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Perspectives on global energy futures: simulations with the TIME model

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Abstract

Many uncertainties and controversies surround the future of the global energy system. The Targets IMage Energy (TIME) model of which a concise description is given, is used to explore the consequences of divergent assumptions about some uncertain and controversial issues. The IPCC-IS92a Conventional Wisdom scenario is used as a reference and, in combination with two other scenarios, discussed in the context of other recently published global energy scenarios. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

In recent decades numerous analyses have been published on the future of the global energy system. The emphasis has shifted from depletion of accessible oil and gas reserves and oil dependence (e.g. Meadows *et al*., 1974; OECD, 1979) to analyses of the costs and potential of nuclear and renewable energy options and energy efficiency improvements (e.g. Johansson *et al*., 1989,1993). Increasingly, the focus is on the contribution of fossil-fuel combustion to climate change (e.g. IPCC, 1995; IIASA/WEC, 1995; IEA-ETSAP, 1997). Important questions are what a plausible reference scenario is, which assumptions are most crucial with regard to the emissions of greenhouse gases, and at what costs emissions can be reduced to acceptably low levels. Fossil-fuel combustion accounted in 1990 for most of the emissions of greenhousegases: about 84% of anthropogenic CO_2 emissions and about 90, 70 and 32% of emissions of NO_x, SO_2 and N_2O, respectively (Alcamo, 1994). Assuming relatively scarce low-cost oil and gas resources, many forward projections indicate an increase in coal use and in CO_2 emissions. At the same time there is a widely held conviction that the world energy system will undergo a transition over the next century from fossil fuels to bio-mass and other solar-based forms of energy. Not surprisingly, projections of the CO_2 intensity in 2100 ranges from 105 to 10% of its 1990 level (Morita *et al*., 1995).[2]

In this paper we start with a brief outline of the uncertainties and controversies which make any projection of future CO_2-emissions such a hazardous undertaking. These are grouped in three clusters: energy-intensity, fossil-fuel resources and non-fossil alternatives. Next, we describe the Targets IMage Energy (TIME) model and apply this model to reproduce the global energy system from 1900 onwards up to 1990 according to historical data and from 1990 to 2100 according to assumptions similar to those used in the Conventional Wisdom scenario of the IPCC, also referred to as IPCC-IS92a (Leggett *et al*., 1992; Alcamo *et al*., 1994). In the last part of the paper, we explore the sensitivity of some key system variables to divergent positions with regard to the existing controversies. The results are presented in the form of three scenarios which have been constructed on the basis of three coherent sets of assumptions and are discussed in the context of other recently published global energy scenarios.

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[2] The option of CO_2 removal may become feasible in the future for large-scale combustion processes (Blok *et al*., 1993). It is not considered in the present model simulations.

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2. Global energy futures: uncertainties and controversies

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. To supply it is a major part of an industrialized nation's economy. Its dynamics is governed by a complex interplay between resource endowments, prices, technologies, life-styles and strategic aspects. Last but not least, energy use as we know it today has numerous impacts on the natural environment. Some of these can be mitigated by a combination of technology, capital and political will, but others are likely to be more difficult to deal with. From this, one can already discern the major issues in energy policy.[3]

2.1. Energy intensity: a further decline?

In the last few decades energy- and material intensities have been declining in the industrialised regions as a result of changes in activities, products and processes, in combination with new technologies and materials (Schipper and Meyers, 1993). It is as yet unclear whether this trend, which has been spurred by the oil price shocks of the 1970s, will persist. It may be reinforced, e.g. through saturation tendencies, less emphasis on material goods and increasing support for "green" technologies and investments. There are also counteracting trends which go with rising income, e.g. increasing number of luxury cars and decreasing household size (Ironmonger, 1995). For global energy use, an important question is whether the less industrialized countries will circumvent the historical positive correlation between energy-intensity and economic activity growth by seizing the catch-up possibilities which clearly exist (Grubler and Nowotny, 1990).

Recent scenarios show a rather surprising agreement on the possibility to reduce energy intensity significantly. A study for Greenpeace (Lazarus, 1993) claims that energy intensity can be reduced between 1990 and 2100 to 4.6 MJ/US$; a possible future sketched by Kassler (1994) called Dematerialization considers a similar drop to 4.5 MJ/US$. A recent IIASA/WEC study (1995) gives a range between 4.6 and 7.7 MJ/US$ for the year 2050. Although one should be aware of the different backgrounds of these studies and the probability of wishful thinking and collective bias,[4] agreement on such drastic reductions was largely absent in the early 1980s. In a recent and fairly comprehensive overview of scenario studies made for the IPCC (Alcamo, 1995), it appears that almost all analyses assume a significant decrease in the overall energy intensity, 0.45–1.45% per year between 1990 and 2100, as a result of structural changes in the economy and of autonomous and price-induced energy efficiency improvements. Autonomous improvements are estimated to range from 0 to 1.1%/yr in global energy models, with the feasible range for the long term between 0 and 1.5% per year (Matsuoka *et al*., 1995)[5]. One of the major controversies has to do with the effects of rising energy prices.[6]

2.2. Depletion of fossil fuel resources

In 1886 Jevons warned in his book "The coal question" about the rapid depletion of British coal fields which was threatening the British Empire. Numerous appraisals of coal, oil and gas availability have been made since then, many of them for strategic reasons. Environmental concerns and two oil crises have intensified the debate on fossil-fuel use and resources. The key question is whether the world is really facing depletion of its high-quality low-cost oil and gas resources, and whether this will show up as sudden price increases and supply disruptions or as a smooth transition towards alternative fuels. Behind this is the question of resource quality, in terms of depth, seam thickness, composition and location. There is general agreement that the coal resource base is large enough to sustain present levels of production throughout the next century without major cost increases (e.g. Fettweis, 1979; Edmonds and Reilly, 1985; WEC, 1989,1993). Most researchers expect rising costs to find and produce the as yet undiscovered deposits of conventional oil and gas but there are large uncertainties and controversies on when and how much. Estimates during the 1980–1995 period of ultimately recoverable oil and gas range from 8000 to 40,000 EJ, respectively. Most estimates are without specific information on costs or probability and consequently long-term supply cost curves for conventional crude oil and natural gas are controversial (Edmonds and Reilly, 1985;

[3] Other issues with regard to the energy system are strategic dependence and capital requirements. OECD countries are again becoming more dependent on Middle-East oil; for the fast growing economies of East Asia oil may also soon become an issue of security (Calder, 1996). Expansion of the energy system will require enormous investments, an increasing share of which will be needed in the presently less developed regions (Dunkerley, 1995; Subroto, 1992).

[4] See, for example, Sterman and Richardson (1983) on the evolution of estimates of ultimately recoverable oil in the USA.

[5] In energy efficiency scenarios, they are between 1.12 and 2.85%/yr. The authors elegantly point out that it is partly a matter of focus: "Where there is no great attention paid to energy conservation [in the models], the annual rate is between 0 and 0.5%, whereas if large energy savings are assumed, this rises to 1.0%" (Matsuoka *et al*., 1995).

[6] Most experts agree that rising energy prices will induce energy conservation but estimates of the price-elasticity suggest great uncertainties in the rate and degree. The price elasticity is difficult to measure and differs for different sectors and countries partly because of varying substitution possibilities. It may be time-dependent, becoming smaller once more profitable measures have been taken (Dargay and Gately, 1994). Moreover, energy prices relative to interest rates and wages may actually be the relevant variable.

McLaren and Skinner, 1987; Odell, 1994). Unconventional oil occurrences like tar sands and oil shales also play a recurrent role in the debate. It is known that oil shales and tar sands can provide large additional amounts of oil, possibly up to three times the conventional oil resource base.[7] For natural gas there may also be huge unconventional occurrences (Lee *et al*., 1988, Rogner, 1997). Another controversial option is the liquefaction and/or gasification of coal, which could supply the world with oil and gas substitutes for a long time to come. The prospects for such conversion processes seem to have diminished since the initial euphoria of the 1970s[8].

2.3. Alternatives to fossil fuel

Until the early 1980s the prevailing view on future energy supply was that fossil fuels and nuclear power would dominate the scene in the 21st century. New options for further decarbonization are electricity from solar cells and from wind turbines and the production of liquid and gaseous fuels from biomass. The latter could be as an expansion of present usage forms, e.g. agricultural residues, but most of it will have to be in the form of 'commercial' or 'modern' — as opposed to 'traditional' — biofuels, in which case biomass can become a substitute for gasoline in the transport sector or for coal in electric power generation. From the consumer point-of-view, the trend towards more flexible, convenient and clean forms of energy appears to favour fuels such as methane, ethanol, methanol and hydrogen which could be derived from a mix of nuclear and renewable sources.

