The Targets/IMage Energy (TIME) 1.0 Model

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Global Dynamics &
Sustainable Development
Programme

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research for
man and environment

Cover design: Martin Middelburg, studio RIVM
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CONTENTS

SUMMARY

This report contains a detailed description of the five submodels which constitute the Targets/IMage Energy (TIME) model. It also includes a brief description of the Economy model. The Minerals model is described elsewhere (Vries and Van Vuuren 1996). Together, the models make up the Energy-Economy-Minerals block in the TARGETS1.0-model (Rotmans and De Vries 1996). The Energy model is referred to as the TARGETS/IMAGE1.0 model because the energy demand modelling in IMAGE2.1 is a regionalized version of the one in TARGETS1.0 (cf. Vries et al. 1994, Bollen et al. 1995). The results of the integrated analysis, including scenario's up to the year 2100, are reported in a separate document.

After the introduction, in which also some methodological aspects are touched upon, Chapter 2 describes the Economy model. Chapter 3 describes in some detail the Energy Demand (ED) model, and includes some calibration results for the world 1900-1990. The essence of the model is the conversion from useful energy demand to secondary fuel-for-heat and electricity use on the basis of trends in autonomous and price-induced energy efficiency improvements. A more detailed description, implemented for 13 world regions, can be found elsewhere (Bollen et al. 1995).

Chapter 4 and 5 describe the supply dynamics of liquid and gaseous fuels in the Liquid Fuel (LF) and Gaseous Fuel (GF) submodels. In both models, the occurrence of learning-by-doing which reduces the capital-output ratio and depletion which raises it are the two major factors. The trajectory of this ratio is strongly influenced by assumptions about the long-term supply cost curve of [conventional] oil and [natural] gas. If the production costs of oil and gas increase, a biomass-based alternative penetrates the market. For these, too, the forces of learning-by-doing and depletion determine the trajectory of yields and thus costs and penetration rates. Other options of liquid and gaseous fuel supply, e.g. electricity-based hydrogen and coal liquefaction/gasification are not yet considered.

Chapter 6 documents the Solid Fuel (SF) submodel. It simulates the production of coal from underground and surface mines in response to solid fuel demand. Solid fuel comprises the aggregate of anthracite, [sub]bituminous and coking coal and lignite. Essence of this model is that, while underground coal experiences rising costs due to depletion which is only partly offset by capital-labour substitution, surface coal is still at the stage where economies of scale and innovation tend to lead to lower costs and hence growing market shares. The actual trajectory is strongly influenced - as with oil and gas - by one's assumptions about the characteristics of the world's coal resource base.

Chapter 7 gives a documentation of the Electric Power Generation (EPG) submodel. Demand for electricity is converted into required installed capacity, both base- and peak-load, which then leads to investments in hydropower, fuel-based thermal power and non-thermal power based on either nuclear or renewable sources. The most important aspect of this submodel is the penetration of some, rather unspecified, non-thermal alternative into the electric power generation market when fossil fuel prices start rising and the potential for hydropower expansion decreases.

Finally, the appendices discuss some of the methodological aspects in more detail and include a list of the submodel variables and data sets used for calibration.

SAMENVATTING

Dit rapport bevat een gedetailleerde beschrijving van de vijf submodellen die samen het Targets/IMage Energiemodel (TIME) vormen. Het bevat ook een beschrijving van het Economiemodel. Het Mineralenmodel wordt elders beschreven (Vries en Van Vuuren 1996). Tezamen vormen deze modellen het Energie-Economie-Mineralenblok binnen het TARGETS1.0-model (Rotmans en De Vries 1996). Er wordt naar het Energiemodel verwezen als het TARGETS/IMAGE1.0 model omdat de energievraagmodellering in IMAGE1.0 een geregionaliseerde versie is van de energievraagmodellering in TARGETS1.0 (cf. Vries et al. 1994, Bollen et al. 1995). De resultaten van de geïntegreerde analyse, inclusief de scenario's tot het jaar 2100, worden gepresenteerd in een afzonderlijk document.

Na de inleiding, waarin ook kort enkele methodologische aspecten aan de orde komen, wordt in Hoofdstuk 2 het Economiemodel beschreven. Hoofdstuk 3 beschrijft het EnergieVraag (ED) model alsook enkele calibratieresultaten voor de wereld 1900-1990. De kern van dit model wordt gevormd door de omzetting van de vraag naar nuttige energie in het gebruik van secundaire brandstofvoor warmte en electriciteit. Dit gebeurt op basis van trends in de autonome en de prijs-geïnduceerde verbeteringen in de energie-efficientie. Een meer gedetailleerde beschrijving, geïmplementeerd voor 13 wereldregio's, is elders gegeven (Bollen et al. 1995).

Hoofdstuk 4 en 5 beschrijven de aanbod-dynamiek van vloeibare en gasvormige brandstoffen, in de Vloeibare Brandstoffen (LF) en Gasvormige Brandstoffen (GF) modellen. In beide modellen zijn de belangrijkste factoren het optreden van leereffecten hetgeen de kapitaals-intensiteit verlaagt, en uitputting waardoor deze verhouding stijgt. Het feitelijke ontwikkelingspad van deze verhouding wordt sterk beïnvloed door de gehanteerde veronderstellingen over de lange-termijn aanbodcurve van [conventionele] olie en [aard]gas. Als de productiekosten van olie en gas stijgen, wordt de markt gepenetreerd door een op biomassa gebaseerd alternatief. Ook hiervoor gelden de krachten van leren-door-te-doen en uitputting, die tezamen de ontwikkeling van de specifieke opbrengst bepalen en daarmee de kosten en de snelheid waarmee de markt wordt gepenetreerd. Andere mogelijkheden voor de voorziening van vloeibare en gasvormige brandstoffen, zoals op electriciteit gebaseerde waterstof en de liquefactie/vergassing van steenkool worden nog niet in beschouwing genomen.

Hoofdstuk 6 documenteert het Vaste Brandstoffen (SF) model. Hierin wordt de productie van steenkool in ondergrondse en dagbouwmijnen in antwoord op de vraag naar vaste brandstoffen gesimuleerd. Vaste brandstoffen zijn in dit verband het aggregaat van anthraciet, [sub]bitumineuze kolen en cokeskolen en bruinkool. De kern van de dynamiek in dit model is dat enerzijds de kosten van ondergronds gewonnen steenkool stijgen door uitputting hetgeen slechts ten dele teniet wordt gedaan door kapitaal-arbeid substitutie, terwijl anderzijds de kosten van steenkool uit dagbouwmijnen blijven dalen door schaalvoordelen en innovaties hetgeen het marktaandeel ervan doet toenemen. Het feitelijke productiepad wordt, net als bij olie en gas, sterk bepaald door de veronderstellingen over de eigenschappen van de steenkoolreserves op aarde.

Hoofdstuk 7 geeft een beschrijving van het Electriciteits-Opwekking (EPG) model. Hierin wordt de vraag naar electriciteit omgezet in vereist geïnstalleerd vermogen, uitgesplitst naar basislast en pieklast, hetgeen leidt tot investeringen in waterkracht, brandstofgestookte thermische centrales danwel een niet-thermisch alternatief dat is gebaseerd op nucleaire of stromingsbronnen. Het meest belangrijke kenmerk van dit model is dat het de marktpenetratie van een, niet nader gespecificeerd, niet-thermisch alternatief simuleert zodra de prijzen van fossiele brandstoffen beginnen te stijgen en de ruimte voor verdere uitbouw van waterkracht kleiner wordt.

De appendices, tot slot, bevatten enkele methodologische punten en geven een lijst van de modelvariabelen en van de voor de calibratie gebruikte gegevens.

ACKNOWLEDGEMENT

The research for this work has been done within the Global Dynamics & Sustainable Development group at the dutch National Institute for Public Health and the Environment (RIVM). This group of between 5 and 15 people has worked hard in the past three years, under the autocratic but motivating leadership of Jan Rotmans, to produce a sequel to the first generation of 'world models' of which the World3-model to the Club of Rome has been the most widely discussed and controversial one (Meadows et al. 1973, 1991). Despite the many shortcomings of the World3-model, we owe a lot to it both as an example and a warning. As the main author of the models presented here, I (BdV) would also like to thank the members of the Balaton Group which have been a constant source of inspiration in the background.

Several parts of the energy models presented here rely on previous work done in the field of systems dynamics. We are especially indebted to the modelling work done by John Sterman, Roger Naill and Paul Davidsen. Of course, many other people have directly and indirectly contributed to the the intellectual contents of this energy model. We are especially grateful to Thomas Fiddaman who helped formulate the first model versions during a three-month stay at RIVM in 1992.

Within RIVM we would like to give special thanks to the members of the Global Dynamics & Sustainable Development group and to the members of the Image-team. Several members of the Image-team, notably Johannes Bollen, Jos Olivier and Sander Toet, have in varous stages of the work helped to work out the ideas and their implementation. Indeed, the project leader Joe Alcamo kept - and keeps - struggling to make sure that the team is not overwhelmed by NIBI's (Non Implementable Brilliant Ideas). The members of the Global Dynamics & Sustainable Development group have been a source of inspiration, too. Special thanks go to Marco Janssen for his translation of the present Stella-based model version in the new simulation environment 'M' - the results of which are presented in a separate report, and for the promise which his innovative optimisation work holds for future application of the energy model. We are also grateful to Bart Strengers for his scrupulous reading of what we mistakenly thought to be the final text.

We sincerely hope that this integrated long-term energy model will contribute, as a tool, to the ongoing debate on possible energy futures and to the assessment of [in]consistencies and assumptions in a variety of past and future energy scenario's. The wider contribution would then, hopefully, be that the world community is able to take timely and intelligent action in the face of the risk of climate change due to the enhanced greenhouse-effect.

1. GENERAL INTRODUCTION

The Economy-Energy-Minerals (EEM) models are part of the TARGETS1.0 model. The Economy model (Ch. 2) is basically a driver. The Energy models contain five submodels (Ch. 3-7). The Minerals model is described elsewhere.

1.1 The Economy-Energy Minerals (EEM) models

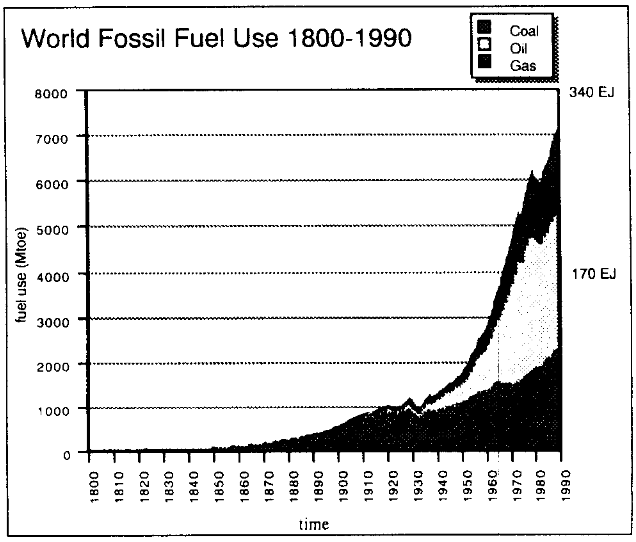
The human world system as it has developed over the past centuries requires a constant flow of processed fuels and materials. Until some 200 years ago energy needs were largely met from renewable fluxes like water and biomass. Since then it has increasingly been derived from fossil fuels - coal, oil and gas. To be useful these fuels have to be found - exploration, produced - exploitation, and processed and converted to heat : transport, refining, distribution, combustion. For all these steps production factors are required : capital, labour, land, as well as operational energy and material inputs. Waste flows accompany all three steps, the largest one being the emission of carbon dioxide (CO_2) during combustion. Material inputs have been supplied from renewable sources for a long time, too, the most important flows being related to food provision. Yet, exploration, exploitation and processing of non-renewable mineral deposits for the production of iron, copper, silver, salt and various building materials have a long history. In the last few centuries these mineral flows have increased enormously, and so have the concomitant flows of capital, labour, energy, land and waste. *Figure 1.1* shows the annual use of fossil fuels in million tons of oil equivalents. In mass terms only the flows of iron ore - which are strongly related to coal - and possibly sand/stone are of similar magnitude. Total sales of commercial fuels are in the order of 1.5 % of Gross World Product. It is seen from this graph that first oil and then natural gas have complemented coal. On top of this but not shown are the flows of renewable energy sources, of which hydropower and traditional biomass are the most important ones, and nuclear energy. Even today, the share of traditional biomass is in the order of 55 EJ/yr, i.e. about 13% of world energy use (Hall and House 1994).

The EEM-submodels figure as part of the TARGETS 1.0 model. *Figure 1.2* gives a Causal Loop Diagram (CLD) of part of the TARGETS model. A plus-sign indicates a positive, reinforcing feedback loop; a minus-sign indicates a negative, stabilizing feedback loop. The two major positive feedback loops relate to population and industrial capital. The rates determining these two levels are influenced by a variety of factors a.o. the availability of food, water and health services for population and the investments, average lifetime and productivity for industrial capital. Within the larger framework of TARGETS 1.0 the Economy model serves to simulate a simple one-factor production process the output of which is allocated among the demand for [investment and consumption] goods from other models.

The Energy and Minerals models are basically calculating the demand for commercial fuels, electricity and minerals from economic activity levels, and the required investments to supply them. More specifically :

- calculation of the demand for fuels-for-heat, electricity and metals on the basis of driving forces related to variables in the Economy-

Figure 1.1: Use of fossil fuels in the world, 1800-1990 (Klein Goldewijk and Battjes 1995)



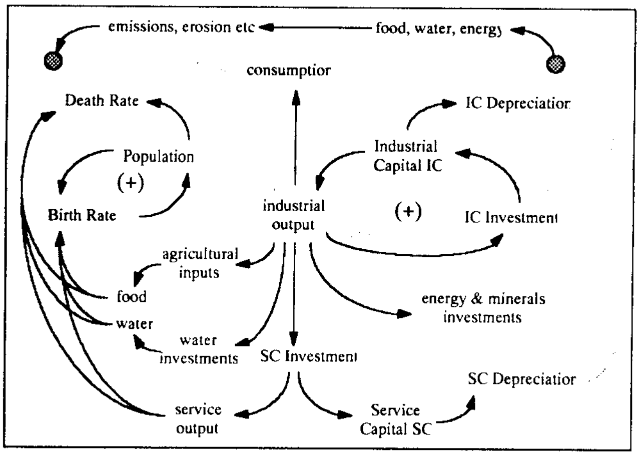


Figure 1.2: TARGETS 1.0 Causal Loop Diagram(IC Industrial Capital, SC Service Capital

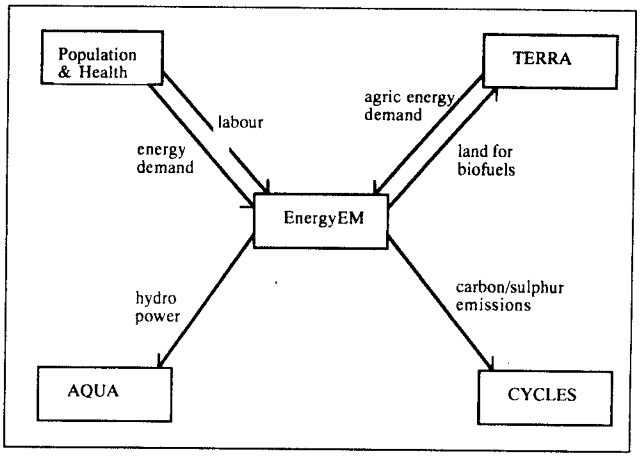


Figure 1.3: Positioning of EEM-model within the integrated TARGETS 1.0 model. Only interactions of the EEM-model are shown

model, and of the supply of solid, liquid and gaseous fuels and metals in response to demand from the Energy Demand and Electric Power Generation models; and

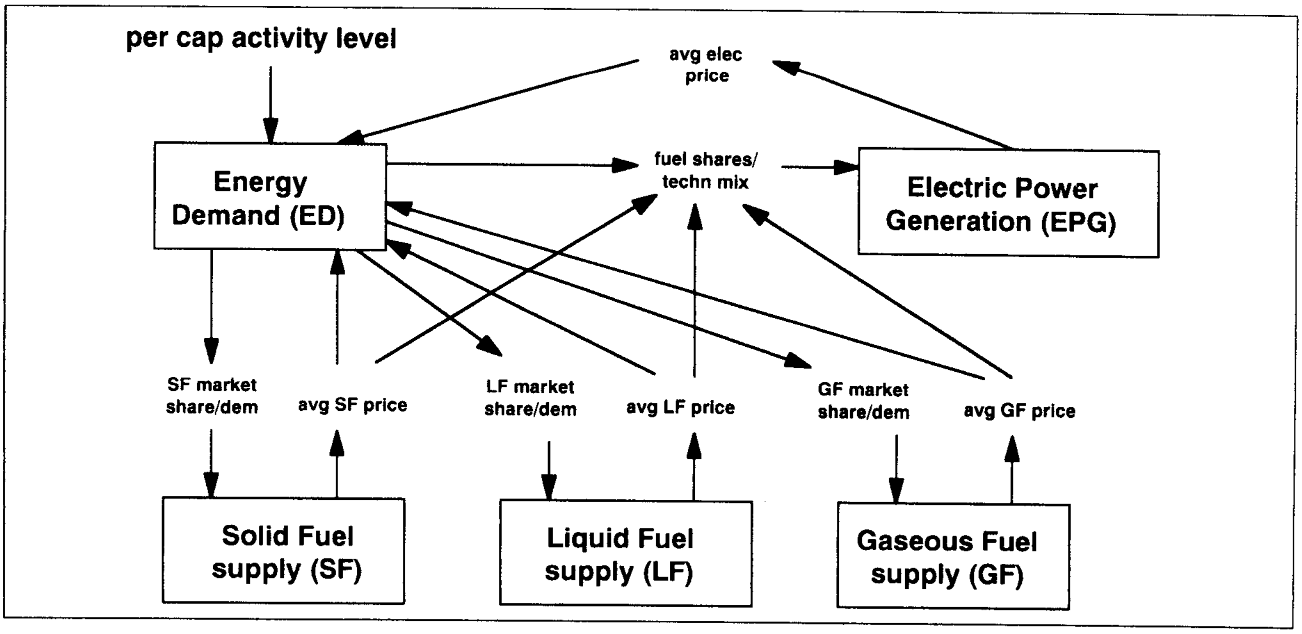
- calculation of the required inputs of industrial investment goods ("capital"), labour and land to generate these supplies and of the corresponding conversion losses and emission of carbon dioxide, methane and mining waste.

