If energy system innovations are slow and modest, as in the BASE scenario, any delay in introducing measures such as a carbon tax will incur high costs – or yield much lower benefits – unless one uses a high rate of social time preference. This, however, is only compatible with a world view in which such innovations are fast and large – in which case, a delay in introducing measures is anyway less relevant. Modest technological optimism should be combined with a modest mitigation policy – in accordance with the taoïst saying: ‘Stretch a bow to the very full, and you will wish you had stopped in time’.

## Acknowledgements

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## Appendix A. TIME-Model Equations

The model equations in the TIME-model include all kinds of forward anticipatory and backward time lags and feedback loops. In this appendix, we only outline the basic equations governing the submodel dynamics, leaving out all these details.

The Energy Demand (ED) submodel can be summarized in a single formula:

$$\mathrm{S}_{t,r,s,j} = \mathrm{A}_{t,r,s} * \mathrm{POP}_{t,r} * \mathrm{SC}_{t,r,s} * \mathrm{AEEI}_{t,r,s} * \mathrm{PIEEI}_{t,r,s} * \alpha_{t,r,s,j}/\eta_{r,j}\ .$$

It says that in any year $t$, the use of secondary fuel $j$ in sector $s$ in region $r$, $\mathrm{S}_{t,r,s,j}$, equals the product of per capita activity level $\mathrm{A}_{t,r,s}$, the population $\mathrm{POP}_{t,r}$, and four terms which are specified in detail below:

- the structural change factor SC,
- the Autonomous Energy Efficiency Improvement factor AEEI,
- the Price-Induced Energy Efficiency Improvement factor PIEEI, and
- the market share of fuel $j$ in sector $s$ in region $r$, $\alpha_{t,r,s,j}$, divided by the efficiency with which this fuel is converted to useful energy, $\eta_{r,j}$.

This formula is applied for the energy function heat. The energy function electricity is dealt with in the same way, the only difference being that the term $\alpha_{t,r,s,j}/\eta_{r,j}$ is replaced by an exogenous assumption about the overall conversion efficiency of the electricity generating system.

The key equations in the Electric Power Generation (EPG) submodel are:

$$\begin{aligned}\mathrm{E}_{t,\,\mathrm{ordered}} \;=\; & \mathrm{E}_{t,,\mathrm{req.\,in\,baseload}} + \mathrm{EP}_{t,\,\mathrm{req.\,in\,peakload}}/(\mathrm{PLF}_{t,\,\max} * \beta - \\ & - \mathrm{E}_{t,\,\mathrm{installed}} + \Sigma \mathrm{E}_{t,j}/\mathrm{LT}_{t,j} \qquad \mathrm{MWe}\end{aligned}$$

$$\mathrm{MS}_{t,k} = \mathrm{X}_{t,k}^{-\lambda}/\,\Sigma_k \mathrm{X}_{t,k}^{-\lambda} \qquad k = 1..\,n$$

$$\mathrm{CE}_{t,j} = \{a * \mathrm{I}_{t,\,\mathrm{specific}} * \mathrm{E}_{t,j} + \mathrm{FP}_{t,i} * \mathrm{MS}_{t,i} * \mathrm{EP}_{t,j}/\eta_{t,j}\}/\mathrm{EP}_{t,j} \qquad \$/\mathrm{GJe}\,.$$

The first equation states that the additional electric power capacity ordered in year $t$, $\mathrm{E}_{t,\,\mathrm{ordered}}$, amounts to the capacity required in baseload, $\mathrm{E}_{t,\,\mathrm{req.\,in\,baseload}}$, plus the electricity required in peakload and converted to capacity given a maximum load factor for peakload capacity of type $j$, $PLF_{t,\max}$. These are both derived from a two-step load duration curve. The factor $\beta$ converts from MWe to GJe and equals $8760 *$ 3.6 GJe/MWe/yr. To this is subtracted the already installed capacity, $E_{t,\text{installed}}$, and is added the amount depreciated, $\Sigma E_{t,j}/LT_{t,j}$, with $LT_{t,j}$ the technical lifetime of capacity stock of type $j$ ($j$ = FE, NFE, HYDRO). The allocation between the two generating options Fossil Electric (FE) and Non-Fossil Electric (NFE), the market share MS, is based on the second formula, $X_{t,k}$ being the costs of electricity generated with capacity stock of type $k$; it is the formulation of the multinomial logit. The third equation states that these costs of electricity generated with capacity stock of type $j$ in year $t$, $CE_{t,j}$, equal the fixed costs $a * I_{t,\text{specific}} * E_{t,j}$ with an annuity factor, $I_{t,\text{specific}}$ the specific investment costs including non-fuel operating costs (in $/kWe) and $E_{t,j}$ the capacity (in kWe) and for $j$ = FE the fuel costs. The latter are calculated as the price of fuel I, $FP_{t,i}$, times the market share of fuel $i$ times the total amount of electricity produced in FE capacity, $EP_{t,j}$, divided by the thermal efficiency of FE capacity, $\eta_{t,j}$. The specific investment costs for NFE capacity are a function of the ratio of cumulated production in year $t$ and in a starting year (1960). The market share of fuel $i$ is determined also from the second formula, X being the effective fuel price. This formulation neglects the differences between coal-, oil- and gas-based FE capacity.

The key equations in the Fossil Fuel (FF) supply submodels are:

$$F_{t,i,\text{ordered}} = EPIP_i * \gamma_{t,i,m} * ADFF_{t,i} - F_{t,i,\text{installed}} + F_{t,i,\text{installed}}/LT_{t,i} \qquad \text{GJe}$$

$$MS_{t,k} = X_{t,k}^{-\lambda} / \Sigma_k X_{t,k}^{-\lambda} \qquad k = 1..n.$$

The first equation states that new investments in exploration ($m = 1$) and production ($m = 2$) of fuel $i$, $F_{t,i,\text{ordered}}$ (in GJ), equals the capital-output ratio, $\gamma_{t,i,m}$, times the anticipated demand for that fuel, $ADFF_{t,i}$, times a multiplier, EPIP, which accounts for the fact that investments will be a decreasing function of the expected profits, that is, market price minus exploration and production costs. To this is subtracted the already installed capacity, $F_{t,i,\text{installed}}$, and added the amount depreciated, $F_{t,i,\text{installed}}/LT_{t,i}$, with $LT_{t,i}$ the technical lifetime of capacity stock of type $i$ ($i$ = coal – underground or surface mined, crude oil, natural gas). The capital-output ratio is a function of cumulated production plus identified reserves divided by the initial resource base (depletion) and of the ratio of cumulated production in year $t$ and in a starting year (1900) (learning). The second equation governs, in the same way as in the previously discussed submodels, the allocation of investments between competing options of underground- vs. surface-mined coal, of crude oil vs. liquid biofuel (LBF), and of natural gas vs. gaseous biofuel (GBF), with X being the exploration plus production costs of the corresponding option. These costs are calculated with an annuity factor in the same way as in the EPG submodel.

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