There are still major controversies on the rate at which the costs of fuels or electricity from these supply technologies can be brought down — and hence about their penetration rate (Lenssen and Flavin, 1996; Statoil, 1995; Williams, 1995; Johansson *et al*., 1993). Firstly, there is the world-wide controversy on the acceptability of nuclear fission technology, which depends on the prospects for safer reactor designs, acceptable solutions to radioactive waste disposal and the possibility of breeder and/or fusion reactors. Secondly, most analysts agree that the large cost reductions of solar photovoltaics in the last few decades will continue but how much they have to be lowered for large-scale market penetration is controversial (Trainer, 1995). Thirdly, there are large uncertainties on costs and land requirements for large-scale production of commercial biofuels, and on the interference with food production and climate change. There are similar controversies about the cost and acceptability of energy carriers like hydrogen and promising technologies like fuel cells. The difference in outlook shows up in the scenarios: in the Conventional Wisdom IPCC-IS92a scenario the proportion of fossil fuel is still 56% by 2100, but the Fossil Free Energy Scenario (FFES) for Greenpeace claims that a complete phase-out of fossil fuels is feasible at an almost three times larger GWP per capita level (Lazarus *et al*., 1994). A recent IIASA/WEC study (1995) suggests that, in the ecologically driven scenario, the proportion of fossil fuels can be reduced to at most 20% by 2100.

3. Model description and calibration

3.1. General features

Most global energy scenarios rely to a smaller or larger extent on quantitative, computer-based simulation models. An often made distinction is between process-oriented models with a bottom-up orientation vs. macro-economic models with a top-down orientation (Kydes *et al*., 1995). The former focus on engineering and cost aspects of energy resources and technologies; the latter are general equilibrium optimisation models with price-based market clearing.[9] The TIME model described in this paper is best characterized as a systems dynamics model with a non-equilibrium process orientation.[10] During its construction, we have been guided by a few explicit objectives which reflect the issues discussed in the previous paragraph. Firstly, within the climate change debate, there is a need for a simple and transparant, yet comprehensive energy model which simulates long-term (50–80 years) dynamics. Secondly, the model should integrate the insights about the energy supply side

[7] A nice illustration is the hypothesis of huge reservoirs of pressurised gas and clathrates (Lee *et al*., 1988).

[8] The successful large-scale introduction of these conversion routes are behind the enormous expansion of coal in the Conventional Wisdom IPCC-IS92a scenario.

[9] The two types of model were conceived and designed within different disciplines and for different purposes. They have each their pros and cons and may lead to different conclusions. According to Wilson and Swicher (1993), they represent two conceptually incompatible ways of seeing and describing the world and their results fuel a debate where the choices are made on political rather than scientific grounds.

[10] A detailed description is given in De Vries and Van den Wijngaart (1995) and De Vries and Janssen (1996). 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*., 1996). The energy supply models have originally been developed as part of the Global Environmental Strategic Planning Exercise [GESPE] project (De Vries *et al*., 1993) and they build on previous energy models such as the Fossil-2 model (AES, 1990; Naill, 1977) and a systems dynamics model of the U.S. petroleum sector (Davidsen, 1988; Sterman, 1981). The Energy Demand and Electric Power Generation models build on work from De Vries *et al*. (1991) and Schipper and Meyers (1992). The models 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 implemented as one of the modules in the TARGETS1.0-model (Rotmans and De Vries, 1997).

as well as the energy demand side. Thirdly, the model should merge top-down with bottom-up and micro-economic with engineering approaches. To this end, the model contains physical and informational delay and feedback/feedforward mechanisms and explicit decision rules based on information about the state of the system.[11] Other requirements are that the modules should adequately reproduce the 1900–1990 data on sectoral secondary fuel use, on exploration and exploitation in the fuel supply sectors and on electricity generation. It has to describe adequately the balance between depletion in the form of rising average production costs and technological progress in the form of learning by doing. Fuel prices, calculated from capital and labour costs, should function as signals to direct investment behaviour and at least two non-carbon alternatives, one in the heat market and one in the electricity market, are to be included.

In its present form, the TIME-model consists of five modules: energy demand (ED), electric power generation (EPG), solid fuel (SF), liquid fuel (LF) and gaseous fuel (GF) supply. The ED-module simulates the demand for commercial fuels and electricity, given economic activity levels. This demand is converted to demand for secondary fuels and electricity, taking into account autonomous and price-induced changes in the energy intensity and price-induced substitution between secondary fuels. Demand for electricity is supplied from either thermal or non-thermal power plants. Demand for secondary fuels, including that for thermal generation of electricity, is met by the three supply sectors. 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. Fig. 1 gives an overview of the five modules and the important relationships.

3.2. *The energy demand* (*ED*) *module*

We distinguish five sectors: residential (or consumption), industrial, commercial (or services), transport and other and two forms of energy: heat and electricity,[12] and three determinants of energy-intensity changes: changing activity patterns, products and processes ('structural change'), autonomous energy efficiency improvements (AEEI) and price-induced energy efficiency improvements (PIEEI). First, useful energy demand without any changes in technology or prices is calculated based on the hypothesis that end-use demand is the product of population and a structural change (SC) multiplier. It represents the hypothesis about how end-use energy per unit of activity changes with rising activity levels; it is a function of per capita activity and normalized to the year 1900. It is multiplied by the autonomous energy efficiency increase (AEEI) multiplier to account for non-price related efficiency improvements. This multiplier is assumed to decline exponentially to some lower bound and is linked to the turnover rate of sectoral capital stocks.[13]

Energy demand after AEEI is multiplied by the price-induced energy efficiency (PIEE) multiplier which is determined by end-use energy costs which in turn depend on prices and market shares of secondary fuels. The conceptual and empirical basis for this formulation is the energy conservation cost curve; it represents the cumulative investments as a function of the fraction with which useful energy demand is reduced[14]. Energy efficiency investments are taken up to the point where the marginal investment costs to save one GJ equal the product of the desired payback time and the money which is saved annually as a result of these investments. Efficiency investments are implemented with a delay and irreversibly.[15] To account for the fact that regulation and mass production will tend to make many energy efficiency measures cheaper, the cost curve is assumed to decline over time according to an exogenously set rate. The resulting heat demand after AEEI and PIEEI is satisfied by a price-determined mixture of four secondary fuels.[16] Their economically indicated market shares are calculated for each sector from their relative prices through a multinomial logit function (Bollen *et al*., 1996). Actual market shares follow the economically indicated ones, with a delay.

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[11] This is similar to the applied general equilibrium (AGE) approach in economic modelling 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).

[12] Heat is a shorthand way of referring to all non-electric end-use applications of energy for which commercial secondary fuels are used.

[13] Formalisation of the underlying technology dynamics is beyond the scope of the present submodel. As to the lower bound: it is hard or even impossible to base the lower bound on physical considerations if output is measured in monetary units.

[14] A variety of such curves has been published in the literature over the past 5–10 years (Ledbetter and Ross, 1990; UNEP, 1992; Blok *et al*., 1993; Bollen *et al*., 1996). Reliable estimates are only available for a few countries. It should be noted that our formulation implies that the price-elasticity decreases when energy prices go up, reflecting the phenomenon that price changes induce fewer conservation investments once the cheapest options are introduced. No sharp distinction between autonomous and price-induced efficiency measures can be made, but the PIEEI-factor will primarily represent retrofit investments in existing capital goods which are then maintained in new capital goods if energy prices do not fall.

[15] There is some evidence for partial reversibility (Dargay and Gately, 1994; Haas and Schipper, 1998). Preliminary simulations with alternative formulations suggest that this is rather unimportant for most longer-term scenarios.

[16] We distinguish four commercial fuel types: solid, liquid and gaseous fuels, with the liquid fuels split into light (LLF: gasoline, kerosene, etc.) and heavy (HLF: fuel oil and distillates). Fuelwood in the residential sector and all kinds of agricultural and industrial waste flows used for energy functions are not (yet) included.