Figure 1.3 indicates the Energy model within the TARGETS-framework. Chapter 2 discusses the Economy model in seperation. In the remainder of this report, we confine ourselves to the five energy submodels, henceforth called the Targets/IMage Energy or TIME-model. The Energy submodels are, with their major interrelationship, depicted in *Figure 1.4*.

During the construction of the various models, we have been guided by the following objectives :

- the models should adequately simulate the long-term dynamics, i.e. 1900-1990, of exploration, exploitation and recycling processes within the fuel and minerals sectors;
- the degree of adequacy has to be established on the basis of historical time-series within at least one world region, henceforth referred to as [dynamic] calibration or [structural] validation;
- they should allow for the simulation of the pene-

Figure 1.4: The five submodels within the Targets/ IMage1.0-Energy (TIME-model)



tration in the long term, i.e. 1990-2100, of at least one alternative fuel c.q. electric power generation option with distinctly different characteristics; and
- fuel and metal prices, derived from capital and labour costs, should function within the models as signals for investment actions to expand supply and/or reduce demand.

These considerations, in combination with the available model descriptions in the literature and the desire for transparancy and a manageable degree of interactiveness, have shaped the present model versions. We have also endeavoured to focus on model variables and relationships which are meaningful in a global model with high aggregation levels.

The major issues to be dealt with in the TIME-models are the following :
- to what extent and under which conditions can the growth of industrial output satisfy the demand for investments in the provision of energy and minerals ?
- how do assumptions on the resource base and the technology to exploit them influence cost developments and, thus, over-all efficiency of use ?
- what are the trade-offs between depletion of finite fossil fuel and mineral resources on the one hand and new technologies with their requirements for capital, labour and land on the other hand ?
- what is the relation between resource use and the accumulation of natural sinks with substances like CO_2, CH_4 and SO_2 ?

One way to summarize the issue about energy and minerals is : how does the energy transition, from fossil carbon to renewable non-carbon fuels, look for different population and economic trajectories and which resource depletion and emission pathways go with it ?

Evidently, there are many deficiencies, omissions and potential refinements in the EEM-models, partly a consequence of the very attempt to construct a generic model from regional/local scale-level to be applied at global-scale level. Some deficiencies and omissions are not relevant because they are assumed not to affect the over-all long-term system behaviour. For example, the aggregation of various solid fuels into a single one with fixed characteristics. Others may be relevant but are part of avenues which have not been explored yet. For example, the price-driven investment behaviour within the oil and coal sector may be adequate for the USA but fail to capture crucial dynamic factors within regions like CIS and China. Using such behaviour at the aggregate global level may be erroneous - in ways which are not easy to foretell.

Table 1.1: EEM-model items and their respective time-scales

Time: short <5 yr	medium 5-25 yr	long >25 yr
price formation	investment dynamics energy supply	depletion & learning dynamics (COR)
demand [anticipation]	resource base evaluation (RPR)	penetration of new supply technologies
retrofit conservation investments	end-use cost based fuel substitution	structural change within economy & sectors
solid waste	effects of acidifying emissions	effects of greenhouse-gas emissions

Of the items which are not included in the various models and therefore restrict their domain of applicability and their capability for long-term explorations, we mention the following ones :
- traditional fuels and the use of fossil fuels and biofuels as feedstocks are not considered; calibration for the period 1900-1990 has been based on historical use of commercial fuels excluding use for feedstocks;
- there is no linkage in the model between demand for electricity and demand for other energy forms (heat); this is important in e.g. electric heating and electric vehicles;
- there are no capital, labour and land markets in the models; prices and revenues are calculated to direct investments but without tracing the corresponding money flows; interest rates are exogenous; labour costs for some energy supply systems are simply related to a proxy for Gross World Production (GWP);
- the economy has been modelled in an extremely simple fashion, with desired industrial output growth generating investments and consumption treated as a remainder; no statements are possible about the causes, dynamics and differentiation behind such economic growth;
- there is no government actor in the models; therefore, taxes, subsidies and R&D-expenditures do influence autonomous market-driven processes but are not accounted for in money terms;

As such the model is best seen as a complement to macro-economic models used in the climate change discussion.

1.2 Modelling : conceptual issues

There are a few issues in the background of our modelling efforts which need discussion. They relate to scale, aggregation, complexity and decision support (see also Rotmans et al. 1994). More specifically, they have to do with :

- spatial and temporal scales and [dis]aggregation;
- the systems dynamics modelling approach;
- actor-oriented modelling with explicit behavioural rules; and
- the micro- and macro-dynamics of the Pressure-State-Impact-Response (PSIR) cycle.

In this paragraph we briefly indicate these issues; Appendix B-C give a more elaborate discussion.

With regard to the *spatial and temporal scales*, it is important to distinguish between global, regional and local scale and short, medium and long term. *Table 1.1* indicates the most important model elements within the EEM-submodels in terms of time scales. Although TARGETS 1.0 is for the world at large, most conceptual items in the submodels stem from regional/local experiences - in that sense these models are considered to be generic. Calibration has been and is being done at the regional scale (USA, India, China, CIS).

The *modelling methodology* is largely based on systems dynamics [Forrester 1961, 1971; Sterman 1981]. It is a non-equilibrium approach in which producing capital stocks are based on past investment decisions which in their turn were based on anticipated demand and price developments. In the heat and electricity demand markets and in the penetration of new technologies, a price-based multinomial logit approach has been used. Technological developments are partly endogenous in the form of loglinear learning relations. Some of the generic structures are discussed in Appendix A.

The EEM-submodels attempt to represent human behaviour explicitly. This can be structured with help of a three-layered approach (cf. Appendix B).

Table 1.2 EEM-model : state variables, driving forces and signifiers

State variable	Driving force	Signifier
industrial capital	desired Industrial Output	[exogenous]
service capital	[indicated] Service Output per caput	Industrial Output per caput [required] health services
consumption	desired Consumption per caput	[exogenous]
energy demand	meet required heat&elec supply minimize end-use energy costs	economic activity levels conservation options [desired] payback-time [relative] commercial fuel prices
oil/gas supply capital	meet [anticipated] demand meet desired profit rate	[anticipated] market price R&D-efforts biofuels learning-by-doing rate biofuels
coal supply capital	meet [anticipated] demand meet desired return on investment	[relative] costs undergr/surf coal
electricity supply capital	meet [anticipated] demand	capital availability [exogenous] hydropower R&D-efforts NonThermalE learning-by-doing NonThermalE
minerals supply capital	meet [anticipated] demand meet desired return on investment	industrial activity level [anticipated] market price

At each of the three levels there are different degrees of know-ability and manage-ability, as well as different degrees of actor degrees of freedom and behavioural complexity. Presently this approach is explored with a simple simulation game, SusClime (Vries 1995). Within the EEM-submodel documentation the three levels show up in the ways of model representation. Apart from submodel representation in the form of Causal Loop Diagrams (CLD), we use two other representations :

- the info-level representation shows the physical stocks and flows in a [sub]model : the first level, and the overlay structure which represents the behavioural rules of the important actors : the second level;
- the interactive representation shows how the [sub]model is related to other models at the first and second level, but also which decision levers and key assumptions the model user is confronted with : the third level.

The three-level approach can also serve as a principle in desaggregating TARGETS : one or more regions can be modelled at the regional level with more detail while the rest of the world is only dealt with at the physical level, i.e. energy and material accounting and conservation. Only later on, the more complex interactions between regions at the higher levels are taken into account. Within the present EEM-submodels we have not yet introduced generic decision rules for actors with different degrees of intelligence and different perspectives. This is, however, one of the research items within the GD&SD-group (cf. Asselt and Rotmans 1995).

Finally, the so-called *Pressure State Impact Response or PSIR* approach is chosen as the organizing framework for TARGETS 1.0 (cf. Swart and Bakkes 1995). The background for this is the Pressure-State-Response distinction made by the OECD in designing indicators for sustainable development. It is important to distinguish between the micro-level and the macro-level. Most of the dynamics in the [human] world can be understood as the result from a discrepancy between a desired state and the state as perceived by individual actors on the basis of information available to them. The discrepancy generates driving forces which result in pressures in the PSIR-framework. Some of these are corrective actions on the basis of [anticipated] [perceived] impacts, i.e. they are part of the response. In as far as human perceptions and desires cluster into more aggregate organisational structures, macro-dynamics emerges. Policy-oriented research is usually focused on this level. A more detailed discussion is given in Appendix C.

The relevance of this for the present modelling effort is illustrated with *Table 1.2.* It lists the most important state variables within the EEM-model, and the underlying driving forces and informational variables ('signifiers') which are most crucial within the model.

1.3 Outline of this report

The present report documents in detail the five submodels on energy demand and energy supply. It also includes a brief description of the Economy submodel. The two minerals submodels and the integrated assessment of various exogenous global long-term energy scenario's will be presented in separate reports.

In the remainder of this report, we start with a brief description of the Economy model (Chapter 2). Its main function is to allow for the allocation of industrial output. In the future we hope to replace this simple model with a more refined, regionalized macro-economic model which takes labour and trade explicitly into account. The next chapter describes the Energy Demand (ED) model which is identical to the energy demand model within the IMAGE 2.0 model (cf. Alcamo et al. 1994, Bollen et al. 1995). Its function is to convert a set of [economic] activity levels into the demand for electricity and secondary fuels. In Chapter 4 the Liquid Fuel (LF) model is documented in considerable detail. It generates, in response to [anticipated] demand for liquid fuels, the exploration for and exploitation of oil deposits and the introduction of biomass-based liquid fuels. Required investment flows, corresponding carbon-dioxide and methane emissions and land requirements are calculated. The next chapter describes the Gaseous Fuel (GF) model which is almost identical to the LF-model. Chapter 6 documents the Solid Fuel (SF) model which simulates the production of coal in underground and surface mines on the basis of anticipated demand. Here, too, investment flows and emissions are calculated. Finally, the Electric Power Generation (EPG) model is dealt with in Chapter 7. It describes in rather much detail the separation in base and peak demand and the subsequent generation of electricity with thermal, i.e. fossil-fuel and biomass fired, non-thermal, i.e. nuclear and/or solar, and hydropower. Required investments are calculated. The Minerals (M) model is documented in a separate report.

2. THE ECONOMY SUBMODEL

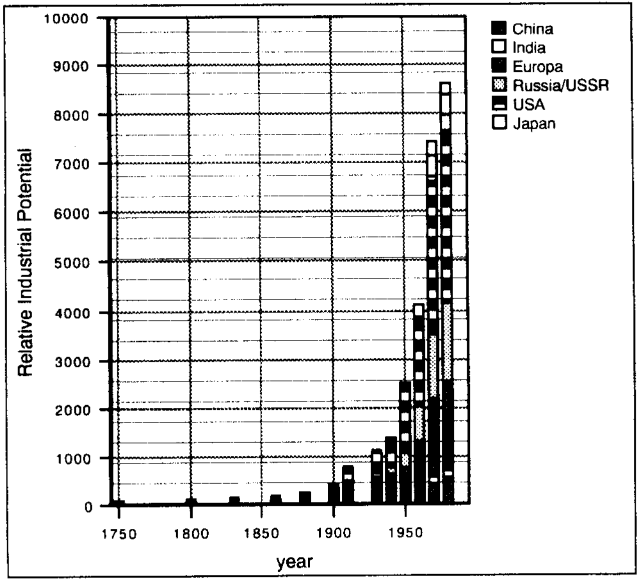
This submodel describes the calculation of industrial and service capital stocks and their output . This depends on the allocation of industrial output among consumption and investments in industry and services, which is exogenously done. Required investments for agriculture, energy and water are substracted first as they are assumed to be satisfied fully.

2.1 Introduction

No doubt, economic activity levels are with population size the most important driving force behind the derived demands for energy, minerals, transport and water. *Figure 2.1* gives a picture of the enormous expansion of industrial production in the last 200 years. The Industrial Revolution was accompanied by an enormous migration of people from rural areas to urban areas which in its turn was made possible by an increase of agricultural productivity. Mechanisation of agricultural activities but to a much larger extent the emergence of industrial manufacturing has led to an enormous increase in the use of fuels, electricity and minerals.

The first waves of industrialisation had their characteristic processes and products, like coal mining and steam engines, the expansion of canals and later railways, the introduction of electric power and internal combustion engines etc. The latest wave, by some authors interpreted within the theoretical framework of Kondratiev waves (see e.g. Sterman 1992, Grübler and Nowotny 1990), is characterized by a decline in energy- and material-intensities. Apart from technological developments like the emergence of new materials, miniaturization, 'economies of scope' etc., the changing character of people's activities both as producer and as consumer plays a role. Ayres (1987) has argued that increasingly the informational content is the major component of value added, and that this is at the basis of the declining energy-intensity in advanced economies[1]. Similarly, Grübler and Nowotny (1990) show that the freight-transport-intensiveness in GJ/$ in advanced economies is no longer increasing "which stems from the gradual transition in the output mix of these economies in the direction of information- and value-intensive, but material-extensive, products and the availability of higher-quality and lighter substitutes in the form of advanced materials" (op. cit. pp. 450). This change is closely related to what has been called the transition to the service-economy, the coming of the information-age etc. Whatever the names given, there is no doubt that the industrialized nations are experiencing profound changes in their economies and that technological change is, again, one of the major propellants. Any meaningful discussion of future trends requires a more in-depth understanding of technological dynamics. Among the useful concepts are logistic substitution dynamics (see e.g. Marchetti 1995), the product life cycle, and technological breakthroughs as a function of [cumulative] R&D-efforts (Ayres 1987).

Figure 2.1: Industrial production capacity, world regions 1750-1980



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

However, the picture is at least as complex with regards to the developing countries. Many of them are experiencing an industrialization process which in some respects is similar to the earlier one in Europe and North-America : surplus labour from rural areas is attracted by urban jobs in the growing industrial sector. There are also important differences, among them that much of the capital and the knowledge incorporated in it is provided by multinational companies which have their centre in the advanced economies. An interesting question is whether this enables these economies to jump over the energy- and materials-intensive stage straight into the new era of high-tech and high-info. Grübler and Nowotny (1990) argue against the postulate of global convergence along historical development trajectories, pointing out that late-comers have catching-up possibilities and that countries are heterogenous with regard to process and product saturation levels. This argument clearly makes sense for much of manufacturing. It may also be valid inasfar as transport infrastructure is concerned : canals and railways may never reach the densities they reached in Europe because the automobile-road system is a preferred alternative in most industrializing countries. However, it is not obvious that this is a less energy- and material-intensive development pattern than Europe's historical trajectory. It is equally hard to anticipate whether major construction works for dwellings and offices and major consumption trends following North-Americal life-style patterns will affect energy- and material-intensities negatively or positively. Recent research in The Netherlands, for example, did not find evidence that intersectoral shifts in consumption expenditures have led to a declining energy-intensity between 1950 and 1990 (Blok and Vringer 1995). One wonders what changes in consumption patterns are needed and plausible to make the consumer expenditures in industrializing regions of the world less energy-intensive.

In the present TARGETS1.0 version, there is no macro-economic model as such. The basic structure is one which has been derived from the World3-model (Meadows et al. 1974). It has two producing capital stocks : industrial and service capital, both with a fixed capital-output ratio. Industrial capital produces goods which are allocated according to a simple set of rules among investments (for industry, services, agriculture, energy, water) and consumption. Important and interesting aspects like relative factor prices and substitution, innovation dynamics and Kondratiev waves, technology transfer and the transition to an information-based economy are not captured in the model.

Because the present TARGETS-version is implemented for the world as a single aggregate, many of these aspects cannot meaningfully be dealt with at this level of aggregation. We rely on economic projections made by other researchers and institutions for the key driving forces. We have chosen this approach due to lack of time and in an attempt to avoid duplicating work done by others. Another reason is that economic modelling is presently experiencing a period of serious controversies. Consequently, it is in no way evident which of the various concurrent [macro-economic] concepts, theories and models are most appropriate in the present context. The discomfort with parts of economic theory is even growing to the extent that one has to consider completely novel approaches.

It is our intention to improve the present version in due course, with the help of one or more of the research groups who are presently involved in regional macro-economic modelling (Duchin and Lang 1995; Geurts and Timmer 1993). These efforts will be coordinated with the ongoing work at RIVM and CPB to link the IMAGE- and the Worldscan-model (Gerlagh et al. 1995).

2.2 Submodel representation

The [world] economy is thought to consists of an aggregate capital stock which produces industrial output. This excludes agricultural, minerals and energy production and service output. It includes the large spectre of products within what is called 'manufacturing' : fertilizers, machinery, buildings, cars, household appliances etc. This aggregate is then each year allocated among durable goods, non-durable goods and re-investments into the industrial capital stock (cf. *Figure 2.2*).

2.3 Submodel description

The relationships between the various sectors can be phrased in terms of an input-output matrix. This is done in *Figure 2.3*. It is seen that the manufacturing sector ('industry') provides the capital goods ('investments') for the six sectors plus final demand. The latter, called consumption, absorbs all industrial output which is left over after the investments are allocated according to some set of rules. It includes consumption goods with short and long lifetimes : cars, dwellings, household appliances etc.

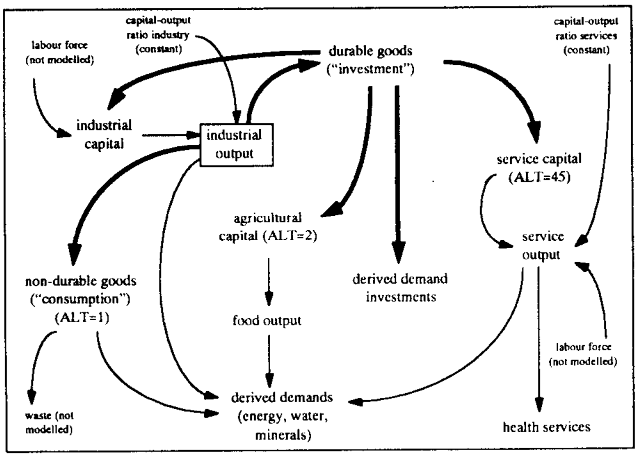

Figure 2.2: Flow of industrial output through the economic system (ALT= Average Life Time)

The service sector delivers all its output for consumption. In the economy model these final demand deliveries have no consequences. However, the level of consumer goods and service output per caput are important drivers in other submodels.