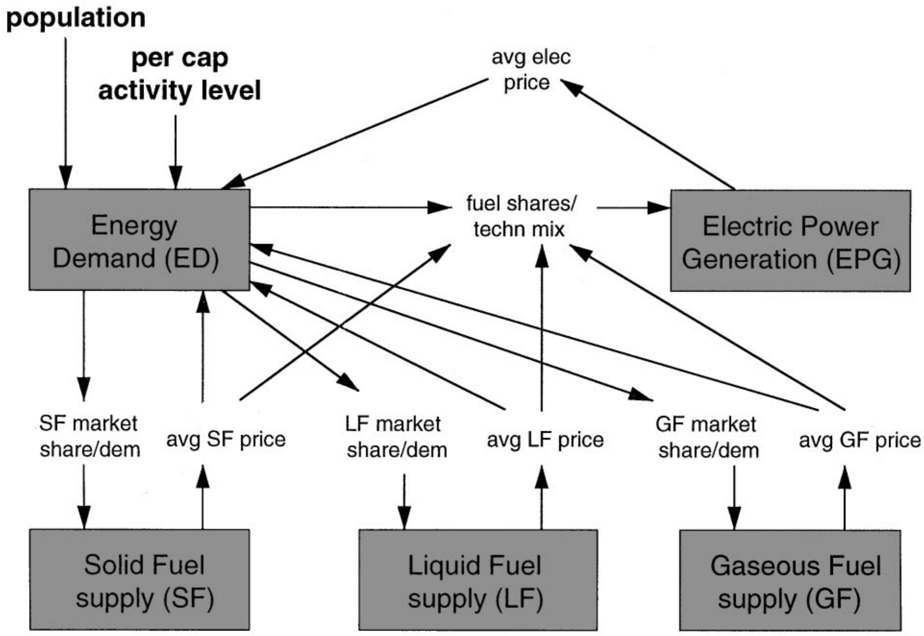

Fig. 1. Outline of the TIME-model.

There are two additions to this formulation. Non-price factors influence the decision to use certain fuels, e.g. strategic and environmental. Because of this and to account for transport and storage costs and taxes, we apply sectoral premium factors to the calculated secondary fuel costs. Secondly, the available user technologies and distribution networks did and do not always allow an unconstrained choice of one of the three secondary fuels. Hence, we have put exogenous constraints on the substitutable part of useful energy demand — a conceptually more plausible approach than adjusting the premium factor to unrealistically high values.[17]

3.3. *The electric power generation (EPG) module*

Net demand for electricity from the ED module is converted into anticipated gross demand and split into two fractions: base load and peak load. The calculation of the required base-load capacity is derived from the assumption that each generating option has a constant load factor, i.e. fraction of the year that it is operated in the base load. The peak-load capacity results from the peak fraction in the load duration curve and an assumed maximum load factor for capacity operated in the peak-load periods. Capacity shortage induces additional investments; overcapacity shows up as increasing costs, which negatively affects demand.

[17] For example, road transport was not an alternative for rail transport at the beginning of the century so we confined the market share of the transport sector, for which coal was a possible substitute, to 90% around 1900 down to 10% around 1990.

There are three options for capacity expansion: hydro, thermal and non-thermal, each with their specific construction time and economic and technical lifetime. Expansion of hydropower (H) capacity is an exogenous scenario, assuming increasing marginal specific investment. Whether the remaining new capacity ordered is fuel-based thermal electric (FE) or other electric (NFE) is based on the difference between the production costs. For thermal power plants, conversion efficiency and specific capital costs are exogenous time paths. The market share of each of the three fuels (solid, liquid, gaseous) is based on relative fuel prices.[18] For the non-thermal power generating options, cumulated production induces learning in the form of decreasing specific investment costs. This leads to lower generation costs which in turn accelerates their penetration — a positive, reinforcing loop until the non-thermal plants are pushed into the peak-load which increases the generating costs. From the annuitized investments and the fuel inputs and prices, electricity prices are calculated and used as an input for the ED module where they in turn affect the demand for electricity.

[18] For the FE-NFE and the fuel allocation, we use a multinomial logit formulation. A premium factor is used to allow for differences between fuel costs and the prices as perceived by utilities. Evidence for this can be found in, for example, Moxnes (1989) who found for electricity generation in OECD Europe as of 1983 that coal has a premium equivalent to a price discount of 29%, whereas natural gas has been discriminated against at the equivalent of a 12% price increase.

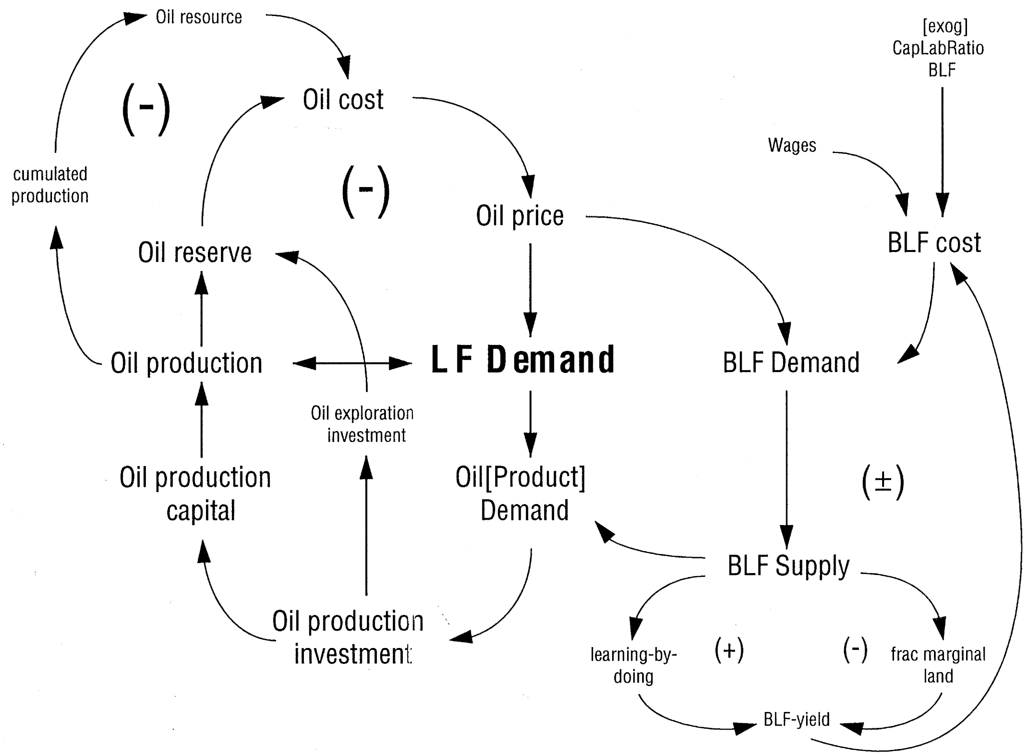

Fig. 2. The demand – investment – price loop in the liquid fuel (LF) module. The left-hand part is the demand-driven oil exploitation loop with price-induced exploration, depletion and learning; the right-hand part is the penetration and depletion and learning dynamics of bioliquidfuels (BLF).

3.4. The fuel supply modules

Fig. 2 shows the liquid fuel (LF) module as a causal loop diagram; the gaseous fuel (GF) module has an almost identical structure and will not be separately discussed. The solid fuel (SF) module distinguishes in addition two production modes (underground and surface mining) because of their quite different cost functions.[19] For all three resources (coal, crude oil and natural gas), the basic resource flow is from the resource base into identified reserves and then into cumulated production c.q. emissions. Identified reserves increase as a consequence of exploration investments and/or an exogenously introduced discovery rate.

Fuel production is determined by the operating fuel producing capital stocks and their capital–output ratios. Required investments are equated to the depreciation of the existing capital stock plus the additionally required capacity which is based on anticipated demand and exploitable reserves, and are added after a construction period to the producing capital stocks. Actual investments depend on expected profit levels: if these are too low, less than the required capacity will be ordered. If demand exceeds 90% of potential supply, prices start rising to generate additional investments; this demand–supply equilibrating mechanism operates via a multiplier and various delays. The long-term production costs are governed by a depletion and a learning multiplier which operate on the capital–output ratio of the corresponding capital stocks. The former reflects the rising cost of discovering and exploiting occurrences when cumulated production increases.[20] 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.

Learning-by-doing in coal production is only operating on surface-mining capital. For underground coal

[19] We consider only one generic type of coal, at 29 GJ/ton, also referred to as 'solid fuel'. The use of coal as feedstock is not accounted for, except in the case of coking coal for pig iron production, where it is part of industrial fuel use.