Each of the six sectors has a demand for capital goods : machinery and fertilizers, oil and gas rigs, coal mining machinery, water supply equipment, minerals mining and processing machinery etc. The demand for these capital goods is based on the anticipated demand for the required output from these sectors. These outputs, measured in physical units, are the inputs for the manufacturing and services sector, for agriculture and for operating the consumer capital stocks c.q. goods. In fact, the submodels described in the remainder of this report, are fairly elaborate descriptions of how the technical input-output coefficients change over time. Labour requirements are only specified for three activities : underground coal mining, liquid biofuels and gaseous biofuels. The reason is that for these activities, the labour inputs are considered to be important cost determinants. Labour costs are approximated by expressing them as fixed fractions of per caput consumption. In all three cases, labour is presumed to be substituted for by capital.

It is clear that for the manufacturing, services and agricultural sector, labour requirements and costs are extremely important. However, we have not attempted to incorporate these dynamics in the present model version. This is consistent with the over-all aim of providing only a consistent and transparant allocation mechanism as a driving force for the demand and supply to and from the other sectors.

The major objective, then, is to have a transparant structure which satisfies the following requirements :

- direct economic activity levels i.e. industrial production, service sector output and consumption, according to some exogenous trajectories;
- account for the depreciation of the major producing capital stocks i.e. industrial and service sector; and
- allow for experiments with simple allocation algorithms and productivity developments.

Figure 2.3: Input-output representation of the Economy submodel

	Industry	**Services**	**Agriculture**	**Energy**	**Water**	**Minerals**	**Consumption**
Industry **Services**	**InvInd**	**InvServ**	**InvAgr**	**InvEn**	**InvWat**	**InvMin**	**ConsGoods** **ServOutput**
Agriculture							**FoodOutput**
Energy **Water** **Minerals**	fuel/elec water minerals	fuel/elec	water			fuel/elec	fuel/elec water
Capital **Labour**	● ○	● ○	● ○	●	●	●	**GWP**

● put equal to investments, cost accounting through annuitization,

○ important but not accounted for in costs, assumed to be available and used

The Economy submodel does **not** include a labour market, a capital market, trade or explicit treatment of labour-capital substitution and productivity change processes. The absence of an explicit link between economic performance and labour may be a serious omission. It also does not allow for an adequate link between labour productivity c.q. income and the costs of labour-intensive fuels like underground coal or biofuels. The absence of capital markets implies a fixed, though sector-dependent interest rate which obscures the important allocation dynamics of investments in various subsectors.

From the point of view of economic theory, major omissions in this approach are

- the lack of endogenous production factor substitution for the manufacturing and services sector;
- the absence of a relationship between the manufacturing and service sectors and consumption in the form of intermediary deliveries c.q. final demand;

2.4 Submodel calibration

Because the Economy model serves as a driver of activities and a generator of investment goods and services, calibration is confined to such an allocation of industrial output that the historical 1900-1990 values for Gross World Product (GWP) are reproduced. Food output, in physical terms, has been calibrated separately. Consumption is based on a historical time-series. The savings rate, i.e. the amount of industrial output re-invested in industrial capital, is adjusted in such a way that historical trajectories for value added in industry and services are matched. Then, investments required to satisfy food, water, energy and minerals demand are taken out of industrial output. It is our intention to experiment with different allocation rules, taking into account the long-term economic scenario's made by other researchers and institutions.

The relevance of the allocation of economic output among the various sectors within TARGETS1.0 is evident. If, for example, there is an exogenously forced consumption-per-caput trajectory, there will be a constraint on the industrial output available for investments. If the GWP-trajectory is fixed, too, the allocation of a potential shortage applies to agriculture, services, water and energy. For most submodels, the response to insufficient investment goods is not yet analysed. The allocation also affects energy demand because sectoral per caput output levels are used as driving forces.

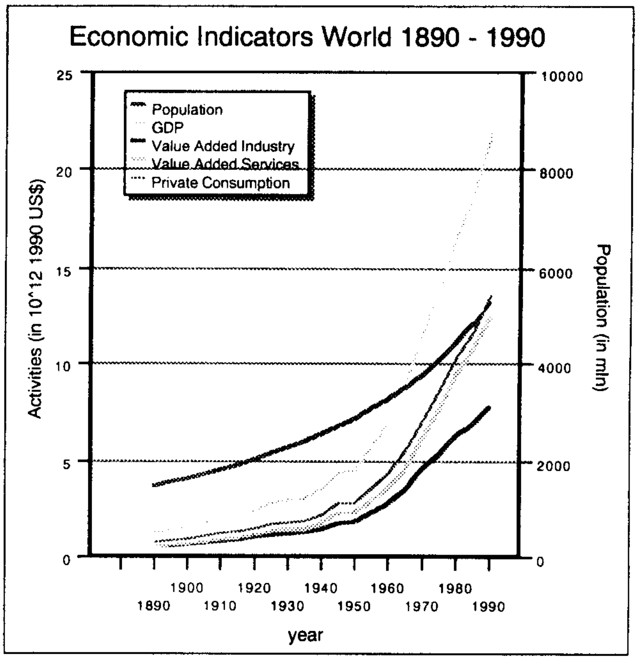

Figure 2.4: Exogenous GWP- and VA-series and population used for model calibration, world 1890-1990 (Klein Goldewijk and Battjes 1995)

For the simulation in the present report, we have not used the economy-model. Instead, we have taken historical GWP and Value Added (VA) in Industry and in Services as exogenous inputs. *Figure 2.4* shows the exogenous GWP-, VA- and Private Consumption series which have been used to calibrate the model. For scenarios these series are extended into the future according to some external scenarios and assumptions about population, about the share of VA of Industry and Services in total GWP and about the ratio of VA Industry and VA Industry plus Services. The latter assumption represents a possible change towards a [information-oriented] service-economy; the former reflects a further relative decline of agricultural output and population .

2.5 Future work : interactions and investment allocation

Whatever the economy model used, there are some important issues with regard to the interactions between the economy and what is simulated in the other submodels. In principle, one can distinguish three levels :

- direct inputs of [investment] goods

In the various TARGETS-submodels (cf. Figure 1.3) there is a need for [investment] goods to deliver what is demanded : fertilizer, farm machinery, water

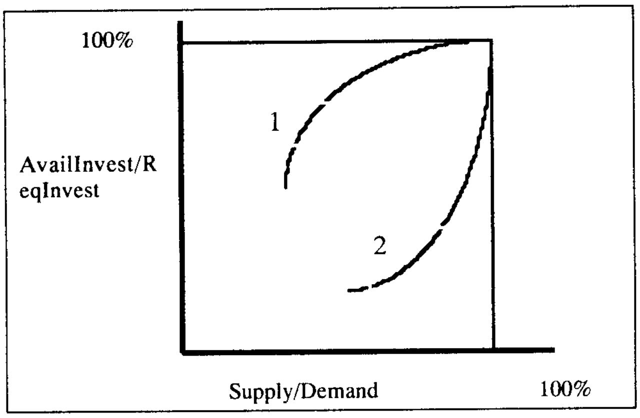

Figure 2.5: Possible input-output response relations

supply systems, hospitals etc. Those developments which can be judged as negative externalities and are expressed within the submodels in money terms, are accounted for because the means to counteract them are part of the [investment] demands from the economy[2] .

- mismatch in demand-supply of [investment] goods

The second interaction occurs when there is a discrepancy between the demand for and the supply of [investment] goods within one or more subsectors. Usually, macro-economic models responds with changes in interest rates and the like. We intend to use a few simple rules according to which the economic [industrial] output is allocated among the various subsectors. Depending on these rules, there may be shortages in one or more of the subsectors. If this happens, we explore the system's dynamic behaviour with response curves of the form shown in *Figure 2.5*. Curve 1 is an example of a strong response : some 25% less inputs causes a reduction in output with 50%. Curve 2 is a weak response : the first 25% shortage give only 10% less output.

An analysis of these response curves is also important in an attempt to introduce cultural perspectives into the model experiments because they are a reflection of the way in which societies respond to [capital] shortages. Shortage of [investment] goods affects subsector performance in quite different ways. It is known that electricity shortages are seriously thwarting economic growth in countries like India and China. Lack of investments for water supply have an impact on expansion of irrigation, and hence on food production, and on sanitation, and hence on health and mortality. A complicated intermediary interaction is through the productivity of labour, which is assumedly influenced by factors like literacy rate, health level and food availability.

- environmental factors

Through the calculated changes in climate-related variables like [average] surface temperature and precipitation, the dynamics of all subsectors will be affected. This shows up in the model only to the extent that additional [investment] goods are required to counteract or adapt to these changes or in the ways in which the various subsectors respond by changes in their demand for [investment] goods. However, many possible impacts on the functioning of subsectors are not explicitly, in monetary terms, included in the models. Consequently, at this third level there are consequences which are not accounted for in the TARGETS1.0-simulations. One can think of the impact of changing temperature/humidity on mortality rates, e.g. through changing disease exposure, on increased storm and flooding frequencies which affect availability of arable land etc. In the future, such impacts can be incorporated by translating the response to such changes in monetary terms which are then channeled into the economic sector.

The relevance of the second and third level can be judged from the fact that the various subsectors within TARGETS1.0 (food, water, energy) account for 10-20% of the total activities in the world economy as measured by GWP. In the future this fraction may increase (due to e.g. more medical services or expenditures for energy) or decrease (due to e.g. agricultural intensificaton). To put it the other way around : the larger fraction, up to 80%, of "commercial" monetarized and officially measured human activities take place in the crudely modelled economy sector and the various subsectors generate the derived demands (for health, food, water, energy etc.). As a result, every feedback to the productivity with which people produce goods (in the industry sector) and services (in the public and private service sector) have immediate and large consequences for the over-all behaviour of the system. Such feedbacks are not [yet] incorporated in TARGETS1.0.

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[2] As has been said before, most submodels do not formulate a demand for labour and in the default allocation mechanism consumption is considered as a "left-over" with no further interactions or consequences.

3. THE ENERGY DEMAND (ED) SUBMODEL

This submodel describes the calculation of the demand for solid, liquid and gaseous fuels and electricity for five sectors in the economy. Each sector has an activity which drives energy demand, an autonomous and a price-induced energy productivity increase, and a price-based allocation of secondary fuels.

3.1 Introduction

The demand for energy is modelled according to insights and methods which have been developed over the last decades throughout the world (see e.g. Schipper and Meyers 1992, Johansson et al. 1989, Vries et al. 1981). The main elements of this submodel have been developed first as part of the ESCAPE-project, then the IMAGE 2.0 project and, in its present form, the IMAGE 2.1 project. For more detailed descriptions of earlier and present versions, we refer to Vries et al. (1994), Toet et al. (1994) and Bollen et al. (1995). In this report we give an overview of the model and the calibration exercises for the world 1900-1990.

The ED-model incorporates a few issues which have gained acceptance among most of the energy-economy researchers. First, the demand for useful (or end-use) energy per unit of activity (e.g. value-added) tends to increase in the first stages of [economic] development after which it tends to decrease. It reflects the relatively large energy-intensiveness of basic materials processing. Due to differences a.o. in development stages and due to regional interactions, different parts of the world may show this bell-shaped trend in widely diverging forms (see e.g. Sassin 1980, Le Bel 1982). Secondly, energy productivity, i.e. the process output per unit of energy input, has an autonomous growth which can only be understood in the context of mostly qualitative and speculative theories of long-term technology and economy dynamics (see e.g. Clark and Juma 1986, Sterman 1981). As we have not included such theories, we have introduced such an autonomous energy productivity growth as exogenous. Thirdly, it is widely acknowledged that energy prices have an impact on the efficiency of energy use and thus on energy intensity. The actual response is difficult to measure and differs for different sectors. Because energy is partly a complement to capital and a substitute for labour, relative factor prices may actually be the relevant variable. In the ED-model we have opted for an approach intermediate between the bottom-up engineering analyses and the top-down macro-economic approach. It is based on an energy conservation supply cost curve which represents the costs and effectiveness of energy conservation options. This curve is itself dynamic; in combination with a return-on-investment criterium the degree to which energy efficiency investments are made is determined from this curve.

3.2 Submodel representation

An overview of the Energy Demand model is given in *Figure 3.1*. It shows how exogenous time-series for activity lead to demand for end-use heat and electricity. Energy-intensity may decline (as shown in Figure 3.1) or first rise and then decline; depending on the stage of economic development. Due to technological and price-induced energy efficiency improvement, the actual demand is lower. The difference between postulated end-use demand (a virtual quantity) and calculated end-use demand reflects autonomous and price-induced efficiency improvements. Heat demand for five sectors is satisfied by a price-determined mixture of solid, liquid and gaseous fuels. Electricity demand is aggregated for all sectors and is met by electric power generation as described in the EPG-submodel. *Figure 3.1* is the description as used for the IMAGE 2.1 model. *Figure 3.2* gives the interactive representation of the ED-model.

3.3 Submodel description

3.3.1 Structural change

Demand for energy is calculated from the activity levels of three sectors : industrial (or manufacturing), commercial (or services) and residential (or

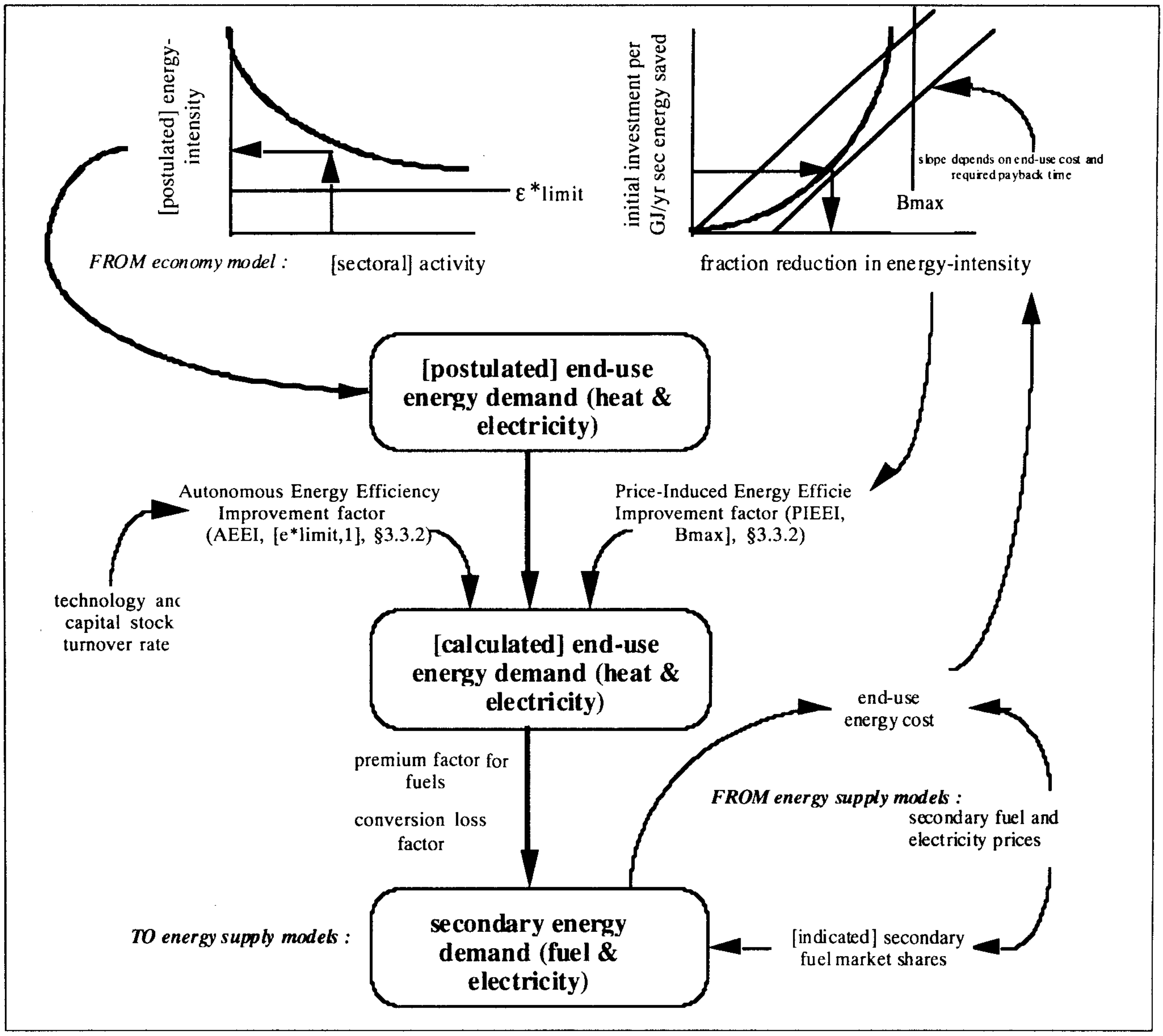

Figure 3.1: Overview of the dynamics in the Energy Demand submodel in one of the five sectors (Bollen et al 1995)

consumption). The two other categories of energy demand are transport and other, the latter including the agricultural sector. Because part of the primary sectors (coal and minerals mining, oil and gas production) are separately modelled within the TARGETS-model, we have to use an interpretation - and thus numbers - which differ from the sectors in IMAGE 2.1. Each sector within the Economy submodel is represented by a capital stock which generates output and which decreases due to depreciation (1/L with L average lifetime) and increases due to investments. Sectoral output is taken as the activity level which governs the demand for useful energy (cf. Chapter 2).

If the activity level changes, so does the energy-intensity. This captures the phenomenon of structural change within a sector[3]. It represents the fact that the composition of the sectoral output (in money units) changes over time because of changing and new activity patterns which result from changing income levels, preferences and technologies. One of the key assumptions in the model refers to this relation between sectoral activity and demand for useful heat and electricity. This relation, associated with income elasticity or sectoral energy growth elasticity, has been modelled by expressing the energy-intensity, ε, as a function of increasing sectoral per caput activity level, A :

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[3] Changes in energy-intensity due to intersectoral change come from differential sectoral growth rates.