[20] Conceptually, we follow here the often used hypothesis that the cheapest resource deposits are exploited first. In the past, this has obviously not been the case at the world level. For example, an obvious violation was the discovery of the giant low-cost oil fields in the Middle East (Yergin, 1991). We have therefore inserted these discoveries as exogenous, zero-cost exploration successes. Yet, the above hypothesis may be increasingly correct because of trade liberalization and the downward trend in transport costs. For oil there is already effectively one world market; a world coal market is in rapid development (Ellerman, 1995). For natural gas, this is not yet the case due to high transportation costs. Transporting gas in an onshore pipeline might cost 7 times as much as oil; to move gas 5000 miles in a tanker may cost nearly 20 times as much (Jensen, 1994).

mining, we use a Cobb–Douglas production function with an exogenously rising capital–labour ratio which represents ongoing substitution of capital for labour. For oil and gas, investments may be diverted into biomass-plantations once the biomass-derived fuels (BLF/BGF) can economically compete with light liquid fuels (LLF) and natural gas, respectively. The simulation of biofuel production is based on a production function with capital, labour and land as production factors.[21] A fixed capital–output ratio and an exogenously increasing capital–labour ratio reflect the transition towards less labour-intensive techniques. Land requirements are derived from an average yield factor, which increases due to learning-by-doing and decreases with a rising ratio between actual and potential supply, incorporating the assumption that increasingly less productive land is used for biomass plantations. The supply potential is exogenous. The penetration dynamics of commercial biofuels is determined by its cost relative to the LLF c.q. natural gas price acording to a multinomial logit formulation.

3.5. *Model calibration*: *world 1900–1990*

Calibration has been done for the period 1900–1990 for the world at large, partly based on calibrations for the regions USA and India (Berg, 1994). Historical data are from IPCC (1992), Klein Goldewijk and Battjes (1995) and various IEA, World Bank and UN statistical surveys. Historical time series for population and sectoral activity levels are used as exogenous inputs and these are combined with data on sectoral commercial fuel use and price paths to calibrate the ED module.[22] In the residential, services and other sector, structural change has led to declining intensity of useful energy (heat); for transport and electricity the opposite is found due to ever more and intensive user applications. The AEEI-factor is set for all sectors at a constant 1%/yr decline towards the lower bound, which has been fixed at 0.2 for heat and 0.4 for electricity. The steepness of the conservation cost curves are estimated from bottom-up engineering analyses; they range from 30 to 50 $/GJ investments required to reduce useful energy demand with about 60%. The rate at which the cost curves decline is set at a low 0.1%/yr. For the desired payback time we use values between 1 and 3.5 year. Fuel cross-price elasticities and premium factors have been used to gauge the secondary fuel use. Next, the EPG- and the three-fuel supply modules have been calibrated using historical supply and price paths. The main parameters used for the calibration are the depletion multipliers and learning coefficients, and the premium factors for fuels used for electric power generation. Resource supply cost curves for fossil fuels and renewables are estimated from literature (JPDA, 1993; ECN, 1995; McLaren and Skinner, 1987; Edmonds and Reilly, 1985; Battjes, 1994; Grubb and Meyer, 1993; Moreira and Poole, 1993; Raabe, 1985). The supply–demand multiplier relations are based on Naill (1977), Davidsen (1988) and Stoffers (1990). For nuclear electricity we had to assume a negative learning coefficient for the period 1965–1990 to account for additional safety measures and long construction delays. Finally, the integrated model has been calibrated in a series of iterations during which a limited set of parameters within the four supply modules had to be adjusted to correct for minor discrepancies between simulated and historical values.

Simulated secondary fuel and electricity use are within 1–2% of the historical estimates; historical trends in fossil-fuel production and CO_2-emissions from fossil-fuel combustion coincide well with the published estimates. Depletion and capital-productivity increasing innovations lead to fossil-fuel prices which are in reasonable agreement with the [scarce] data on historical [world] prices. The declining trend in prices is in line with historical observations for most regions and reflects the fact that technological improvements have more than compensated depletion effects. The average price of electricity has decreased even more rapidly, because improving thermal efficiency has been coinciding with declining fuel costs. The model calibration indicates that it is possible to reproduce historical time series of secondary and primary fuel use satisfactorily, provided the model is fed with some exogenous time series to account for effects which are not part of the model dynamics. These are, notably, technical constraints on market penetration, the related discrepancies between actual and perceived market prices ('premium factor'), the historical nuclear power programmes in the 1960s and 1970s, the large oil discoveries in the 1940s and 1950s and the oil price hikes of the 1970s.[23]

A systems dynamics model such as the TIME-model cannot be calibrated unambiguously. There are always

[21] Labour may be important input, especially in low-labour productivity regions. In fact, biofuels may initially only have a competitive advantage — apart from strategic considerations — because large amounts of cheap labour can be absorbed.

[22] We have chosen IMAGE 2.0: value-added in constant (1990) US dollars for industry and commerce, consumption expenditures in constant (1990) US dollars for residential areas, and GWP in constant (1990) US dollars for transport and other (Toet *et al.*, 1994).

[23] Setting all premium factors to zero causes oil and especially gas to penetrate much faster than has happened historically. If the technological constraints are also removed, the system immediately jumps to the present market shares for oil and gas, which is a price-determined equilibrium. The longer-term consequence is that oil and gas are depleted more rapidly and coal is revived earlier and stronger. These simulation experiments point to the importance of non-economic factors in explaining the energy system evolution over the past 90 years. Our simple way of introducing the complex dynamics of technical innovations, in the form of exogenous constraints to market penetration, turns out to be a decisive factor in calibrating the model.

Table 1
Perspective-based model routes: indication of assumptions

Parameter	Hierarchist	Egalitarian	Individualist
AEEI ('technology')	Average 1%yr, all sectors moderate	Faster	Faster
PIEEI ('prices')		Cheaper and long payback times accepted	Much cheaper and short payback times
FE (thermal electric) efficiency	Rising to an average 50% in 2100	Rising to an average 52% in 2100	Rising to an average 60% in 2100
NFE (non-thermal electric) cost	Moderate improvement	Moderate improvement	Fast learning, hence cheaper
Coal cost	Slow increase	Removal of subsidies, hence fast increase	Removal of subsidies and no learning in SF (Surface Coal), hence fast increase
Gas resource base and cost	Medium estimate moderate improvement	Less, at higher cost higher labour cost, more severe land constraint	More, at lower cost lower labour cost less severe land constraint
BLF/BGF (Bio Liquid/Gaseous fuels) cost	Moderate improvement	Moderate improvement	Fast improvement
Carbon tax	No	Towards $500 per tC ($12.5 perGJ) in 2020, constant thereafter	No

multiple ways in which the scarce available historical observables can be reproduced. For example, in the ED module end-use energy demand is a non-observable quantity: it is implicit in the actual observations of secondary fuel use and activity level. Hence, a multiplicity of parameter calibrations is possible. The same holds for the relative importance of technology vs. depletion in the fuel supply modules. This is the consequence of modelling aspects of real-world dynamics which are not falsifiable in a strict sense (Randers, 1980; Graham, 1984). 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 behaviour.[24]

4. How plausible is conventional wisdom?

4.1. Reproducing the IPCC-IS92a scenario

From the introductory section in this paper, it is clear that future energy developments hinge on all kinds of uncertainties. To assess the importance of these uncertainties for the climate change debate, we have constructed three divergent sets of assumptions about the most important controversial themes. These have subsequently been used for uncertainty analysis and the construction of scenarios. We have attempted to apply Cultural Theory as a heuristic in formulating and bring coherence into these sets of assumptions (Thompson *et al*., 1990; Schwarz and Thompson, 1990; Adams, 1995; Rotmans and De Vries, 1997). Accordingly, the scenarios are associated with the hierarchist, the egalitarian and the individualist perspective. Important model parameters have been given values which are thought to be representative for a particular perspective, based on a large variety of literature sources and summarized in Table 1.[25] Each perspective is associated with a trajectory for the world population and the gross world product (GWP).[26] Important perspective-based assumptions have to do with autonomous and price-induced reductions in sectoral energy intensity, with thermal electric conversion efficiency, with the learning coefficients for non-fossil-based electric power generation (NFE) and biofuels, and with the long-term supply cost curves for fossil fuels. Also the desired payback times for energy conservation measures and the premium factors for coal

[24] A third way of validation is to run the model without certain exogenous events (e.g. the oil price rise between 1973 and 1986 and the change in premium factors) to explore the model dynamics per se (see De Vries and Janssen, 1996).

[25] Of course, the model formulation itself is biased in various ways, e.g. in the relative importance of prices and technology. Hence, a more rigourous implementation of the three perspectives would require the inclusion of different model routes (cf. Rotmans and De Vries, 1997).

[26] A more detailed account of these trajectories is given in Rotmans and De Vries (1997). It should be noted again that there are no feedbacks in the model from energy system requirements or carbon taxes upon the population and economic growth paths.

have been varied. For NFE also the base-load factor has been differentiated in order to account for different views on the type of technology and storage and system characteristics. For coal, labour costs in underground mining and the learning coefficient for surface mining are made perspective-dependent. A carbon tax on fuels and RD&D-programs for NFE and biofuels are implemented for the egalitarian perspective.

Maintaining established order is an important goal within the hierachist perspective. Hierarchist institutions favour a risk-reducing control approach and anticipate and respond on the basis of scientific expert knowledge. Hence, natural systems can — and should — be managed responsibly on the basis of scientific insights. Decisions are supported by [mathematical] tools like cost minimization, cost–benefit analysis, etc. Energy consumers can and should be guided towards "rational energy use" — which is the justification for regulation, taxes, information campaigns and the like. Resource estimates and technology assessments are usually prudent or even conservative. Hierarchist institutions will tend to suppress egalitarian and individualist counterforces unless they become a threat to their power in which case they are accommodated (e.g. Greens, markets). With regard to climate change policy: there is a keen awareness that fast and stringent cutbacks in CO_2-emissions may be socially disruptive and create competitive disadvantages and a carbon tax should therefore be "realistic" and part of an internationally negotiated consensus.[27]

From an energy point-of-view, the IPCC-IS92a scenario is best characterized as a coal-based Business-as-Usual future. From the normative perspective of the Cultural Theory, it comes closest to a hierarchist scenario. Hence, we have used the assumptions behind the IS92a scenario to construct a hierarchist reference scenario (Leggett *et al*., 1992), introducing some additional assumptions and some simplifications, e.g. coal liquefaction/gasification is implicit (De Vries and Janssen, 1996). In using the IS92a-future as a hierarchist future, we are aware of the fact that it has some undesirable aspects because of its "muddling through" character (Lindblom, 1959). For instance, its high carbon emissions may cause severe climate disruptions — and many hierarchist institutions would put a lot of effort into avoiding such a high emission path, e.g. through a carbon tax.

The simulation experiments of the IPCC-IS92a Conventional Wisdom scenario with the TIME-model provide a rather detailed picture which largely coincides with the published results (Leggett *et al*., 1992). Use of secondary fuels and electricity increases from the present 220 EJ/yr to over 800 EJ/yr by 2100. The proportion of electricity in final demand climbs from the present 16% to over 40% — a level which is almost reached now for the US residential sector. About 40–45% of demand reduction between 1990 and 2100 is from autonomous improvements (AEEI); rising energy costs induce energy efficiency investments which lead to an additional reduction in the energy intensity of 3% for electricity up to 40% for the transport sector (PIEEI). By 2100 electricity is for over 50% generated in non-thermal electric (NFE) power plants; thermal electricity is for 90% generated by burning coal. The resulting primary energy production rises to over 1200 EJ/yr in 2100 (Fig. 3). Coal production increases almost fivefold to about 700 EJ/yr; its proportion drops until 2010 after which it starts rising. Simulated price paths for solid fuel (SF - coal), light liquid fuel (LLF) from crude oil and natural gas and their biomass-derived substitutes (BLF, BGF) are shown in Fig. 4. Coal prices only slowly increase because surface-mined coal emerges as a cost-stabilizing option which counteracts rising labour costs and depletion in underground mining. The hierarchist view on oil and gas resources is conservative: only 60 and 30% of the ultimately recoverable oil resp. gas resource base (set at 72,000 and 60,000 EJ) can be exploited at cost levels less than 20 times the 1900-value. As a consequence, biofuel-based substitutes largely take over in the second half of next century and stabilize price levels at about 15 $/GJ (100 $/bbl). Later on, the use of less productive lands and the fading away of learning-by-doing causes an increase in biofuel costs. In similar fashion, NFE-electricity becomes cheaper in the first half of next century and functions as a buffer against the increasing cost of coal-based electricity.

Although energy use per capita doubles, there is a continuous decline in the energy intensity, i.e. the ratio of primary fuel supply and GWP, from 14 MJ/$ in 1990 to 5 MJ/$ in 2100 (Fig. 5). The investments into the energy system rise from about 400 10^9 $ in 1990 to a plateau of 2500 10^9/yr after 2060 (Fig. 6).[28] Electric power generation is a major part of the investment flow due to the capital-intensive nature of the NFE-options. The over-all energy costs (or expenditures), defined as the product of secondary fuel and electricity use and their respective prices, are rising as a fraction of GWP from about 6% at present to a 10% for the second half of next century. The

[27] In the past there has been a certain preference for technologies which can be planned and controlled. In the context of ambitious government plans for nuclear power expansion in the USA and the former USSR, the phrase "nuclear priesthood" was coined; in France some spoke of "Les nucleocrates" (Simonnot, 1978). Cf. the recent debate about privatization of the electricity industry in Europe (Grubb and Vigotto, 1997).

[28] The calculated investment requirements are in remarkable agreement with recent estimates for 1990 (Nakicenovic and Rogner, 1995). Overall cumulative investments in the period 1990–2020 are in the order of 18.10^{12}, 1012, 1990 US $. This too compares reasonably well with the recent estimates of cumulative capital requirements of 16.10^{12}, 1012, 1990 US $ for a medium growth scenario (Nakicenovic and Rogner, 1995).

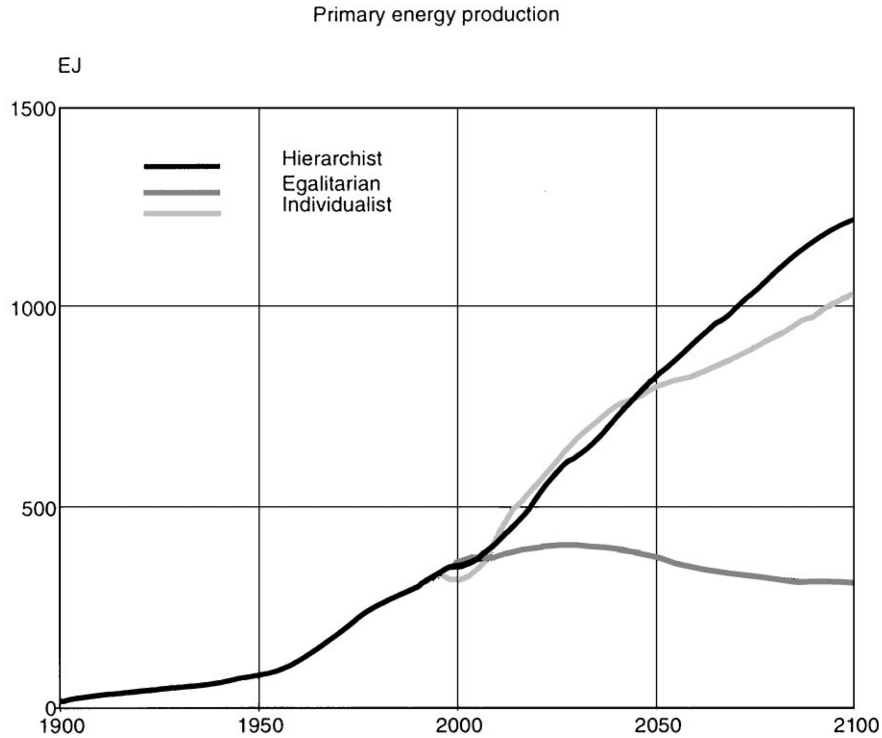

Fig. 3. Simulated primary energy (fossil and renewable) production for the IPCC-IS92a hierarchist scenario and for the other two perspectives (egalitarian and individualist).