Inputs from the rest of the [model]world

physical	Investments in energy efficiency
informational	Sectoral activity levels (GDP, Cons Exp, Value A Industry & Services Solid, Liquid and Gaseous primary fuel prices

Outputs to the rest of the [model]world

physical	
informational	[Past] Solid, Liquid and Gaseous Fuel demand

Relevant parameter assumptions (for 5 heat and 1 elec sector)

Energy demand vs. Activity relation parameters

Ratio Energy-demand intensity in 2100 vs. 1990

Autonomous Energy-Efficiency Improvement (AEEI) rate

Maximum energy-intensity (AEEI) reduction

Conservation investment cost curve parameters (PIEEI)

Rate of cost decrease in conservation investments

[Desired] payback times for conservation investments

Non-substitutable fraction in secondary fuel demand

Fuel premium factors

Fuel cross-price elasticities

Performance indicators (for 5 heat and 1 elec sector)

Energy-intensities (in GJ secondary fuel per unit of activity)

Energy end-use cost

Decision levers (for 5 heat and 1 elec sector)

Implementation of tax on fuels through changes in fuel premium factors

Subsidies and RD&D for energy conservation

[Desired] payback times for conservation investments

Figure 3.2 Interactive representation of the ED-model

$$\varepsilon_t = \varepsilon_{A(t\rightarrow\infty)} + (\beta_1 + \beta_2\ A_t)\ e^{-\beta_3 A_t} \quad \text{GJ/\$} \qquad [3.1]$$

with $\varepsilon = E/A$ and E sectoral per caput energy demand.

Figure 3.3 shows two of such curves, normalized to $\varepsilon_{1900} = 1$, as calibrated for the world and for the residential and transport sector for which per caput consumption has been chosen as the representative driving force. Curves like these are based on time-series and cross-country observations over the past 50-100 years. The model calibration, in turn, is done with historical per caput consumption and end-use energy demand estimates. This is not an unambiguous procedure because end-use energy *demand* is a non-observable : it is implicit in the actual observations of secondary fuel use and activity level. A more detailed discussion of how to disentangle the various determinants of sectoral energy-use is given in Schipper and Meyers (1992).

Equation [3.1] shows that the estimated energy-

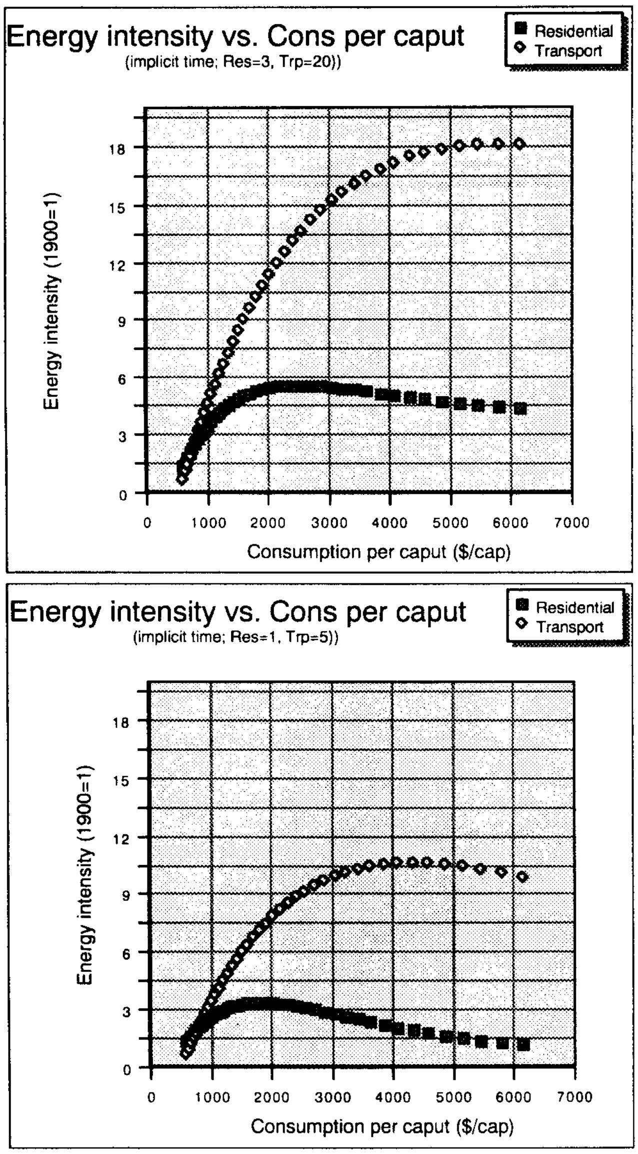


Figure 3.3: Energy-intensity without Energy Efficiency increase as a function of activity level for the residential and transport sector.

intensity in the year 2100 ($A_{(t\to\infty)} \sim A_{2100}$) chosen as future reference) is an important determinant for the future development of energy end-use demand. Unfortunately, its value cannot adequately be assessed because it requires an implicit statement about the kind of activities which make up a monetary unit of activity 105 years from now. It is hard or even impossible to formulate a lower bound on the energy-intensity if the latter is measured in energy units per unit of money. In principle, one can imagine a society which, at least at the margin, generates hardly any energy and material flows per unit of monetary activity - e.g. through further penetration of information technology. The ratio between $\varepsilon_{A\to\infty}$ and $\varepsilon_{t=1900}$ is chosen differently in the two graphs. For example, for transport one may assume that in the year 2100 future economic activity is 20 times more energy-intensive in terms of transport services than in 1900 (upper graph) or only 5 times (lower graph). Similarly, for residential - in which case climate considerations can be made part of the assessment. The points in the graphs indicate how the intensity of end-use energy develops as a function of increasing activity per caput levels. Both graphs are for activity levels up to 6000 $/caput.

We have based the parameters on cross-country time-series for 1970-1990 (cf. Appendix D). Historical calibration at the world level is, admittedly, a dangerous procedure to extrapolate into the long-term future for at least two reasons. First, past useful heat demand was a reflection of the climate, culture and technology of a rather small subset of the human population - coinciding largely with the present OECD-region. If, as is expected, future increase in per caput consumption takes place mostly in areas like South- and East Asia and with improved technology, past correlations may be a bad guide. Secondly, the world average per caput consumption level crosses only a small part of the curve : between 1900 and 1990 per caput consumption rose from an estimated 600 to 2650 1990 $/cap. In such a situation the calibration strongly depends on this rather small domain of the curve. Nevertheless, we follow this approach because it captures the major long-term features.

Two omissions in the present model formulation have to be stated. First, tradional sources of heat and power are not included in the present version. This implies that parametrisation has been done on the basis of sectoral use of commercial fuels 1900-1990, and that the substitution dynamics from traditional to commercial fuels is implicit. One consequence is, apart from the relation between traditional biomass use (fuelwood, dung etc.) and land use, that we have underestimated historical heat demand c.q. overstated the historical growth elasticity. Within the simulation experiments with TARGETS1.0, we have introduced the use of traditional fuels as an exogenous time-series.

A second point is that the substitution between heat and electricity is implicit in the parametrisation, i.e., model calibration generates parameter values which incorporate past interactions between heat and electricity use. This requires consistent scenario construction in the sense that e.g. an "all-electric society" requires a combination of higher electricity and lower [sectoral] heat intensities. So far, such consistency has not yet been explored with the model. Also the interaction between heat and electricity through combined heat-and-power or CHP schemes (cogeneration, district heating) is not [yet] implemented.

3.3.2 AEEI and PIEEI

The product of activity level and energy-intensity, i.e. the end-use energy demand, is then multiplied with the Autonomous Energy Efficiency Increase (AEEI) factor. This factor is exogenously set but it applies only to the latest capital vintage. Thus, with rapid growth in the activity level, the energy-intensity will drop faster than with slow or even negative growth. This represents the fact that the rate of [energy] productivity increase is related to the rate of growth of the economy and, more specifically, to the turnover rate of capital stocks. Omitting this capital-vintage effect (cf. Bollen et al. 1995), the expression for the AEEI-factor is :

$$\mathrm{AEEI} = \varepsilon^*_{\mathrm{limit}} + (1 - \varepsilon^*_{\mathrm{limit}})\, e^{-c * (t-1900)}\,] \qquad [3.2]$$

with $\varepsilon^*_{\mathrm{limit}}$ the lower limit on the energy-intensity. This limit reflects the fact that only part of the end-use energy demand without any price-induced measures can ultimately be conserved by technical means. It is tempting to relate such a lower bound to the second-law of thermodynamics. Unfortunately, here too it is hard to relate physical/engineering information to aggregate money flows

The time-dependent parameter c in eqn. [3.2] indicates the [exogenous] rate of autonomous energy efficiency increase. This cannot always be compared with values cited in the literature, because often the AEEI incorporates also structural change (cf. Alcamo et al. 1995).

The resulting useful energy demand after AEEI is then multiplied with a factor which represents Price-Induced Energy Efficiency Increase (1-PIEEI). In reality, the AEEI- and PIEEI-factor are not independent. This factor captures the result of those investments in energy conservation which are made in response to energy price changes. Many of these investments will have a retrofit character, i.e. they are added to operating capital stocks. Its value is determined on the basis of a conservation investment cost curve, and a simple rule which says that people take conservation measures with cost benefits until marginal investment costs equal the product of their desired payback time and the marginal (purchase) costs of saved energy (see e.g. Velthuysen 1995). This mechanism, applied with a delay and irreversibly in the sense that action is only taken if energy end-use costs go up, is extended with another factor which lowers the cost curve over time according to an exogenously set rate. This is a simple way to account for the fact that regulation and mass production will tend to make many energy efficiency measures cheaper c.q. integrated.

The marginal investment costs IC as a function of PIEEI are estimated by:

$$\mathrm{IC}_{\mathrm{marg}} = \alpha / (\mathrm{B}_{\mathrm{max}}{}^2 * (1+d)^{t-1975}) * [(1-\zeta)^{-2} - 1] \quad \$/\mathrm{GJ} \quad [3.3]$$

with $\mathrm{B}_{\mathrm{max}}$ the ultimate reduction achievable and $\zeta = \mathrm{PIEEI}/\mathrm{B}_{\mathrm{max}}$. The time-dependent parameter d reflects the autonomous rate at which energy conservation investments become cheaper. It starts in 1975 on the assumption that before 1975 no price-induced changes have occurred. The parameter α is a scaling constant which allows gauging the curve to empirical estimates. A variety of such curves have been published in the literature over the past 5-10 years (Vries 1986, Blok et.al., 1990). Figure 3.4a-b show a number of those curves, based on marginal and cumulative investment costs respectively. It also contains the curve used in the model for $\alpha = 30$ and $\mathrm{B}_{\mathrm{max}} = 0.9$ at t=1973.

In case all investments are taken at year t, the cumulative investment costs are:

$$\mathrm{IC}_{\mathrm{cum}} = \alpha / (\mathrm{B}_{\mathrm{max}} * (1+d)^{t-1975}) * [\zeta^2/(1-\zeta)] \quad \$/\mathrm{GJ} \quad [3.4]$$

If $\zeta \rightarrow 1$ then $\mathrm{IC} \rightarrow \infty$ and if $\zeta \rightarrow 0$ then $\mathrm{IC} \rightarrow 0$. The factor $\alpha / (\mathrm{B}_{\mathrm{max}}(1+d)^{t-1975})$ can be interpreted as the total investment costs associated with a reduction of the energy intensity with a factor $(\sqrt{5} - 1)/2 \sim 0.62$. Thus, a rule of thumb is that the choice of $\alpha / (\mathrm{B}_{\mathrm{max}}(1+d)^{t-1975})$ indicates the level of the average investment costs per GJ conserved at which a total reduction in energy-intensity of 62 % is realized.

The PIEEI-factor is the outcome of numerous decisions to maximize the difference between cumulative investment costs and revenues per unit of end-use energy saved. In the model this factor results from equating the marginal investment costs to the product of the average sectoral end-use energy cost, UEcost, and the assumed payback time which energy users apply within the sector, PBT :

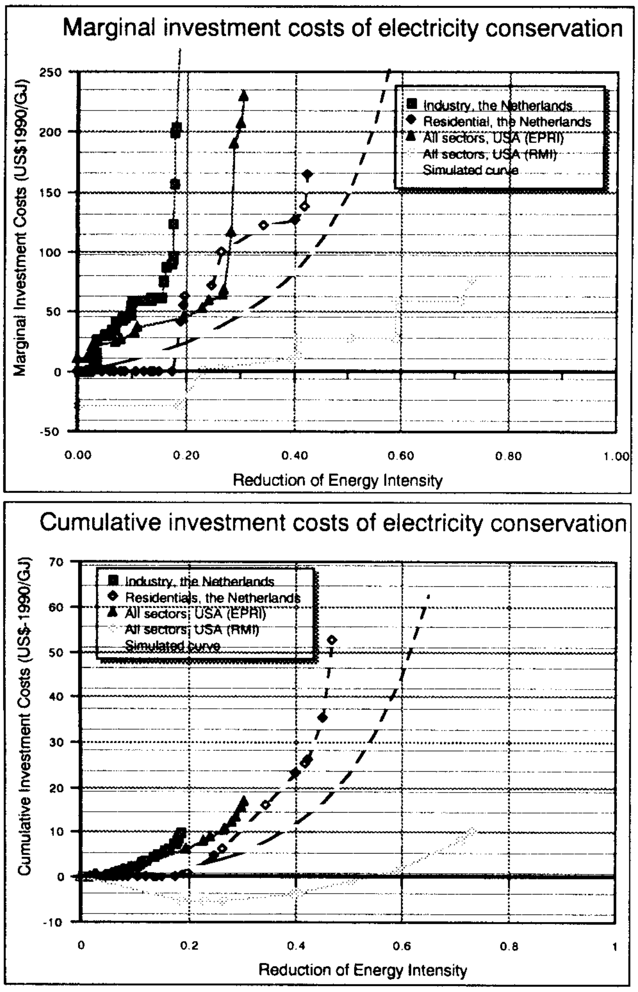


Figure 3.4a-b: Simulated marginal (a) and cumulative (b) investment curve of electricity conservation with parameters B_{max} = 0.9 and α = 30 and empirical estimates for the industry and residential sector in The Netherlands (Beer et al. 1993) and for all sectors in the USA (EPRI - Ficket et al. 1990)[4].

$$\text{PIEEI} = B_{max} - 1 / [\sqrt{(B_{max}^{-2} + \text{UECost} * \text{PBT} * (1 + d)^{t-1975} / \alpha)}] \qquad [3.5]$$

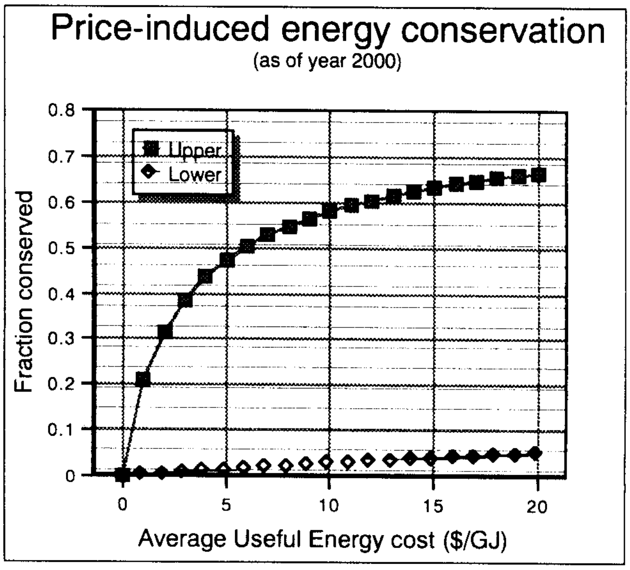
The UECost are calculated by dividing the fuel costs by an average (fuel-dependent) conversion efficiency and adding a (fuel-dependent) fixed capital cost component.

Figure 3.5 gives an indication of how useful energy prices affect the degree of energy-efficiency improvement. The upper curve assumes a great reduction potential : B_{max}=0.9, PBT = 5 years and d = 2%/yr. By the year 2000 the price-induced reduction of the energy-intensity may be over 50% for a cost increase from 1 to 6 $/GJ. The lower curve reflects much more modest assumptions about the conservation potential due to price increases : B_{max}=0.4, PBT = 1 years and d = 0%/yr.

Two things should be noted here. First, as it is assumed that energy conservation starts from a zero energy cost level, some efficiency improvements are implemented right away. Secondly, this formulation implies the use of a price-elasticity which depends on the degree of conservation c.q. the energy cost and on time. Figure 3.6 shows the implicit price-elasticity defined as the ratio of percentage change in energy use and percentage change in energy cost with the 1 $/GJ situation as the reference. It tends to lower when energy prices go up, reflecting the phenomenon that price changes induce less conservation investments once the cheapest options are introduced.

From the previous equations it is easily calculated what the ultimate reduction in the 1900-value of the energy-intensity is : $\varepsilon_{A\text{->}\infty} * e^{*}_{limit} * (1 - B_{max})$. This is for the chosen parameter values between 0.01 and 0.03 for the non-electricity (heat) sectors and 7.2 for electricity. With regard to the 1990-values, the ultimate reduction is in the order of 0.05-0.25 for non-electricity use. Because the structural effect is assumed to be less important in the future than in the past, this is more correctly related to a thermodynamic lower bound. Several analyses focus on such a thermodynamic lower bound of the energy-

Figure 3.5: Degree of energy-intensity reduction as a function of the useful energy cost.



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[4] Investment costs include annualized operation and maintenance costs

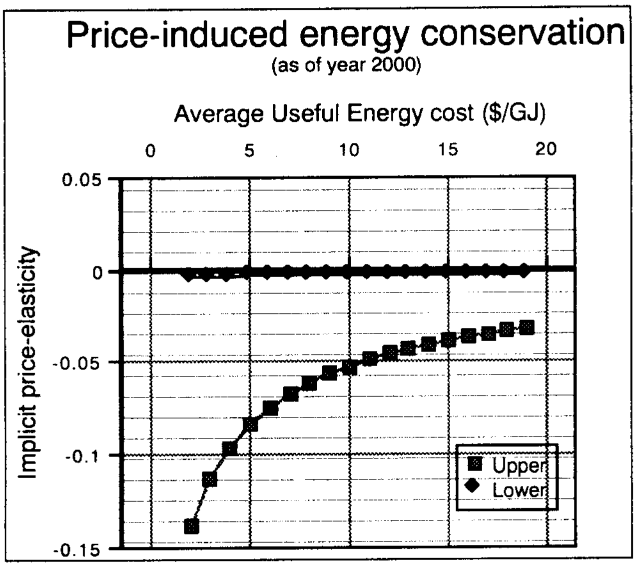

Figure 3.6: Implied price-elasticity if energy cost increase from the initial value of 1 $/GJ

intensity in energy units per unit of weight or mass (see e.g. Nakicenovic 1989). A measure for this is the over-all exergetic efficiency which is for many [industrial] processes between 5% and 15% of actual exergy use.