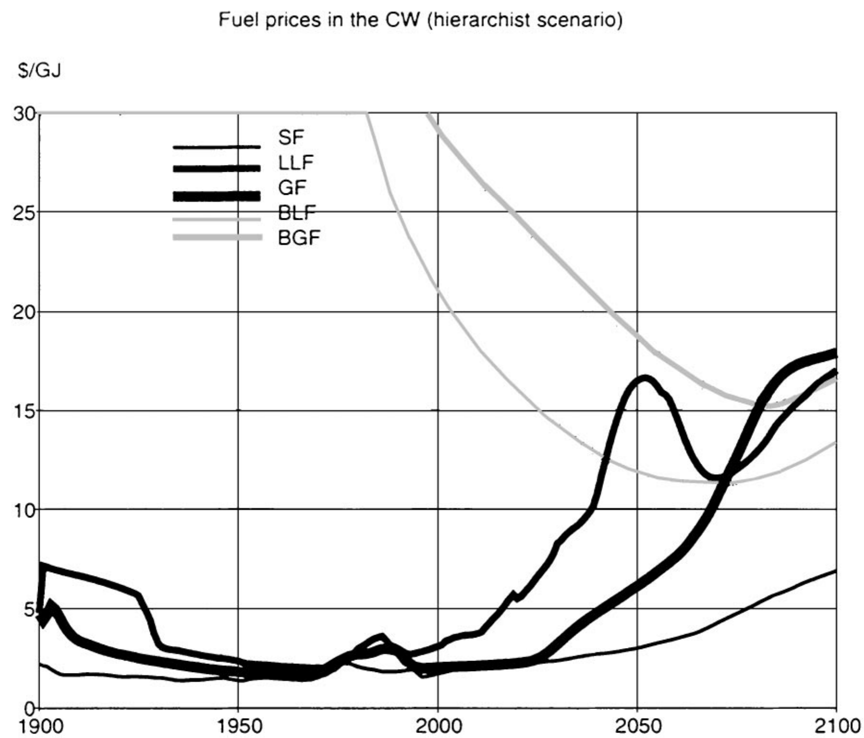

Fig. 4. Simulated secondary fuel prices for the IPCC-IS92a hierarchist scenario.

carbon emissions in this scenario rise throughout the next century up to about 20 Gton/yr by 2100 compared to about 6 GtC/yr in 1990 (Fig. 7).

We have done several simulation experiments to explore the sensitivity of certain key variables for the assumptions made. An example is given in Fig. 8 which

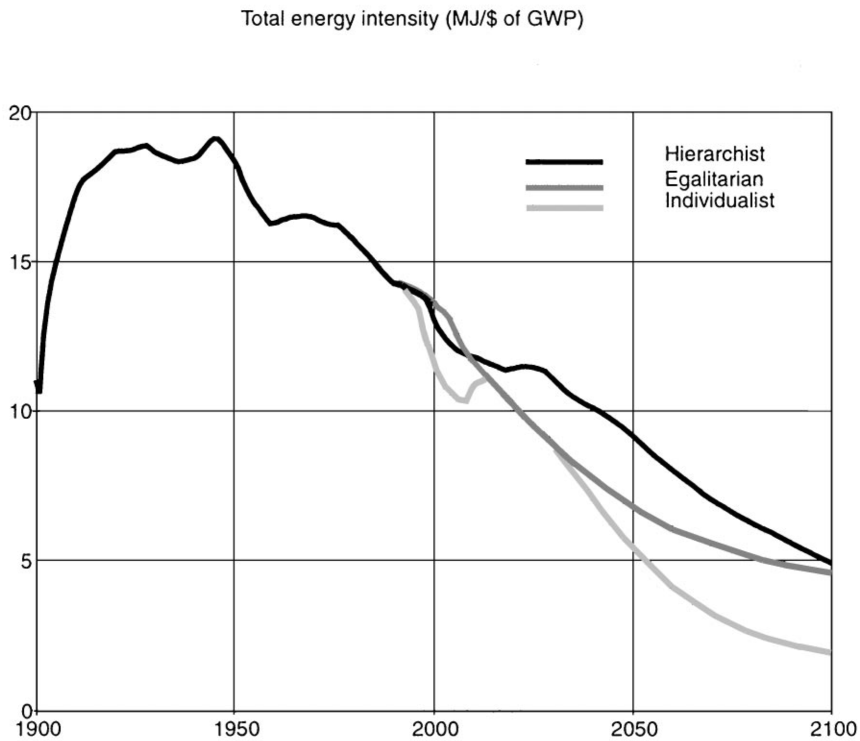

Fig. 5. Simulated average energy intensity (in MJ per $ of GWP) for the IPCC-IS92a hierarchist scenario and for the other two perspectives (egalitarian and individualist).

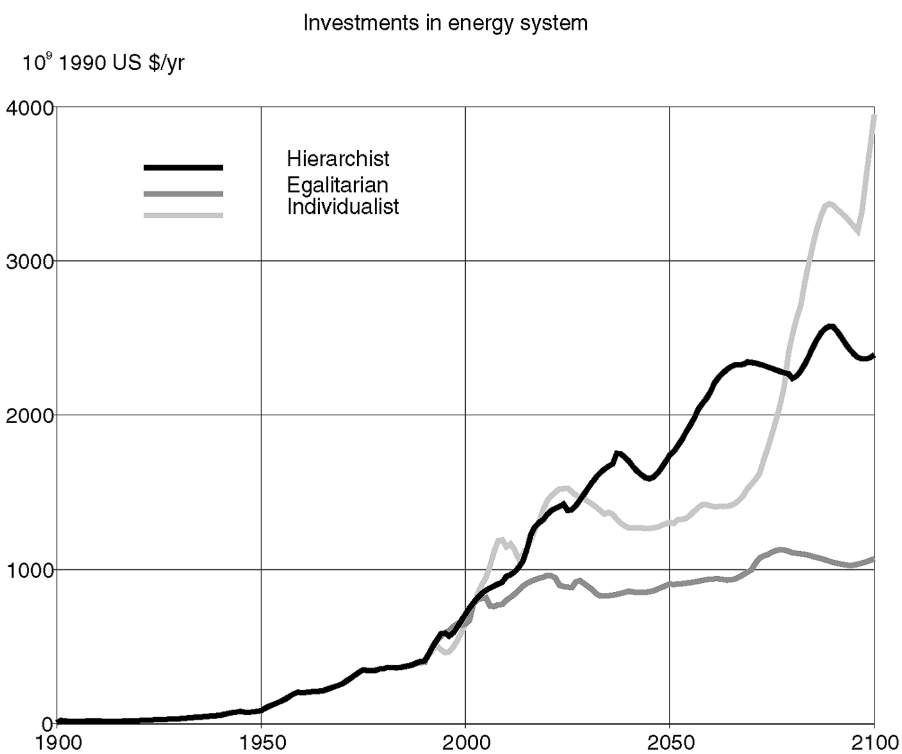

Fig. 6. Simulated investments flows (in 10^9 $) for the IPCC-IS92a hierarchist scenario and for the other two perspectives (egalitarian and individualist).

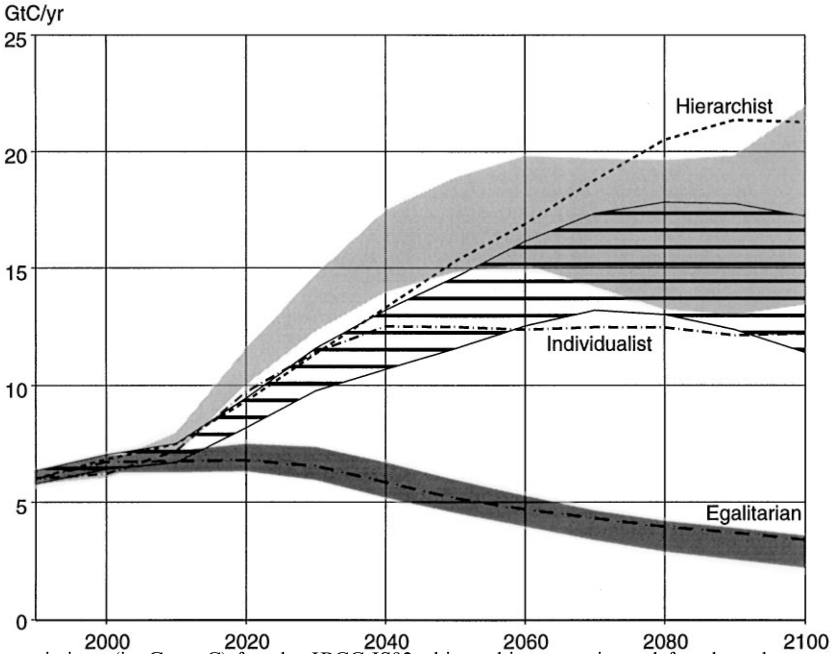

Fig. 7. Simulated carbon emissions (in Gton C) for the IPCC-IS92a hierarchist scenario and for the other two perspectives (egalitarian and individualist).

shows the sum of crude oil and natural gas production trajectories if the long-run supply cost curves for oil and gas are made twice and half as steep, respectively. Obviously, the controversial estimates on size and cost of conventional oil and gas resources may have a large impact on the emission profile and, indirectly, on the need for emission reduction policies.[29] Another way to explore the uncertainty in the outcomes of the IS92a hierarchist scenario is to apply a Monte Carlo stochastic variation of a set of relevant model parameters. To this end, we use the upper and lower bounds of the three perspectives as the uncertainty domain keeping world population and GWP trajectories fixed (cf. Table 1).[30] Key scenario variables have a wide margin of uncertainty (the 2.5 and 97.5 percentile values are shown in Table 2). Ninety-five per cent of the paths of secondary fuel and electricity use in 2100 fall between 600 and 800 EJ/yr. A similar uncertainty is found for primary energy supply, whereas CO_2-emissions in 2100 vary between 12 and 17 GtC, significantly below the IPCC-IS92a value of about 20 GtC (Fig. 7). These experiments suggest that the IPCC-IS92a scenario values are biased in an upward direction, which is a reflection of the underlying assumption of only modest progress in energy efficiency and renewable energy technology.