3.3.3 Secondary fuels

The next step is to determine the market shares of the various fuels. Unlike in IMAGE 2.1 we distinguish only four commercial fuel types in TARGETS 1.0 : solid, liquid and gaseous fuels with the liquid fuels split into light liquid fuels (gasoline, kerosene etc.) and heavy liquid fuels (fuel oil and destillates). This implies that fuelwood in the residential sector and all kinds of agricultural and industrial waste flows used for energy functions are not included. This will be taken care of in the next version, based on the corresponding parts in the IMAGE 2.1 model. One consequence is that alternative developments in which local/traditional biomass e.g. are not phased out as happened in the past cannot be simulated.

The market shares of the four commercial fuels are for each sector calculated from a multinomial logit function (cf. Appendix A), which uses relative end-use costs as the determinant. If with n fuels all end-use costs are identical, i.e. after taking into account the fixed costs and losses for conversion into useful energy, each has a market share 1/n in this formulation. We assume that the market shares as calculated from the end-use cost in year t are leading to actual changes with a few years delay. This simulates the delayed response of energy users to changing relative fuel prices, as well as the positive correlation with the rate of useful energy demand growth.

The last step is to multiply sectoral useful energy demand (after AEEI and PIEEI) with the respective market shares to get commercial fuel use. Conversion losses are included with a constant factor. It should be mentioned that these new market shares in turn affect the end-use costs, and consequently the degree to which energy conservation actions are taken in year t+1.

The consumers in the five sectors are naturally faced with different prices because transport and storage costs differ. Moreover, non-price factors influence the decision to use certain fuels, e.g. strategic and environmental. Therefore, we apply for each sector a premium factor which corrects for the lack of pricing differentials across sectors and for differences between perceived costs and actual market prices. The resulting perceived fuel price is partly a proxy for a shadow price. For calibrations we have used this premium factor as one of the means to calibrate the model, in combination with the multinomial logit parameter (or cross-price elasticity).

A second consideration in simulating fuel shares is that over the period 1900-1990, the available user technologies and distribution networks did not always allow an unconstrained choice of one of the three secondary fuels. An obvious example is transport : gasoline was not an alternative for rail transport in the beginning of the century. On the other hand, a large part of industrial energy use was tied to coal (iron ore, cement) for most of the first half of the 20th century. To incorporate this phenomenon, we have constrained the market share which was actually open to competition from liquid and gaseous fuels for the period 1900-1960. This appears to be a conceptually more plausible approach than adjusting the premium factor to unrealistically high values.

It turns out that for all sectors premium factors different from unity are required to simulate past use of secondary commercial fuels. There are a variety of possible and sometimes plausible explanations. For example, in the residential sector the coal price does not reflect the problems of lacking infrastructure, health risks and storage and ash removal problems. Another example is natural gas, where the existence and density of a grid in combination with policy-based priority users can, especially in the starting period, strongly perturb price-based market dynamics (Moxnes 1989). Another part of the explanation is that we have kept the conversion efficiency (from secondary fuel to useful demand) constant. Historically, this has not been the case. For example, penetration of natural gas has been accelerated by successful introduction of heating equipment with high conversion efficiency. In effect, our model formulation is an attempt to resolve the question of technological vs. economic forces in a transparant - but certainly not unequivocal - way.

3.4 Submodel calibration

3.4.1 Parameter values

For five sectors : industrial, residential, commercial, transport and other, historical data have been collected for USA 1950-1990 and World 1900-1990. These data are : sectoral activity level[5] and sectoral fuel prices to drive the model, and sectoral fuel use to calibrate the model.

The calibration has been done in three steps :

- collection of historical data on activity levels and secondary fuel c.q. electricity use for sectors and their prices, world 1900-1990;
- estimating parameters on the basis of endogenous prices as supplied by the four energy supply models (which are described in the following chapters) in such a way that they generate the estimated historical prices;
- re-adjusting fuel prices with help of the cross-price elasticities and the premium factors for each fuel and each sector, in combination with parameter changes.

Given time-series for sectoral activity and fuel price levels, the key parameters for the calibration are :

- the functional which expresses end-use energy demand without Energy Efficiency Increase as a function of activity level and the value in the target year 2100;
- the rate of autonomous energy efficiency increase (AEEI) and its lower bound;
- the form of the conservation investment cost curve (α) and its rate of change(d);
- the fuel cross-price elasticities and premium factors.

With these and assumptions for the average conversion efficiency from end-use to secondary fuel, the total fuel use can be calculated and compared with the historical values. The conversion efficiencies from secondary fuel to end-use are the same for all sectors and constant : 0.65 for coal, 0.75 for liquid fuels and 0.85 for gaseous fuels. This calibration is fairly easy, though not unambiguous.

A multiplicity of parameter calibrations is possible because one cannot empirically estimate the various factors separately. For example :

- higher values for the growth elasticity result in higher useful demand and therefore has to be compensated by e.g. a higher estimate of the AEEI;
- lowering the conservation investment cost curve or speeding up its rate of downward change induces larger energy conservation investments which could be offset by a lower estimate of the AEEI;
- lowering the cross-price elasticities changes the rate of fuel substitution which causes a change in the estimated fuel premium factors.

For example, it turned out that natural gas had to be made more and coal had to be made less expensive than their respective market prices to avoid a too early and too fast penetration of natural gas. As indicated in paragraph 3.3.3, it was necessary for the 1900-1990 World calibration to introduce a parameter which accounted for the fact that in the past not every type of fuel could be used. This parameter is an exogenous time-series and declines over time, especially in the industrial and transport sector. Appendix D shows our assumptions for this parameter and for the premium factors.

Table 3.1 gives the values we have chosen for the key parameters in the first two items. For example, for the residential sector, the growth of end-use energy demand is determined by the parameters β_2 and β_3 and the average GJ/$ of value-added in the year 2100 which in this case has been equated to the historical 1900-value. Also indicated is the year in which the energy-intensity before applying AEEI and PIEEI has its maximum, T_{max}. Autonomous change is set at 0.5-1%/yr between 1900 and 1950. The lower limit is set at 25% of the average GJ/$ of value-added in the year 1900. The parameter α for the conservation investment cost curve is based on Toet et al. (1995). It is rather high for electricity because empirical data suggest that the response of electricity-intensity to rising prices is rather small, possibly because for many users electricity is still a small cost item with limited response options once the equipment is purchased.

The upper limit of the PIEEI is set at 90% except in the case of electricity for which it is 40%. The conservation investments are assumed not to have decreased before 1990, i.e., d=0. Payback

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[5] We have followed here the IMAGE 2.0 choice : value-added in constant (1990) US dollars for industry and commerce, consumption expenditures in constant (1990) US dollars for residential, number of passenger cars per 1000 for transport and GDP in constant (1990) US dollars for other. See Toet et al., 1995.

Table 3.1: Parameter choices Energy Demand model, based on calibration, World 1900-1990

Sector :	Residential	Industry	Services	Transport	Other	Electricity
Energy-intensity ('dematerialisation', structural change)						
$\varepsilon_{A\to}/\varepsilon_{t=1900}$	0.8	1	0.5	1	0.5	30
β_2 (10**6)	7.5	10.5	6.5	8	8.8	16
β_3 (10**6)	730	19700	11355	3005	3340	1835
T_{max}	1970	1960	1960	2030	1980	2040
Autonomous Energy Efficiency Increase (AEEI)						
ε^*_{limit}	0.2	0.15	0.2	0.3	0.3	0.4
c	0.5->1	0.55->0.95	0.5	0.5	0.8	1
Price-Induced Energy Efficiency Imporvement (PIEEI)						
α	30	10	40	30	30	50
B_{max}	0.9	0.9	0.9	0.9	0.9	0.4
PBT (year)	2	1.5	1	3.5	1	1
d (%/yr)	0	0	0	0->0.15	0	0
Secondary fuel substitution						
cross-price elasticity	1	1.5	1	0.6	1	na

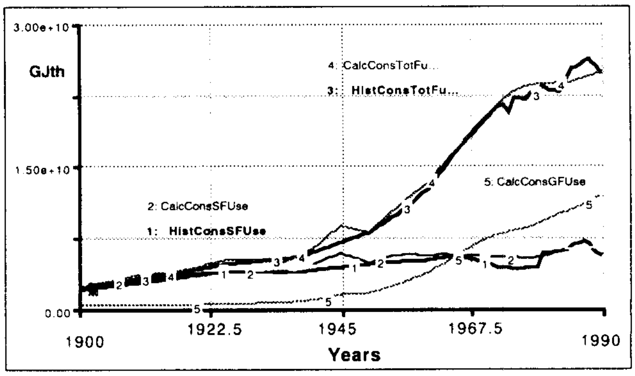
times are all set rather low, at 1-2 years; this is evidently a parameter with which educational and subsidy programs can be explored.

As indicated in paragraph 3.3.2, from these parameter choices it can be derived that the ultimate reduction in the [sectoral] energy-intensity with respect to its 1900-value equals $\varepsilon_{A\to\infty} * \varepsilon^*_{limit} * (1-B_{max})$; they are in the range of the estimated over-all exergetic efficiency for Western Europe. For electricity it is a high 7.2 which reflects the enormous increase in electricity services demand over the last 90 years.

3.4.2 Calibration results

All simulation results shown in this report are from a simulation of the integrated TIME-model with historical activity drivers (cf. Figure 2.4). By way of illustration, we present a few graphs in which simulated sectoral secondary fuel use is compared with historical values. *Figure 3.7* gives the simulated and historical trajectory of total secondary fuel input (for heat) and of coal (for heat) in the residential (consumption) sector. The changes in fuel demand and supply are largely driven by changing relative prices. *Figure 3.8* shows for the same sector the simulated market shares of the three secondary fuels, including the economically indicated market share which is a few years ahead of the actual market share due to assumed delays. *Figure 3.9* and *3.10* shows for the service and industrial sector the simulated and historical use of total fuels and of coal. As for the residential sector, the calibration gives a fair match - the standard deviation from the modal value being in the order of 2-3 % for the 1900-1990 period.

Figure 3.7: Simulated and historical trajectory of total secondary fuel input and of coal (SF) use, residential sector, World 1900-1990. Also indicated is simulated gas (GF) use.



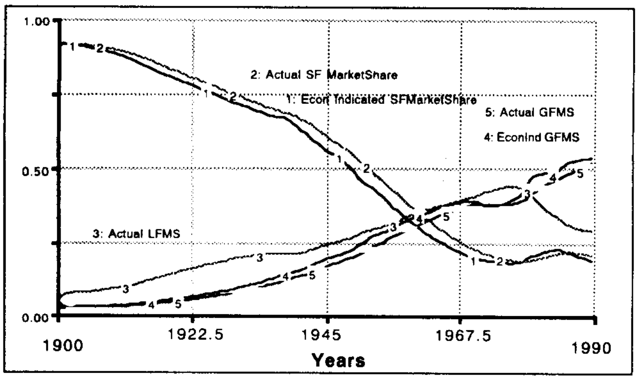


Figure 3.8: Simulated secondary fuel market shares, residential sector, World 1900-1990 (SF solid fuel, LF liquid fuel, GF gaseous fuel)

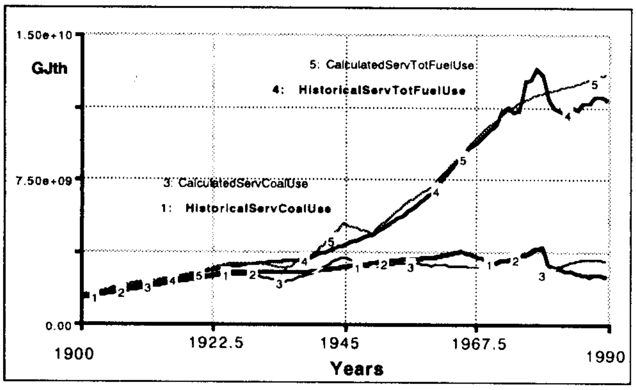


Figure 3.9: Simulated and historical trajectory of total secondary fuel input and of coal, service sector, World 1900-1990

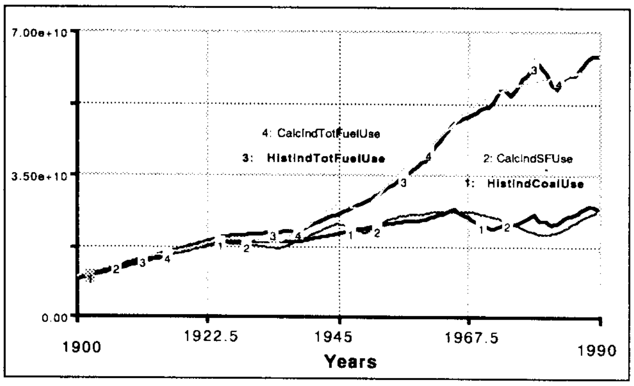


Figure 3.10: Simulated and historical trajectory of total secondary fuel input and of coal, industrial sector, World 1900-1990 (SF solid fuel, LF liquid fuel, GF gaseous fuel)

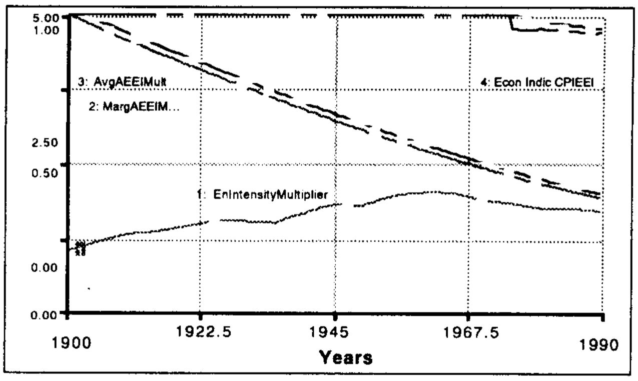


Figure 3.11: Determinants of secondary fuel use, industrial sector, World 1900-1990. The En Intensity Multiplyer represents structural change effects

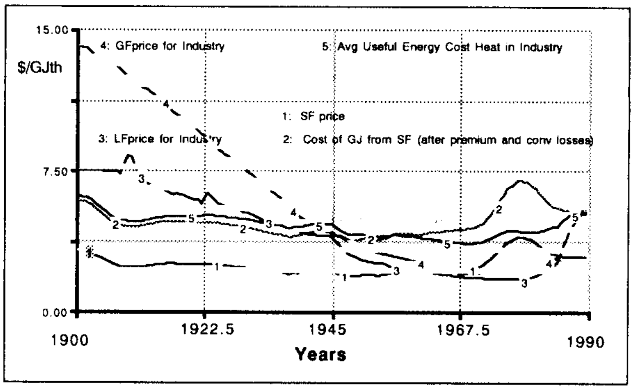


Figure 3.12: Simulated (perceived) fuel prices and useful energy cost, industrial sector, World 1900-1990 (SF solid fuel, LF liquid fuel, GF gaseous fuel)

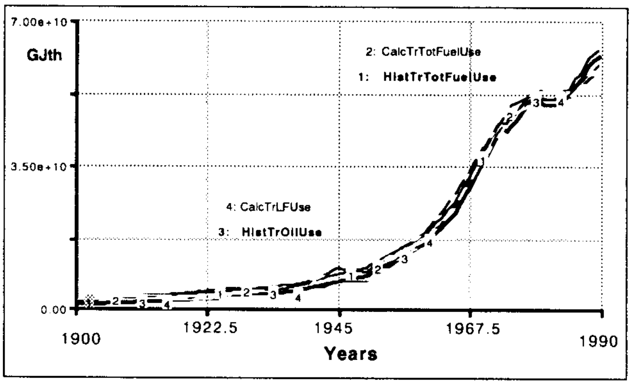


Figure 3.13: Simulated and historical trajectory of total secondary fuel input and of oil, transport sector, World 1900-1990

Figure 3.11 gives for the industrial sector the development of the three determinants of secondary fuel demand, given the exogenous activity level. First, there is structural change which changes the average GJ/$ value-added (EnIntMult). Then, autonomous energy efficiency increase (AEEI) induces an exponentially decreasing energy-intensity. Shown are the marginal value of the AEEI-factor and the average one which is slightly lagging behind, reflecting the growth-rate related adjustment time. Finally, a rise in fuel prices induces an additional decrease in the energy-intensity (PIEEI). Here, too, there is a difference between the economically indicated value and the lagged actual value.

Figure 3.12 shows the coal, oil and gas prices for the industrial sector, for coal both as supplied by the market and as end-use energy cost, i.e. after inclusion of the premium factor and the conversion efficiency. It is seen that the trajectory for the average useful cost of energy is rather stable because of fuel substitution. We have attempted to gauge fuel prices to historical values but the data which are available for the construction of a representative "world fuel price" are too scarce, especially before 1970, to attach much value to such a calibration.

A last graph is given in *Figure 3.13*, now for the transportation sector. Given apparent secondary fuel prices, conversion efficiencies and cross-price elasticities, total secondary fuel input is calculated and compared with historical secondary fuel use. Also the simulated and historical oil use is given - it dominates the transport fuel supply which could only be reproduced in the simulation by increasing the market share in which oil has no substitute from 30% in 1900 to 90% in 1990 (see Appendix D).

Some key results from such a dynamic modelling exercise can already be discussed :

- the response in terms of energy conservation to rising secondary fuel and electricity prices tends to become relatively smaller unless one assumes that standardisation, learning etc. continuously reduce the costs at which such efficiency improvements can be realized;
- the substitition between fuels tends to dampen any price increase in one particular fuel. For example, the oil price hikes of 1973 and 1979-80 did increase the end-use energy price but less than the oil price as consumers switched to other fuels. Of course, such a conclusion is less valid if secondary fuel suppliers are able to get a higher market price for their fuel if one of the other fuels rises in price, i.e. if fuel prices are linked through formal or informal agreements;
- autonomous increase in energy efficiency is, as expected, a major determinant of sectoral fuel and electricity use, but whether there is a lower bound on useful energy per money unit of activity is for the longer term an equally important consideration.

3.5 Shortcomings and future work

Several problems remain which have to be dealt with in later work. First, traditional fuels which still play a major role in rural areas all over the world have only implicitly been included in the calibration process. They show up in the rather steep increase in the use-intensity of commercial fuels in the first stages of the development process. Implicit is the assumption that this commercialisation of energy markets is an inherent characteristic of development. This is not necessarily the case. One consequence is that the dynamics of rural fuelwood and biomass use and its potential for efficiency-improvements does not enter the picture.

Secondly, sectoral activity levels are measured in variables which may not be good indicators: In future work we aim to use more adequate indicators.

Thirdly, the interaction between demand for non-electricity (heat) and electric power has to be incorporated more explicitly. The EPG-model has a subsector which deals with combined heat-and-power (CHP) schemes but it is not yet implemented(cf. Chapter 7). The other interaction is in consumer markets, in the forms of electric heating and electric cars.

Finally, the sectoral desaggregation and the choice of activities have been based on available economic and energy statistics. This is not wholly adequate in view of its use within the TARGETS- and IMAGE-frameworks. For example, in the future energy use for agriculture including traditional biomass should be explicitly modelled whereas in the present formulation it is incorporated in the sector Other. Similarly, the relevant determinant of transport energy is some weighed mix of consumption (passenger transport), manufacturing (freight transport) and services rather than the presently used proxy of Private Consumption. Such refinements may be of interest in view of more adequate and explicit integration linkages.

4. THE LIQUID FUEL (LF) SUBMODEL

This submodel describes the exploration for and exploitation of crude oil and its upgrading to marketable fuels. It also describes the penetration of a land-based alternative liquid fuel (bio-fuel). Oil [products] for non-energy use and from coal through liquefaction are not considered. The goal of the submodel is to provide a plausible and transparant description of the life cycle of conventional oil and the transition to a renewable alternative. Demand for liquid fuels in the rest of the [model]world is satisfied (output); for this investment goods and labour are required from the economy model and land from the food/land model (inputs).

4.1 Introduction

One of the most important fossil fuels for satisfying the demand for energy services is crude oil and a variety of oil-derived fuels (cf. *Figure 1.1*). Making these liquid fuels available to the market requires a large and steady investment flow into exploration, production, transport and refining. This is to a large extent controlled by a dozen of oil companies with their base in the OECD and by a number of mostly nationalized companies in various other regions in the world.[6] Given the role of oil [products] as the most important "swing" fuel on the world market and the domination of private capital in the industry, oil business is dominated by market-oriented dynamics. Moreover, oil is strongly connected to another private capital group : car manufacturing companies. The combined annual sales of Exxon, Royal Dutch/Shell, General Motors and Ford in the early 1990's - about 450 10^9 \$ - exceeded the GDP of the 1.1 billion people living in India and Indonesia. However, as the past has shown, national governments are important co-actors if only because in many countries oil is a large or even dominant source of government and export income[7]. Expansion of crude oil production, transport and refining will require enormous investments; for production alone it is estimated to amount to US \$ 250 10^9 over the period 1993-1998 (Subroto 1993).

From the perspective of energy demand, oil [products] is of special importance for the transport sector which is nowadays almost universally dominated by gasoline-, diesel- en kerosene-based combustion engines and turbines and which is growing relentlessly. Other important consumers of oil [products] are electric power plants (cf. EPG-model) and industry. Another important feature of oil [products] is that they are among the most widely traded commodities in the world system : 80% of oil produced is traded internationally (Subroto 1993).

From the perspective of CO_2-emissions combustion of oil [products] is an important contributor, with a specific emission coefficient of about 70 kg/GJth, lower than coal but higher than natural gas. At the point of combustion, reducing activity or increasing energy efficiency are at present the only feasible options to reduce CO_2-emissions[8]. Oil [product] combustion is also an important source of other emissions, notably NO_x, SO_2 and CO.

There is a variety of ways in which liquid fuels could be supplied once the reserves of conventional crude oil are depleted. In the past, due to constraints on imports, countries like Germany and South-Africa have experimented with coal liquefaction. After the oil crises in the 70's, liquefying of coal again became an important issue. Much research has been done into the conversion of coal into so-called Synthetic Liquid Fuels (SLF), but demonstration plants in the 70's and 80's have shown a consistent underestimation of the costs. The presently available processes are capital-intensive, generate much waste and have a conversion efficiency in the range of 60-

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[6] Van der Linde (1993) summarily expressed this aspect : "...the oil industry in many OECD-countries is privately organized. The private and the public interest run along a different divide than the consuming and producing countries' divide. Not governments but mainly the large private international companies possess the human and technological capital necessary to develop the world's next generation of oil fields".

[7] This is or was not only true for OPEC-countries like the Arab countries, Venezuela, Nigeria, Mexico and Indonesia, but also [for oil and gas] for countries like Norway, Britain and The Netherlands.

[8] For large-scale combustion processes e.g. in chemical and metal industry and for power generation and also in conversion process to e.g. methanol, the option of CO_2-removal may become feasible in the future.

85 %. Liquefaction of coal is not a commercially viable option at today's energy prices. A more attractive option apparently is conversion of coal into Synthetic Natural Gas (SNG) to be burnt in integrated systems for large-scale electric power generation. None of these options is [yet] included in the present model, one of the reasons being that their potential for reducing specific CO_2-emissions is quite limited.

Another potential source of liquid fuels is biomass. The most important case is the sugar-cane derived ethanol which has reached a sizeable market penetration in Brazil. Both ethanol and methanol are also being used in the United States in a mixture with gasoline. In the present LF-submodel, we only consider the biomass-derived liquid fuel alternative to oil [products]. This implies that land will be an important input if biofuels are going to penetrate the market.[9] In fact, nowadays the energy transition is mostly seen as the shift from fossil fuels to biomass- and other solar-based forms of energy.

The concepts used in the Liquid Fuel (LF) model are partly based on previous energy models, especially on descriptions of the Fossil-2 model (AES, 1990; AES, 1991; Naill 1977), on a detailed systems dynamics model of the US petroleum sector by Davidsen (1988) and on research by Sterman (1981, 1983, 1988). Other sources of inspiration and information are listed under the references. Although the Gaseous Fuel (GF) model has an almost identical structure, it will be discussed in a separate chapter.

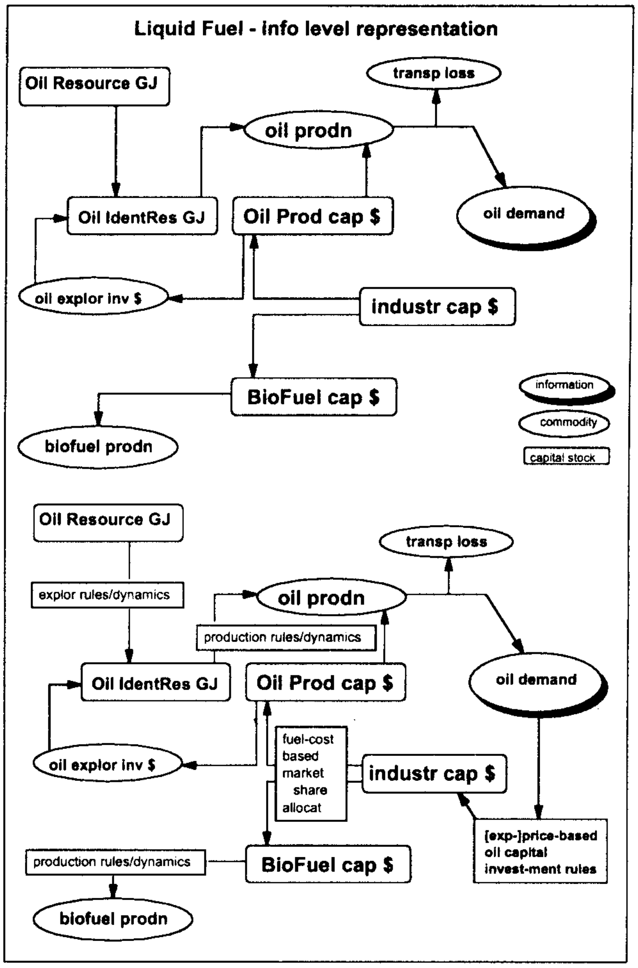

Figure 4.1: Info-level representation of the LF-model. The upper scheme indicates physical flows; the lower scheme shows the added-on behavioural/ informational structures

4.2 Submodel representation

Figure 4.1 is a representation of the LF-submodel at the information level. The physical flows picture the conversion from an [unknown] resource into an identified reserve, which is produced, transported and then - in combustion processes - converted into CO_2. At present we omit the use of oil [products] as non-energy use[10]. To keep this exploitation process going, investment goods are required for the oil production capital stock. Part of this flow sustains the exploration process. If the alternative, indicated from hereon as BioLiquidFuel (BLF) or biofuel, becomes available at lower cost and thus competitive, investments will also be flowing into biofuel production.

The lower scheme shows the information flows and the decisional rules. On the basis of energy c.q. oil [products] demand, private oil industry and governments invest on the basis of anticipated required capacity. If biofuels can be produced at competing cost levels, investment will be made into biomass plantations. Both oil and biofuel production are governed by a production function, which represents both the impacts of declining marginal resource quality and capital-productivity increase due to learning-by-doing. Exploration investments are determined by the desire to keep the reserve-production ratio sufficiently high. For oil exploration and production, the investors also wish to maintain a certain profit level in terms of revenues over costs; otherwise they will direct their capital into other

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[9] Labour may be an important input, especially in low labour-productivity regions. In fact, biofuels may initially only gain a competitive advantage - apart from strategic considerations - because it can absorb large amounts of cheap labour.

[10] In future work the probably important link with the minerals and land submodels will be introduced.

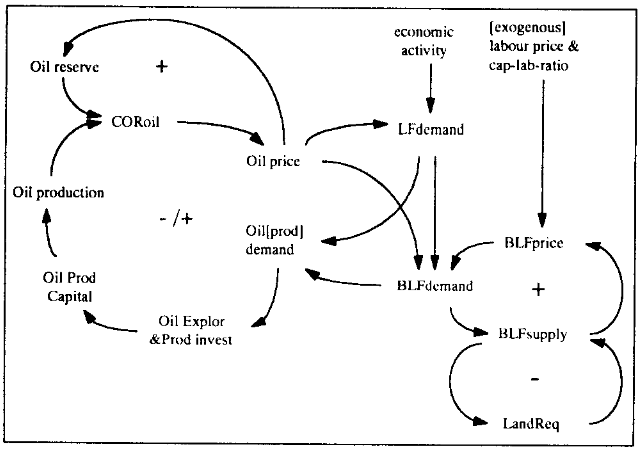

Figure 4.2: The demand - investment - price loop in the LF-submodel. The left part is the demand-driven oil exploitation loop; the right part is the penetration of BioLiquidFuels (BLF).

[non-specified] activities.

The other way of representing the LF-submodel is in terms of causal loop diagrams. The major loops are shown in *Figure 4.2*. The most important short-term loop is the demand - investment - production - price loop. Given a level of economic activity and a resulting demand for energy, the anticipated demand for liquid fuels generates investments into new production capacity. Part of the investments are into exploration, depending on the desired vs. actual reserve-production ratio. An important longer-term loop is that, due to oil production, the liquid fuel price is changing in response to depletion and learning dynamics, which in turn affects liquid fuel demand. In the present submodel, price is calculated by adding the capital costs for transport and downstream operations (refining). Once the alternative fuel reaches a competitive price level, it starts penetrating the market.

A third way to represent the submodel is the interactive one (cf. *Figure 4.3*). This shows which are the in- and outputs to and from the rest of the world as well as the most important parameter assumptions, those outputs which are thought to have an indicator function and the decision levers. The most important inputs from the rest of the world are at the physical level the investment goods (from the Economy model) and at the informational level the demand for LiquidFuels c.q. Heavy Liquid Fuels (HLF) and [Oil-derived] Light Liquid Fuels ([O]LLF). The outputs are the flows of refined crude oil products, the land to be used for biofuels (which can also be considered as an input from the Land submodel) and the required investment goods and HLF- and LLF-prices. The latter three are informational i.e. they serve to induce certain decisions and resulting physical fluxes in other submodels.

There are many assumptions, both with regard to structure and parameter values, in a model like this. It appears that the most relevant ones have to do with the [relative] rate at which depletion and learning are taking place and with the assessment of ultimate crude oil resources and potential biofuel yields. Regarding performance indicators - there are many and only some of the more obvious ones are indicated in *Figure 4.3*. One can interactively change many parameters; key ones are policy actions to influence the price of crude oil through e.g. tax regimes, and to stimulate production of biofuels through e.g. RD&D-projects.

4.3 Submodel description

4.3.1 Liquid Fuel c.q. Crude Oil demand

Demand for liquid fuels, D_{LF}, is generated in the rest of the [model]world and in two forms : Heavy Liquid Fuels (HLF) and Light Liquid Fuels (LLF). We assume that the fraction of total demand which is in the form of LLF, ∂, is given exogenously. It is assumed that only a fraction $(1-\mu)$ of LLF-demand is satisfied by oil products; the rest is supplied by the biofuel (BLF) which only competes on the market for light liquid fuels like gasoline. This biofuel market share μ depends on the relative cost of LLF and BLF on the basis of a multinomial logit formulation (cf. Appendix A). Every ton of oil products requires more than one ton of crude oil, to cover exploitation and refinery energy use and losses; this is expressed with an overhead factor f. Thus, demand for Crude Oil (CO) in any given year is :

$$D_{CO} = f * (D_{HLF} + (1-\mu)\partial\, D_{LF}) \quad \text{GJ/yr} \qquad [4.1]$$

with GJ being thermal GJth, μ the market share of the alternative biofuel and using that $D_{LLF} = \partial\, D_{LF}$. The alternative biofuel is discussed further on. Impacts on demand from competing fuels and from price changes are dealt with in the Energy Demand submodel.

4.3.2 Investment in oil exploration and exploitation

On the basis of anticipated demand for crude oil, oil companies decide to invest in crude oil producing

Inputs from the rest of the [model]world

physical Investment goods

informational [Past] LiquidFuel and OilProducts demand

Outputs to the rest of the [model]world

physical CO, HLF and LLF supply Land for Biofuel

informational Required investment goods HLF and LLF price

Relevant parameter assumptions

Depletion cost multiplier CO exploration/exploitation
BLF depletion/learning parameters
Learning rate CO exploration/exploitation capacity
Learning rate BLF
Initial CO resource base
Potential BLF yield

Performance indicators

HLF and LLF price
Reserve-Production Ratio
Required investment goods
HLF, LLF and BLF cost

Decision levers

carbon/energy tax on CO
RD&D program BLF

CO=Crude Oil HLF=Heavy Liquid Fuel LLF=Light Liquid Fuel BLF=Bio Liqu

Figure 4.3: Interactive representation of the LF-submodel

capacity and, if the reserve-production ratio (RPR) is below a desired level (RPR_d), in crude oil exploration. This anticipated demand is a trend extrapolation over a time horizon of TH years of the form $(1+r)^{TH}$ with r the annual growth rate in the past 5-10 years. Thus, D_{CO} is replaced by $AD_{CO} = (1+r)^{TH} * D_{CO}$. For exploration, the investment decision is based on the rule that oil companies try to find at least some fixed fraction, α_0, of the amount of D_{CO} plus an additional amount of $(RPR_d - RPR) * D_{CO}$ if the oil reserve R is less than $RPR_d * D_{CO}$.

It is assumed that the actual investments into exploration are less than the indicated level if the required price for crude oil, $p_{CO,req}$, exceeds its average market price, p_{CO} (cf. eqn. 4.7a). With the required price equated to the production costs multiplied by a desired gross margin (DGM) factor, this is taken into account by a multiplier Expected Profit from Investments in Production (EPIP) which changes from 1 to 0 for $p_{CO,req} / p_{CO}$ going from 0 to 2 (cf. Davidsen 1988). Thus, investments in oil exploration will only be made if oil companies expect a reasonable profit on selling their oil. Given a capital-output ratio for oil exploration, γ_{expl}, in \$/GJ/yr, the investments into exploration can for any given year t be written as :

$$IEXPL = EPIP * \gamma_{expl} * D_{CO} * (\alpha_o + \alpha (RPR_d - RPR)) \quad \$/yr \quad [4.2a]$$

with $\alpha=0$ for $RPR_d < RPR$ and else $\alpha=1$, and α_0 set somewhere between 0.1 and 1. As a result of such investments, resources will be converted into identified reserves. The dynamics of recovery technology is not explicitly taken into account (cf. Davidsen 1988). In a number of simulations, we have experimented with a lognormal distribution of the size of the oil reservoirs which are discovered.

The second decision to be made is how much to invest in oil production capacity. The producing capital stock, C_{CO}, with its capital-output ratio, γ_{prod}, has the potential to produce C / γ_{prod} GJ/yr. The investments into production are determined by the depreciation of this existing capital stock plus the required additional capacity. The latter is derived from the wish to satisfy demand D_{CO} (eqn. [1]) with the constraint that at most a fraction m of the reserves can be produced in any year. As with exploration investments, here too the multiplier EPIP is used to express the fact that actual investments are less than indicated if the the required price exceeds the market price for liquid fuel. This can be expressed in the following equation :

$$IPROD = EPIP * \gamma_{prod} * AD_{CO} - C_{CO} + C_{CO} / TL \qquad \$/yr \qquad [4.2b]$$

with AD_{CO} the anticipated crude oil demand and TL the technical lifetime of the capital stock. Note that the first term, $EPIP * \gamma_{prod} * AD_{CO}$, equals the desired capital stock for crude oil production in the near (~ 3 year) future, given the profitability requirements of investors. Both for exploration and exploitation investments, it takes some years before investments generate new reserves c.q. produce oil. If $D_{CO} > m\ R$, then demand exceeds the technical potential and $D_{CO} = m\ R$ with m indicating the technically maximum fraction producible from the reserve R per year.