The most important parameters and variables which contribute to the uncertainty band are the AEEI and its lower bound for industry and electricity, the relative cost of labour in underground coal mining, the learning coeficient for NFE and biofuels and the thermal efficiency of fossil-fired power plants. The divergence in the assumptions on NFE-options and biofuels leads to a factor two difference in projected paths for the average energy price, which is partly mitigated by the resulting difference in the incentive for energy conservation. There are more causal chains through which uncertainties cancel each other out. For example, a low rate of energy efficiency improvement can be compensated for by cheap and abundant natural gas which in turn slows down the PIEEI for some time.

5. Two other perspectives on the global energy future

As indicated in the previous paragraph, we have also constructed an egalitarian and an individualist scenario to contrast the hierarchist Business-as-Usual world. The egalitarian perspective is characterized by the wish to reduce inequity and stress the rights of those without a voice: our children, the poor and nature. The natural system is considered to be vulnerable. Energy futures are

[29] However, the CO_2-emission trajectories differ less than the oil and gas production profiles because of counteracting forces (Janssen and De Vries, 1999).

[30] The stochastic variation is done with the UNCSAM-method (Janssen *et al.*, 1992). For each of the three utopias all the input parameters and variables are uniformly varied between the domains derived from literature (cf. Table 1). For some input variables in the form of time-series, e.g. thermal electric conversion efficiency, sampling is done in a way that the shape of the curve is preserved. The population and GWP-scenarios are not varied.

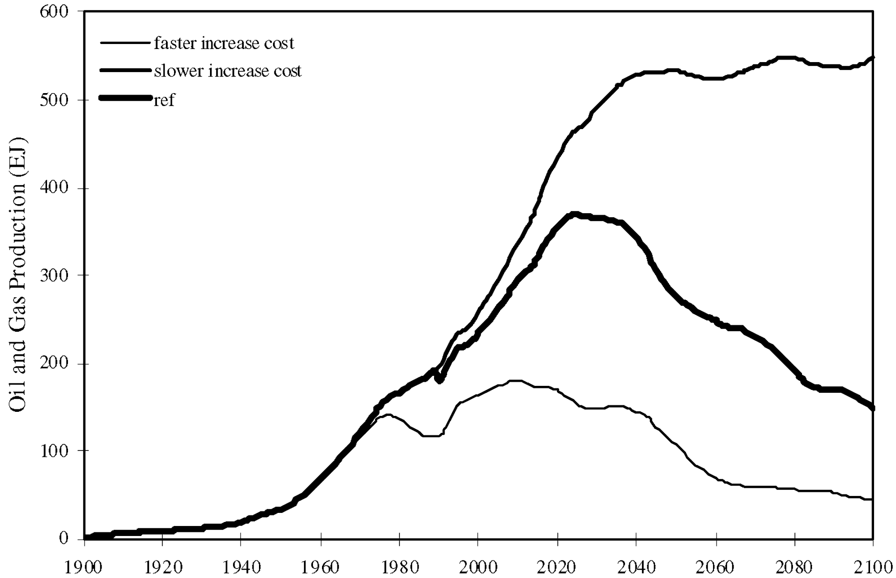

Fig. 8. Simulated carbon emissions (in Gton C) for the IPCC-IS92a hierarchist scenario and for the situation in which the oil and gas resource base can be produced at a twice as high resp. twice as low production cost.

Table 2
Overview of scenario results: key indicators in 2100

Variable (in 2100)	1900-value	Hierarchist < 2.5%	> 97.5%	Egalitarian < 2.5%	> 97.5%	Individualist < 2.5%	> 97.5%
Population (mln)	5300	11,700		1950		13,250	
GWP/cap ($)	4000	21,000		7800		41,000	
Secondary energy use (EJ)	175	610 (810)	790	190 (250)	220	980 (800)	1220
Primary energy production (EJ)	300	830 (1220)	1110	270 (310)	330	1280 (1035)	1630
CO_2-emission (GtC)	6	11.5[a] (20)	17[a]	2.5[b] (3-4)	3.6[b]	14.5 (12)	21.5
Average energy price ($/GJ)	4.9	9.5 (16)	20	8.5[c] (15)	16[c]	13 (11)	24

[a]Peaking in 2080 at 13 resp. 18 GtC.
[b]Peaking in 2000 at 6.5 resp. in 2025 at 7.6 GtC.
[c]Peaking around 2040-2060 at 13.5 resp. 18 $/GJ.

judged not only in terms of costs, but also with regard to distributive aspects and ecological impacts (Goldemberg *et al.*, 1988). Mathematical tools and models can play only a minor role because many of the issues at stake cannot be expressed in numbers or money. Egalitarians advocate a morally founded justification for government regulation and support programs; science and technology can certainly solve part of the problem but not as long as its course is solely governed by markets and multinational corporations. Egalitarians will embrace the "precautionary principle" as a way to express their risk-averse attitude and promote energy taxes as means to change wasteful production and consumption practices and accelerate the transition to an energy-efficient, non-fossil future. Moderate economic growth will probably be necessary but only if it narrows the present income gap between the rich and the poor. There are high expectations about the prospects for energy efficiency and decentralized, clean renewable energy sources (Lovins *et al.*, 1993; Johansson *et al.*, 1989). Estimates of fossil-fuel resources are on the low side.

We have implemented this egalitarian perspective as indicated in Table 1. Both population and economic growth are much smaller than in the hierarchist perspective (Table 2). There will be more incentive to develop energy efficiency oriented technology and stimulate its penetration. Active government support raises the AEEI-rate from 1 to 1.5%/yr and induces a twice as fast decline in the conservation cost curve. Moreover, consumers are willing to use longer payback times, because of information campaigns and concern about impending climate change. Coal subsidies are abolished and external environmental costs are internalized, which makes coal a much less attractive fuel use in both the end-use and for electricity generation. The major policy instrument is a worldwide carbon tax; regions such as China and India are persuaded to revise their coal expansion plans and focus on oil and gas, the availability of which increases because of energy conservation efforts in the industrialized regions.

This smaller population and GWP result, in combination with a carbon tax rising to 500 $/GtC from 2020 onwards, in a much lower demand for secondary fuels and electricity. The proportion of electricity rises towards 50%. The AEEI-factor is about 10% point below the hierarchist scenario values; the price-induced energy conservation increases to 35% (services) up to 55% (transport) by 2100 for heat (for electricity it remains below 5%). In combination with the high carbon tax, the penetration of highly efficient thermal power stations and increasingly cheaper non-thermal electricity generation options leads to a reduction of fossil-fuel input for electricity with a factor of almost 4 compared to the hierarchist future. 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/yr around 2025 (Fig. 3). Renewables make up almost 50% by 2100, of which 40% is in the form of biofuels; coal production remains at the 1990-level. This shows up in CO_2-emissions peaking at about 7 GtC/yr between 2000 and 2030 after which they decline to 3–4 GtC/yr (Fig. 7). Investments are redirected from fossil-fuel supply into energy efficiency and renewable electricity generation (Fig. 6) and rise, as a fraction of GWP, to 10% around 2040 after which they slowly decline to about 8%. In the egalitarian utopia the present generation brings a sacrifice for the next, indeed.

The results of applying the Monte Carlo uncertainty analysis are given in Table 2. Secondary fuel use is in the range of 190–250 EJ/yr, CO_2-emissions 2.5–4 GtC/yr in 2100 (Fig. 7). Compared to the hierarchist scenario, the average energy price is throughout the period 2000–2060 almost twice as large — largely because of the carbon tax. However, after 2060 it rises rapidly in the hierarchist but starts to decline in the egalitarian future. The 97.5% lower limit of the average energy price is well within the hierarchist uncertainty range, but the range of secondary and primary energy use and CO_2-emissions falls completely below the hierarchist and the individualist uncertainty ranges. This indicates that the key determinants of the egalitarian future are the population and economic growth assumptions in combination with the optimistic assessment of the technical and socio-economic prospects for energy conservation and renewable energy options. The carbon tax serves to accelerate their introduction; without a carbon-tax CO_2-emissions in the egalitarian scenario amount to 5.4 GtC/yr in 2100.