If, for convenience, we equate AD_{CO} to D_{CO}, total investments I can now be expressed as :

$$\begin{aligned} I &= IEXPL + IPROD \\ &= EPIP * \gamma_{prod} * D_{CO} *[1 + \gamma\,(0.2 + \\ &\quad \alpha\,(RPR_d - RPR)] + C_{CO}\,(1/\,TL - 1) \qquad \$/yr \qquad [4.2c] \end{aligned}$$

using $\gamma_{expl} / \gamma_{prod} = \gamma$ and $RPR_d > RPR$, and using $\alpha_0 = 0.2$. Following Davidsen (1988) we take γ_{expl} to be a fixed fraction of γ_{prod}. This investment flow is the major link between the LF-submodel and the rest of the [model]world. It maintains a capital stock with a production capacity (or potential production) $PC_{CO} = C_{CO}/\gamma_{prod}$, which is not necessarily able to meet demand and is limited by the technical potential mR.

4.3.3 Depletion and learning dynamics in oil exploitation

The life-cycle of [crude] oil is based on the distinction between the resource base (X), identified reserves (R) and cumulated production (Y). The first represents the ultimately recoverable oil at some technological and cost cut-off level. This figure itself is a function of learning with expert bias (Sterman and Richardson 1983). The second represents those parts of the resource base that have been discovered as part of the exploration process and are identified by the industry as technically recoverable[11]. The main liquid fuel considered is conventional oil (CO); oil from tar sands and oil shales are not explicitly taken into account. The third level, cumulated production, is physically speaking only relevant inasfar as it enters the atmosphere as CO_2; it is also used as a parameter for depletion and learning dynamics.

The key factor in the cost of crude oil, c, is the capital-output ratio, both for production, γ_{prod} , and exploration, γ_{expl} . The change over time of this ratio should represent two trends :

a) additionally discovered oil deposits tend to be of lower quality i.e. deeper, smaller and more distant or offshore[12]. This is represented by a depletion cost multiplier which rises as a function of the ratio between cumulative production plus identified reserves, and the initial resource base, (Y+R)/X;
b) over time, [capital] costs to find and produce one unit of oil tend to decline due to technical progress of all forms. This is represented by a learning-by-doing cost multiplier which falls with the logarithm of cumulated production (cf. Appendix A).

These hypotheses are clearly approximations of the real world, shown valid for some regions in some

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[11] Unlike Davidsen (1988) we do not include explicitly the dynamics of exploration and exploitation techniques due to which an increasing fraction of the identified reserves become technically recoverable over time. It is assumed to be implicit in the learning-by-doing process.

[12] For large area's and longer time periods the trends are quite plausible, but real-world data will show large fluctuations reflecting a.o. the lognormal size distribution of oil and gas fields (see e.g. Vries 1989).

periods and vindicated for other regions in other periods. The most obvious violation of the first hypothesis was the discovery of the giant low-cost oil fields in the Middle East (see e.g. Yergin 1991). In the present submodel these discoveries have been inserted into the simulation as exogenous, zero-cost exploration results. The second hypothesis is questionable because of its application to such a heterogeneous activity as worldwide crude oil production. The strong centralization of geological and technological expertise within the industry and the ever wider use of advanced exploration techniques, however, may make the above hypotheses for the future more, not less accurate.

In formula form, the above hypotheses are expressed for any year t as follows :

$$\gamma_{prod,} = \gamma_{prod,tL,CO} * f_{CO}[(Y + R)/X_{tL,CO}] * (Y/Y_{tL,CO})^{-\pi} \quad \$/GJ/yr \quad [4.3]$$

with f_{CO} the depletion multiplier for oil production, tL the year in which depletion and learning dynamics start and π the learning coefficient. The depletion multiplier is the capital-component of what is known in economic literature as the long-term supply cost curve.

For oil exploration we assume similar depletion and learning cost multipliers. The only difference is that we use undiscovered oil, $X_t - R_t - Y_t$, instead of $Y_t + R_t$ in the depletion multiplier. For both the depletion and the learning factor, it might be better to use a measure like cumulative footage drilled (see e.g. Norgaard 1972) but at present the data are lacking except for the US.

4.3.4 The alternative : land-based BioLiquidFuel (BLF)

Biomass is an important source of both energy and materials, apart from food and fibre. Worldwide, it accounts for an estimated 15% of global energy use. In most African countries its share is over 50% and even in the USA it contributes about 4%. Its use in many countries is not declining and may even be expected to rise (Hall and House 1994). However, due to its variety of supply and use (crop residues, animal dung, charcoal, fuelwood) and its low status as the "poor man's fuel", it rarely enters official statistics and is measured inadequately. This is the main reason why we excluded traditional biomass from our simulation so far.

In the present model we confine ourselves to modern biomass as an alternative to conventional oil-based liquid fuels. After upgrading they can be substitutes for gasoline or be used in electric power generation (see e.g. Johansson et al. 1989, 1993). From the CO_2-perspective this is an attractive future option of satisfying the large demand for especially transport fuels. It will require land as a production factor, as well as labour and capital inputs. In this submodel we assume a production function which is based on three elements :

- fixed costs equal annuitized capital and land costs;
- a fixed capital-output ratio, γ_{BLF}, and an exogenously increasing capital-labour ratio, CLR_{BLF}, reflect the transition towards less labour-intensive techniques;
- a land-output ratio, ß, which increases due to learning (cf. Appendix A) and decreases when the exogenously set upper supply potential, S_p, is approached.

Given some initial estimate of the cost of BLF, its penetration into the market for LightLiquidFuels (LLF) is modelled with a multinomial logit equation (cf. Appendix A). Consequently, the indicated market share for biofuels, IMS_{BLF}, is given by :

$$IMS_{BLF} = c_{BLF}^{-k} / (c_{BLF}^{-k} + p_{OLLF}^{-k}) \quad [4.4]$$

with k the multinomial logit constant, c_{BLF} the cost of BLF and P_{OLFF} the price of oil-based LLF. With a delay, the actual market share μ will grow towards this indicated value which allows the calculation of $S = \mu D_{LLF}$. In eqn. 4.5, not the actual supply S but the indicated supply $IMS_{BLF} * D_{LLF}$, is used. It is assumed that investors, either private or government, decide to invest with a delay into BLF-producing plantations, at the rate of the indicated supply times the capital-output ratio. Consequently, with λ_{BLF} the average life-time of the capital stock, the state equation for the capital stock is :

$$dC_{BLF}/dt = IMS_{BLF} * D_{LLF} * \gamma_{BLF} - C_{BLF} / \lambda_{BLF} \quad \$/yr \quad [4.5]$$

Using the [exogenous] capital - labour ratio, the required amount of labour is calculated and multiplied with the unit labour price p_L to get total labour cost. This results in the following expression for the cost of the biofuel :

$$c_{BLF} = \{ a\, C_{BLF} + p_{land} S/ß + p_L * C_{BLF}/CLR_{BLF} \}/S \quad \$/GJ \quad [4.6a]$$

with p_{land} the lease cost of land in $/ha/yr, S the actual BLF-supply and a the annuity factor[14]. Land productivity ß is expressed as :

$$ß = ß_{tL} * f_{BLF}(S_t / S_p) * (\sum S_t/\sum S_{tL})^{-\pi} \qquad \text{GJ/ha} \qquad [4.6b]$$

with the index tL the year in which learning is assumed to start and f_{BLF} the depletion functional. π is the learning coefficient. The thus determined BLF-price - equated to BLF-costs plus a fixed profit margin - in relation to the LLF-price influences its future market share.

4.3.5 Liquid Fuel costs and prices

The capital costs of crude oil are calculated as an annuity factor times the oil production capital stock plus the exploration investments, divided by the annual oil production[13]. On top of this, it is assumed that the crude oil price is also affected by the ratio between demand and supply. This Supply Demand Multiplier (SDM), generating a cobweb-like dynamics, expresses the fact that the price increases when the ratio between demand and potential production i.e. the capacity utilization factor, approaches or exceeds one. The resulting expression for the crude oil price in any given year is :

$$p_{CO} = SDM * (a * C_{CO} + IEXPL) / P \qquad \$/GJ \qquad [4.7a]$$

with a the annuity factor. In comparison with the previously discussed depletion and learning dynamics, these are short-term fluctuations.

The next step is to incorporate the capital requirements and resulting add-on costs for transport and refining of crude oil. This is modelled in a compact way. It is assumed that these processes have the same capital-output ratio as the oil production capital stock but without the depletion multiplier, and that this ratio increases with an increasing LLF-fraction to account for additional cost of "whitening the barrel". Conversion losses are accounted for by the constant loss factor f (cf. eqn. [4.1]). These [capital] costs are then allocated as add-on costs to the heavy and the light oil products. This has been done on the basis of a fixed price ratio between LLF and HLF and the assumption that transport and refining capital costs, multiplied by a desired margin, have to be recovered from selling the fuels. We assume that $\gamma_{tr\&ref} = \gamma_{prod} / f_{CO}[(Y + R)/X_{tL}]$. The resulting expression for the price of HeavyLiquidFuel (HLF) in any given year is :

$$p_{HLF} = p_{CO} + (1+DGM)\, a\, \gamma_{prod} / ((1-\partial) + \alpha(1-\mu)\partial) / f_{CO}[(Y + R)/X_{tL}] \qquad \$/GJ \qquad [4.8b]$$

with α the price ratio between LLF and HLF. The price of LightLiquid Fuel (LLF) is now given by :

$$p_{LLF} = \alpha\, (p_{HLF} - p_{CO}) + p_{CO} \qquad \$/GJ \qquad [4.8c]$$

The prices for LLF and HLF determine the demand for Liquid Fuels (in the ED-model and the EPG-model) and the penetration of alternative BLF.

4.4 Submodel calibration

4.4.1 Parameter values

As has been discussed in Chapter 1, calibration and validation are only possible at a lower aggregation level. We have chosen the USA 1950-1990 to calibrate the LF-model, because it has the best historical data base, has dominated the oil business for a long time, and is also the region considered in the models by other authors. The calibration procedure is described in Appendix E. In the present case, the historical use of light and heavy oil products has been equated to LLF- and HLF-demand. Historical data have been collected for crude oil reserves, crude oil production and oil exploration and exploitation investments. Oil [product] imports have been introduced exogenously and subtracted from the calculated oil [product] demand. A number of parameters and functionals have been chosen in agreement with the Davidsen's model (Davidsen 1988). The results of this calibration are reported in a sequel report. The results have, in combination with the calibration of GF-model for the USA 1950-1990, been used to make minor changes in the model formulation and parametrisation. Over-all, it has given us confidence that the structural representation of this sector, and the relevance of the various parameters which allow calibration, are well done. This is espcially important since the US oil industry and oil use are of major importance in the historical period 1900-1990.

Next, we have calibrated the LF-model for the world 1900-1990 at large in similar fashion. Here, how-

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[13] An alternative formulation (cf. Davidsen 1988, FUGI 1977) is to base the capital costs on the product of capital-output ratio and an annuity factor. The difference is rather small (cf. Appendix A).

[14] The annuity factor $a = r/(1-(1+r)^{-EL})$ with r the interest rate and EL the economic lifetime of the investment.

ever, the historical time-series are less reliable, both because they are not [officially] published and because of the inclusion of regions which are possibly at the start of their oil production history. Also, some parts of the model dynamics - and consequently the associated parameters and functionals - have no proper meaning at a world level. Especially the investment- and price-based rules, derived and calibrated for the USA, cannot correctly describe a world in which an increasing part of oil production is being associated with government controls of various forms. Several parameters and functionals have been given the USA-values by want of better estimates.

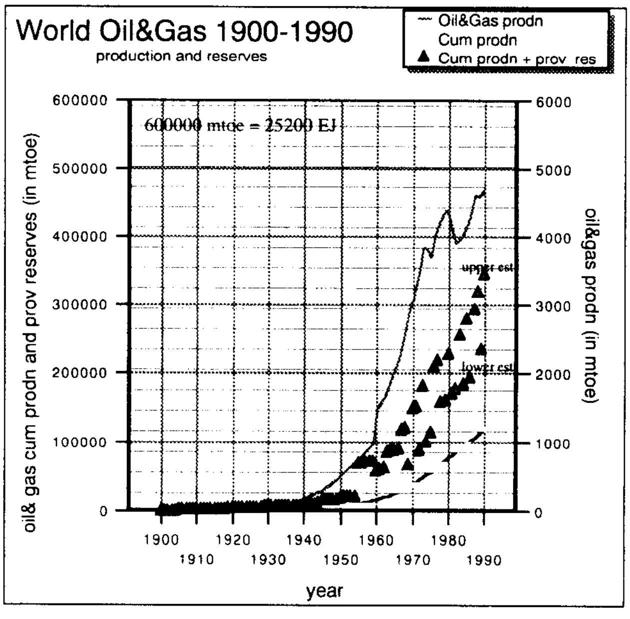
We will now discuss parameters and relationships in some detail. Although calibration is our first concern here, we also discuss some parameters which are crucial in scenario construction. First, the model requires an estimate of the long-term oil supply cost curve, i.e. the expected cost increase due to depletion as a function of cumulative oil production. Estimates of the ultimately recoverable world crude oil resources abound. Over time they have been appreciated upwardly from about 2000-8000 EJ around 1950 to somewhere between 9000 and more than 20000 EJ at present (Grenon 1977, Häfele et al. 1981, Shell 1990). The official consensus view is that the conventional oil resource base around 1985 and recoverable within present economic and technical limitations amounts to some 9000 (WEC 1993) to 15000 (Edmonds and Reilly 1986) EJ. Such estimates of the [ultimately] [technically and economically] recoverable oil depend a.o. on the probability with which it is expected to be exceeded. A median value of expert estimates (50% probability) of the resource base is 11000 EJ, ranging from 7000 EJ (95% probability of being exceeded) to 16000 EJ (5% probability of being exceeded) (McLaren and Skinner 1987). Proved reserves plus cumulated production are an estimated 9000 EJ in 1990. It should be mentioned here that oil reserves are unevenly distributed across the world and that the oil production life cycle is in different stages in the different continents. While in 1980 some two-third of the US resource base is thought to be discovered and less than 50 % remaining in the ground, the 50% larger resource base in the former USSR is thought to be discovered for only one-third with still more than 80% remaining in the ground.

An interesting analysis of the evolution of expert estimates of the ultimately recoverable oil resource indicates that there is a convergence to values around 35000 EJ of which some 21000 EJ is thought to be ultimately recoverable (Sterman and Richardson 1983). This estimate emerges from two divergent assessment methodologies. On top of this there is a large so-called unconventional oil resource base, mostly oil shales and tar sands. Estimates range from 25000 EJ (WEC 1993) up to 90000 EJ (Edmonds and Reilly 1986). We use a value of 36000 EJ for the sum of conventional and unconventional oil resources.

Figure 4.4 shows how oil and gas production, cumulative production and proven reserves have developed over time. It is seen that about half of the proven reserves discovered so far have been produced. The reserve-production ratio has been maintained due to the enormous increase in reserves from 1955 onwards.

For a supply cost curve one also needs estimates of the costs. *Figure 4.5* shows various estimates of these costs as a function of cumulative production from 1990 onwards. In the model this curve is introduced as the production depletion multiplier $f_{CO}\{(Y + R)/X_{tL,CO}\}$ with which the capital-output ratio is multiplied (cf. Eqn. [4.3]). To this purpose it is normalized to 1980 = 1 because the capital-output ratio $\gamma_{prod,t}$ is given a value for 1980 as estimated from the literature. The learning multiplier has been operating from 1900 onwards (tL = 1900) in such a way that it also equals one in 1980.

Figure 4.4: Development of oil and gas production, cumulated production and proven reserves, world 1900-1990. Proven reserve estimates include both lower and upper estimates.

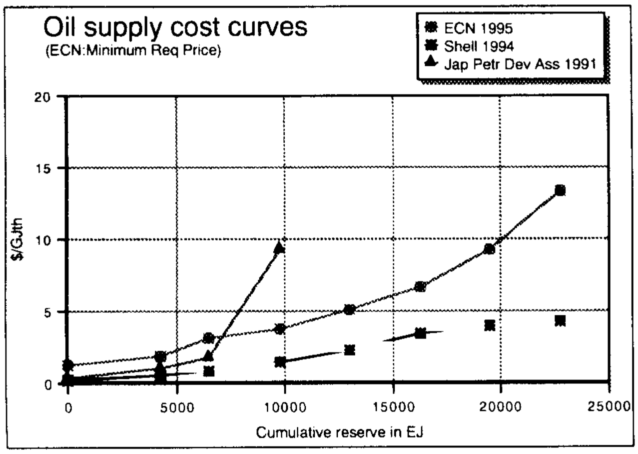


The capital-output ratio's which are the major cost component are difficult to assess over the past 90 years. More research is required, especially for areas outside the U.S. One estimate gives for around 1970 values between 1 (Middle East) and 3 $ per GJth/yr (Logters 1974). Other estimates made around 1975-1980 give values of 0.2-0.4 (Häfele et al. 1981) and 2 (onshore) to 5 (offshore) 1980$/GJth/yr (WEC 1978). We use for 1980 a value of 3 1980$/GJth/yr.

How this ratio has developed and will develop over time is a matter of taste, it seems. A WEC Delphi study in the late 1970's "indicate that there is a wide divergence of opinion as to the recoverability of oil under different cost assumptions - for example, anywhere from 10 to 70 percent of the total resource was estimated to be available at less than five 1976 dollares per barrel" (Edmonds and Reilly 1986, pp. 82). To add to the confusion, most supply cost curves include both depletion and technological learning effects. Learning effects are difficult to estimate but the learning parameter for a wide variety of industrial processes suggests that each doubling of cumulative output gives a 20% reduction in production costs (π = 0.8) (Argote and Epple, 1990; Appendix A). Some estimates made in the 1950's, probably based on cheap Middle-East reserves, are in the order of 0.2-0.4 1980$/GJth/yr; this suggests increasing capital-output ratio's as more offshore fields have been taken into exploitation. However, notably in offshore exploration and production enormous productivity gains have been realized.

The Japan Petroleum Development Association expects a doubling of production costs for the first 7000 EJ after which a steep cost increase would occur. This is clearly a risk-averse, conservative guess. Other estimates, e.g. from Shell (Kassler 1994) and ECN (1995) indicate a much slower cost increase, as *Figure 4.5* shows.

Figure 4.5: Literature values for the oil supply cost curve



The next step is to make assumptions about the fraction of heavy and light liquid fuels (HLF, LLF) in total LF-demand, the cost of transport and refining and the allocation of these costs among HLF and LLF. As to the fraction of LightLiquidFuels in the total demand for LiquidFuels, it is assumed that this fraction gradually rises from 0.06 in 1900 to 0.44 in 1990 and 0.65 around 2100, to reflect the increased "whitening-of-the-barrel".