In the individualist perspective, entrepreneurial freedom and unhindered working of market forces gives the best guarantee for increasing material wealth and at the same time solving resource and environment problems. The key resource is human ingenuity: human skills generate science and technology which will bring options one cannot even imagine now (Simon, 1980). Not much can be said about the distant future anyway — what further opportunities and progress will be brought by information technology, biotechnology, space technology? Technology is also the major driving force of economic growth, which will ultimately also benefit the poor. With regard to the issue of climate change, individualists argue that the Earth is far more resilient than we think and that climate change impacts are probably exaggerated by those advocating strict measures. Market forces will generate the necessary technologies and fuel substitutions, provided that energy companies are allowed to operate in a regime of free trade and with a minimum of government regulation and intereference.[31] Policy measures such as a carbon tax are unnecessary: there are still too many uncertainties about the enhanced greenhouse effect and possible climate change to accept drastic measures, and they are ineffective because industries will move to other countries and consumers will stick to certain lifestyles whatever the costs.

The individualist perspective has been implemented as shown in Table 1. Both population and economic growth are larger than in the hierarchist perspective (Table 2). Energy efficiency improvements and learning for non-fossil supply options is fast once the prices signal their competitiveness. The consumer will tend to use a short-time horizon, i.e. 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. The assessment of natural gas resources is optimistic: the same amount as for the hierarchist is available at half the cost. Thermal power stations reach an average 60% conversion efficiency; learning-by-doing for NFE is high and it can be operated at a high base load factor. Biofuels become quite cheap because of strong and fast learning and relatively cheap labour.

Despite the higher population and GWP, energy demand can be restrained to the hierarchist level of about 800 EJ/yr by 2100, 40% of which is in the form of electricity. The energy intensity declines to 2.5 GJ/$ due to

[31] With regard to expected future CO_2-emissions, this position leads to remarkable coalitions with egalitarians against the official' forecasts (see e.g. Kassler, 1994).

50–70% autonomous efficiency improvements (AEEI) and 20–30% price-induced efficiency improvements (PIEEI) with respect to 1990 (Fig. 4). Because coal prices go up somewhat faster than in the hierarchist scenario, the price of electricity from fossil-fired power plants continues to increase — despite the increase in efficiency — and hence accelerates the introduction of the cheap NFE-options: they rapidly penetrate 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, their market share has increased to 25% by 2100 when both oil and gas have become scarce and expensive. Coal use increases to about 250 EJ/yr by 2100 as compared to over 700 EJ/yr in the hierarchist scenario. Together, these changes lead to a stabilisation of CO_2-emissions from 2030 onwards at 10–12 GtC/yr (Fig. 7) — which is significantly below the high-growth IPCC-IS92e scenario but much higher than suggested in some other high-growth scenarios (Leggett *et al.*, 1992; Kassler, 1994). Prices of oil-based fuels steeply increase but are successfully stabilized by commercial biofuels; after 2060 these start to face land-related constraints and prices go up. Energy investments have increased in 2100 to almost three times the levels in the egalitarian future (Fig. 6), but energy expenditures as a fraction of GWP drop after 2040 to a low 4% from 2070 onwards. 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.

The results of applying the Monte Carlo uncertainty analysis are given in Table 2. The average energy price trajectories are quite similar to the hierarchist ones, ranging from 13 to 24 \$/GJ. Because activity and population levels are higher, secondary fuel use and primary energy production are higher despite the larger energy efficiency improvements. Now, the individualist scenario is at the extreme low end of the uncertainty range: 10–12 GtC/yr in 2100 whereas 97.5% of all uncertainty experiments gives an emission path above 15 GtC/yr between 2050 and 2100 (Fig. 7).

6. Conclusions

The TIME-model is a system dynamics model to simulate long-term structural developments within the (global) energy system. In its present form it satisfactorily reproduces the long-term trends in the period 1900–1990. There is, however, no unambiguous way in which the economic ('prices') forces can be separated from the technological dynamics and life-style related changes. This leaves ample room for controversy with regard to future developments and suggests that a more sophisticated description of the interplay between economic, technological and institutional factors is needed. The model also shows that an integrated approach with decision rules, delays and feedbacks results in stabilizing model behaviour. For example, substitution between secondary fuels tends to dampen price increases in any one particular fuel, if fuel prices are not linked through market or government agreements.

The scenario analysis indicates also that the uncertainty in future CO_2-emissions may well be less than is often suggested because counteracting mechanisms tend to suppress extreme combinations. Examples are the slower

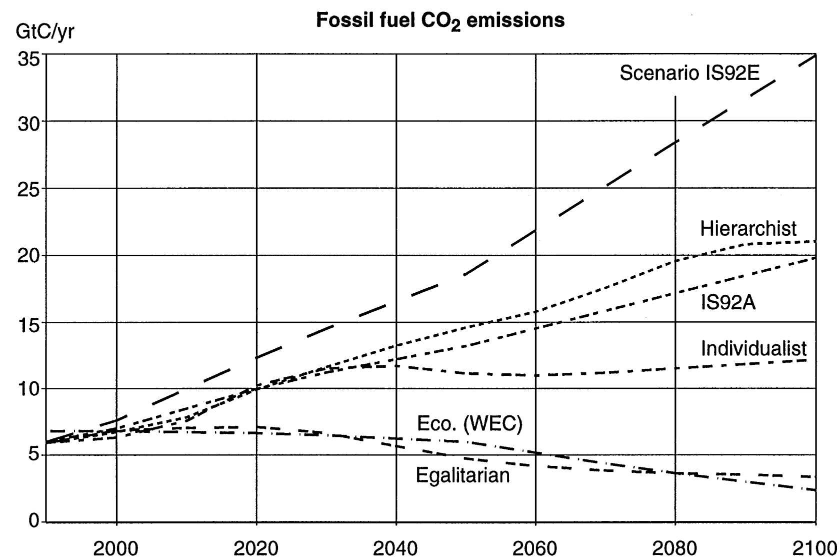

Fig. 9. Simulated carbon emissions (in Gton C) for the three scenarios presented in this paper and three corresponding other scenarios.

rate of energy efficiency improvements if non-carbon supply options experience high rates of cost reduction and the relative improvement of coal's competitiveness which tends to slow down the penetration of non-carbon options in response to rapidly rising oil and gas costs. This convergence is borne out by Fig. 9 in which the three scenarios presented in this paper: hierarchist — akin to the Conventional Wisdom IPCC-IS92-scenario, egalitarian and individualist, are shown in comparison with other recent scenarios. In the IPCC-IS92a Conventional Wisdom scenario, characterized here as a hierarchist Business-as-Usual scenario, energy-intensity decline is impressive, biofuels and non-thermal electricity generation start penetrating the market, but abundant resources bring coal back to the forefront in the second half of next century. This result, and one of its consequences: rising carbon emissions, is mainly caused by the conservative assumptions about oil and gas resources and the characteristics of carbon-free energy supply option and makes its use as a reference scenario questionable. Our simulation experiments suggest that the IS92a-scenario given its population and GWP-trajectories may overestimate the carbon emission path in the second half of next century with as much as 50–100%. The egalitarian scenario follows fairly closely some of the low-energy scenarios presented by other groups, e.g the Ecologically Driven scenario of IIASA/WEC (IIASA/WEC, 1995). However, major questions about its socio-economic and political feasibility of this low-growth "egalitarian" world remain unanswered. The "individualist" world with a high population and GWP-growth has markedly lower energy use and fossil carbon emissions than other high-growth scenarios such as the IPCC-IS92e scenario. This is to be expected as the individualist assumptions about new supply options are much more optimistic than in the IPPC-scenarios. Yet, it seems highly improbable that in a high-growth "individualist" world carbon emission values below 3-5 GtC/yr in 2100 have any plausibility, as has been suggested in some recently published scenarios (Kassler, 1994).

Future activities concentrate on the regionalization of the model as part of the IMAGE-project and linking the model to the CPB Worldscan model, in line with the objective to provide a transparant complement to other, country-oriented energy modelling efforts such as MARKAL (IEA-ETSAP, 1997). Also, some model improvements will be incorporated, among them the way in which traditional fuels are dealt with and the inclusion of combined-heat-and-power (CHP) schemes.

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