From this, costs are converted to prices on the basis of the capacity surplus/shortage. We had to introduce two exogenous events which cannot be expected to be simulated as the underlying dynamics is not part of the model formulation :

- discovery of large oil fields between 1950 and 1970 (Middle-East), and
- a crude oil price increase of 50%-400% between 1973 and 1987 (oil price crises).

The relation between crude oil costs and prices, assumedly a function of the ratio between demand and potential production, is speculative. We use some empirical estimates based on the period in which the two oil crises occurred (Stoffers, 1990). This part of the model has to be researched in more detail; for the moment we have introduced royalties and taxes with a single, constant factor equal to 1.5. In fact, this factor is part of the supply-demand dynamics as the past decades have shown all too clearly. As to the costs of transport and refining activities, more research is needed. Our assumption of proportionality with production costs and the same learning and no depletion influences is only a rough first guess. Some key parameter and functional values are given in *Table 4.1*.

Given historical demand for HLF and LLF, the simulation reproduces the trend of declining HLF- and LLF-prices over the period 1900-1990. Both exploration and production closely follow the historical paths on the basis of demand anticipation as described in the previous paragraph. This indicates that the combination of learning and depletion dynamics allows for a fair reproduction of what is thought to have happened over the past 90 years.

As far as modern biomass is concerned : there is an increasing volume of literature on yields and costs (Johansson et al. 1993, Hall et al. 1994). From the cost expression for BLF [eqn. 4.6a] it is clear that the inverse yield, i.e. land-output ratio ß, is an

Table 4.1: Parameter and functional values in LF-model World

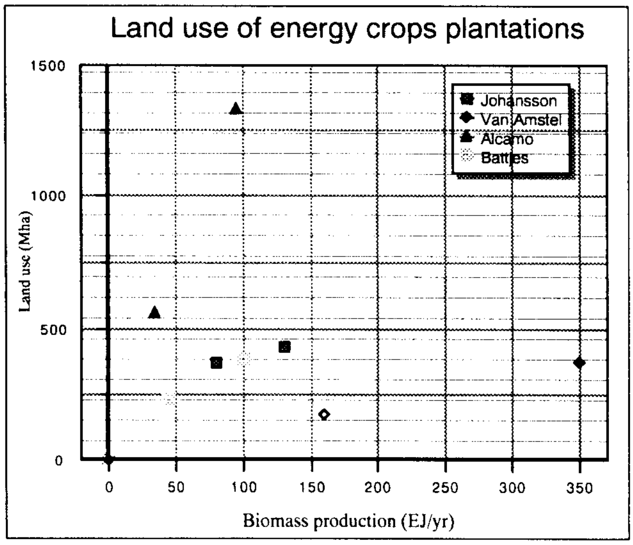
Parameter :	
Initial resource base	36.000 EJ
Oil production depletion multiplier	1(at 8000 EJ) - 12 (at 36000 EJ)
Oil production Capital Output Ratio (COR) in 1980	3
Oil learning factor	1(at 8000 EJ) - 0.3(at 36000 EJ)

important factor. In a recent OECD-study for Europe on biofuels for transport, net energy yields are ranging from 58 GJ/ha for ethanol from wheat to 200 GJ/ha for ethanol from beet. The same study uses a value of 200 GJ/ha for the year 2020 and 300 GJ/ha for the year 2050 (Hall and House 1994). For the tropical regions, higher values are given. In the present model version we assume a reference value of 470 GJ/ha which is based on 195 GJ/ha in the temperate regions, with an estimated 30% share, and 585 GJ/ha in the tropical regions, with an estimated 70% share. Some authors have given estimates for the yield improvement over time; there is, however, neither clarity nor agreement about these issues. Here, we assume a 10% cost reduction for every doubling of cumulative production (cf. eqn. 4.6b).

Unfortunately it is much more difficult to get insight into the capital and labour inputs needed to produce and upgrade biomass for use as commercial fuel. In the simulation results shown we have assumed that wages on biomass plantations equal 50% of the world average per caput consumption and that the capital-labour ratio is exogenous and increases over time from a low 10 \$/manyear in 1960 to 250 \$/manyear in 2100. Also the degree to which a supply potential S_p plays a role is hardly discussed in the literature. There are some recent estimates on the potential energy from biomass (Hall and House 1994). If all potential agricultural land minus the land required for crops is used for biomass, the developing world could produce 245 EJ/yr. An assessment based on 300 GJ/ton and 25% recoverable residues indicates that the substitution of present fossil fuel use of 335 EJ/yr would require a land area of about 15% and 2% of total land in the developed and developing world respectively. This suggests that there will be upper limits to how far biofuels can penetrate the energy market, unless large productivity increases are realized.

In this study we have relied on some empirical analyses for Brazil for the potential yield on biomass/energy plantations and the costs. The ultimate BLF-potential, S_p, has been set at 50% of 270 EJ/yr (Johansson et al. 1993) - the other half is taken for BGF. Thus we assume that up to 80 EJ/yr costs hardly increase; thereafter they rise with a factor 5 when the potential of 135 EJ/yr is reached. As a yardstick for our simulations, we have used an inventory of four analyses the data of which are given in Appendix D. *Figure 4.6* summarizes the results in the form of annual biomass production vs. land area as used in these analyses.

Figure 4.6: Annual biomass production vs. land area - various analyses



4.4.2 Calibration results

To run the model for the world at large we have to initialize the state variables and assess values to a number of parameters and relationships. In the previous paragraph the various parameter and initialisation choices have been discussed. Liquid Fuel demand comes from the ED-model (Ch. 3).

As has been discussed before, the penetration dynamics of biomass-derived fuels can hardly be made on empirically based assessments. Such estimates also have a wide range of values for the world at large, as climate, labour costs, infrastructure etc. are all important cost determinants. Our initial estimate of capital and labour costs for biofuels have

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[15] It should be noted here that biofuels in the present context are fuels from biomass, grown in plantations and for the commercial market. It does not refer to other biomass sources used to satisfy energy services e.g. wood, dung and crop residues.

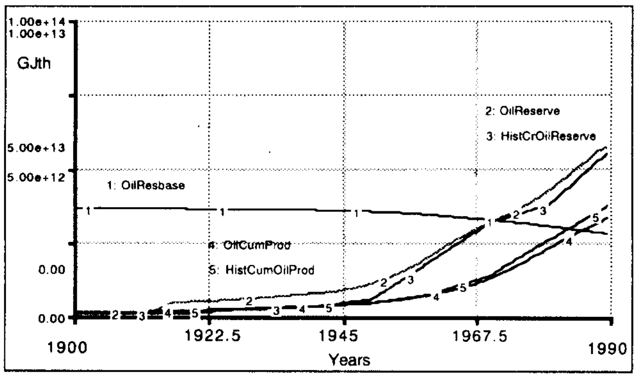


Figure 4.7a: Simulated Oil resource base, identified reserves, cumulative production and, for the last two historical values

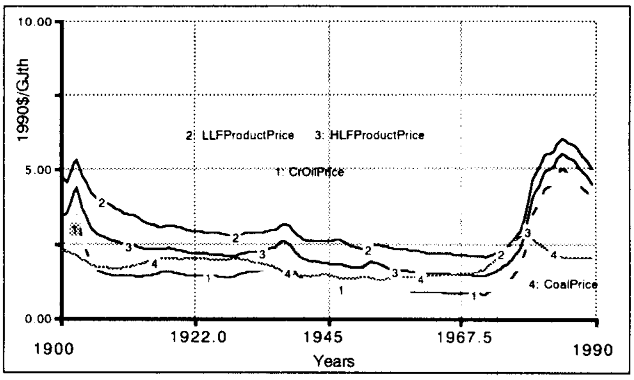


Figure 4. 7b: Simulated prices for Crude Oil, Coal, Light Liquid Fuel (LLF) and Heavy Liquid Fuel (HLF)

illustrative value only; they are chosen to ensure no noticeable market penetration before 1990.[15]

As stated before, we have added three external events into the simulation run to make the simulated past more realistic. First, a zero-cost pulse of [Middle-East] discoveries i.e. exploration successes have been introduced between 1950 and 1970, peaking in 1960 at a value of 160e9 EJ/yr. Secondly, we have introduced an external price pulse in the form of a jump in the factor for royalties and taxes with which the price is multiplied. Thirdly, we have introduced a forced introduction of biofuel plantations at the scale of present worldwide use, peaking around the year 2000 at 2 EJ/yr. This boosts the learning dynamics already in the 1980-1990 period.

Figure 4.7 shows two simulation outcomes. The left graph, *Figure 4.7a*, shows how the resource base is gradually changing into identified reserves and, later, into cumulated production between 1900 and 1990. Demand is almost completely met by oil products; biofuels are far too expensive to penetrate the market and traditional fuels are not considered. The reserve-production ratio does not change much in this run due to the exploration dynamics, emphasizing that it is not a good indicator of scarcity in a dynamic context like this modelworld.

The right graph, *Figure 4.7b*, shows how prices have developed over time. The exploration and production costs are low and declining, while between 1900 and 1990 the learning-by-doing is assumed to compensate the increasing scarcity of the reserve base. Due to royalties and taxes, plus the OPEC-crisis and other supply-demand imbalances, the crude oil price is higher than exploration and production costs and fluctuating. The price of HeavyLiquidFuels (HLF) and LightLiquidFuels (LLF) are higher because of the add-on costs for transport and refining. Biofuels, as noted before, are too expensive to affect liquid fuel prices.

5. THE GASEOUS FUEL (GF) SUBMODEL

This submodel describes the exploration for and exploitation of natural gas, and in a simple way its transport and distribution. It also describes the penetration of a land-based alternative gaseous fuel (biofuel). Gas for non-energy and from coal through gasification are not considered.
The model is almost identical to the Liquid Fuel submodel. Its goal is to provide a plausible and transparant description of the life cycle of conventional gas and the transition to a renewable alternative. Demand for gaseous fuels in the rest of the [model]world is satisfied (output); for this investment goods and labour are required from the economy model and land from the land/food model (inputs).

5.1 Introduction

Since the 1930's natural gas has become an important commercial fuel (cf. Figure 1.1). The USA was the first country where natural gas became an important energy carrier; after World War II Europe was to follow. The discovery of large natural gas fields along and in the North Sea gave an enormous impetus in Europe to the exploitation, distribution and marketing of natural gas as a fuel. Its premium value became clear when market penetration rates exceeded the most optimistic expectations. Somewhat later, important other gas basins came into production, foremost the giant gas fields in northern Russia. Flaring of natural gas, still accounting for an estimated 10% of world production, has declined significantly in the last 4-5 decades. This is largely due to the bridging of producers and consumers by way of long-distance pipelines and Liquefied Natural Gas (LNG) transport by tankers. Nevertheless, the major obstacle to further expansion is the need for capital-intensive transport systems.

5.2 Submodel representation and description

Basically, the GF-model has the same set-up as the LF-model. The only difference is that the capital investments for transport and upgrading are different and that no distinction is made between various grades (like HLF and LLF for liquid fuels). As in the LF-model, there are exploration and exploitation processes, a capacity-related price mechanism and an alternative, biomass-based fuel referred to as BGF. Because of these similarities, the model is not discussed in any further detail here.

5.3 Submodel calibration

5.3.1 Parameter values

As has been discussed in Chapter 1, calibration and validation are only possible at a lower aggregation level. As with the LF-model we have chosen the USA 1950-1990 to calibrate the GF-model, because it has the best historical data base, has dominated the gas business for a long time, and is also the region considered in the models by other authors. The calibration procedure is described in Appendix E.

Historical use of natural gas has been equated to demand. Historical data have been collected for crude gas reserves, gas production and gas exploration and exploitation investments. The role of gas imports has been explored, too. A number of parameters and functionals have been chosen in agreement with Davidsen's model (Davidsen 1988). The results of this calibration are reported in detail elsewhere (Berg 1994). The main conclusions are :

- the development of gas reserves can be reproduced quite well provided that the desired RPR drops over time from about 35 years in 1950 to 17 years from 1970 onwards. This may be related to the maturing of the gas industry;
- up to 1975 the investments for exploration and production are reproduced correctly but the steep increase between 1975 and 1985 cannot be accounted for;
- investments in gas transport and distribution - which are of the same order of magnitude as for exploration and production - also show an increase between 1980 and 1985 which cannot be accounted for. As with exploration and pro-

duction, this may be due to the impact of the oil crisis and the industry's deregulation which are not modelled;

- simulated gas prices are in good agreement with historical prices until 1975. The rise thereafter is not simulated which is probably due to the fact that the market price of gas is not explicitly coupled to the price of oil whereas in the real world they are, certainly in the short term.

The outcome of the result for the USA 1950-1990 have been used to reparametrize some model relations. Over-all, it has given us confidence that the structural representation of this sector, and the relevance of the various parameters which allow calibration, are well done. As with oil this is especially important since the US gas industry and gas use are of major importance in the historical period 1900-1990.

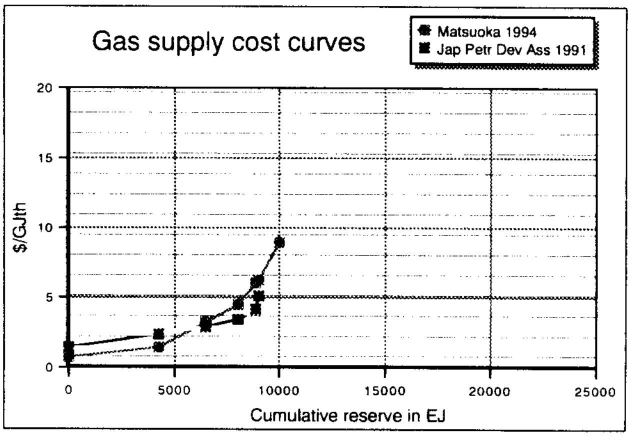
The next step has been to calibrate the GF-model for the world 1900-1990 in similar fashion. As with the LF-model, the historical time-series are less reliable, both because they are not [officially] published and because of the inclusion of regions which are possibly at the start of their gas production history. Also, some parts of the model dynamics - and consequently the associated parameters and functionals - have no proper meaning at a world level. Especially the investment- and price-based rules, derived and calibrated for the USA, cannot correctly describe a world in which an increasing part of gas production is being associated with government controls of various forms. In fact, this is a more serious limitation for natural gas than for oil because long-distance gas transport is much more expensive and rigid than for oil. Nevertheless, several parameters and functionals have been given the USA-values by want of better estimates. This issue will be addressed in future versions in which regions will be separately implemented.

We will now discuss the various parameters and relationships in the same way as with oil. The GF-model also requires an estimate of the long-term supply cost curve, i.e. the expected cost increase due to depletion as a function of cumulative gas production. Estimates of the ultimately recoverable world crude gas resources abound. Over time proven reserves have been appreciated upwardly from 800 EJ around 1965 to almost 4000 EJ at present (cf. Figure 4.4; Grenon 1977, Häfele et al. 1981, Shell 1990). Proved reserves plus cumulated production are an estimated 5700 EJ in 1990. The official consensus view is that the conventional gas resource base as of 1990 amounts to some 4500 (WEC 1993) to 6500 (Edmonds and Reilly 1986) EJ. The ultimate potentially recoverable natural gas depends a.o. on the assigned probability. A median estimate (50% probability) of the resource base is 10000 EJ, of which 13% was burnt up to 1980 and another 34% is considered as proven (McLaren and Skinner 1987). The 95% estimate of the remaining reserve is 5300 EJ, the 5% estimate 15000 EJ, according to the same study by McLaren and Skinner. On top of this there is a large so-called unconventional gas resource base, in the form of methane in clathrates and pressurized deposits (De Vries 1989). It is hard if not impossible to say to what extent they will be recoverable within a given cost range. In the present model version we use 28000 EJ for the sum of conventional and unconventional gas resources.

Figure 5.1 shows a few estimates of the supply costs of natural gas as a function of cumulative production from 1990 onwards. The curve is similar to the one in chapter 4. The Japan Petroleum Development Association expects a doubling of production costs for the first 7000 EJ after which a steep cost increase would occur (*Figure 5.1*). Learning effects are assumed to be similar to those for oil ($\pi = 0.8$).

As with oil, the capital-output ratio's are difficult to assess over the past 90 years. More research is required, especially for areas outside the U.S. Based on data for the U.S. we use 3 1980$/GJth/yr. How this ratio has developed and will develop over time is even more speculative. One would expect an increasing capital-output ratio as deeper and more distant and/or offshore fields have been taken into exploitation - probably the argument behind the upward sloping supply cost curve of *Figure 5.1*. For

Figure 5.1: Literature values for the gas supply cost curve



the giant gas basins in northern Russia, not the resource base but the rising investment costs due to harsh climate and remote location are the key problem for their exploitation. Some analysts state that operating costs of gas extraction in this region have doubled between 1970 and 1980 and that a quadrupling of capital investments for both exploitation and transportation is to be expected (Stern 1990). As to future gas imports for Europe, it is expected that these too will require huge investments in view of distances of 3-5000 km between supplier and market which require either long-distance pipelines or liquefaction. Consequently, an estimate of the long-term cost/supply curve for Europe indicates an increase from 0.4 $/GJ to 2.5 $/GJ if incremental supply exceeds 2 EJ/yr (Stern 1990). On the other hand, there is strong support for the view that natural gas may be much more abundant than in most conventional views and that there is an enormous market potential in view of its characteristics (see e.g. Lee et al. 1988). Large gas deposits of especially non-associated gas have been discovered over the past 10-20 year, and more may follow.

The next step is to make assumptions about the cost of transport and upgrading. From this, costs are converted to prices on the basis of the capacity surplus/shortage.

The relation between gas costs and prices, assumedly a function of the ratio between demand and potential production, is speculative. We use some empirical estimates based on the period in which the two oil crises occurred [Stoffers 1990]. As with oil, this part of the model has to be researched in more detail. As to the costs of transport and upgrading activities, more research is needed. Our assumption of proportionality with production costs and the same learning and no depletion influences is only a rough first guess. Some key parameter and functional values are given in *Table 5.1*.

5.3.2 Calibration results

To run the model for the world at large we have to initialize the state variables and assess values to a number of parameters and relationships. In the previous paragraph the various parameter and initialisation choices have been discussed.

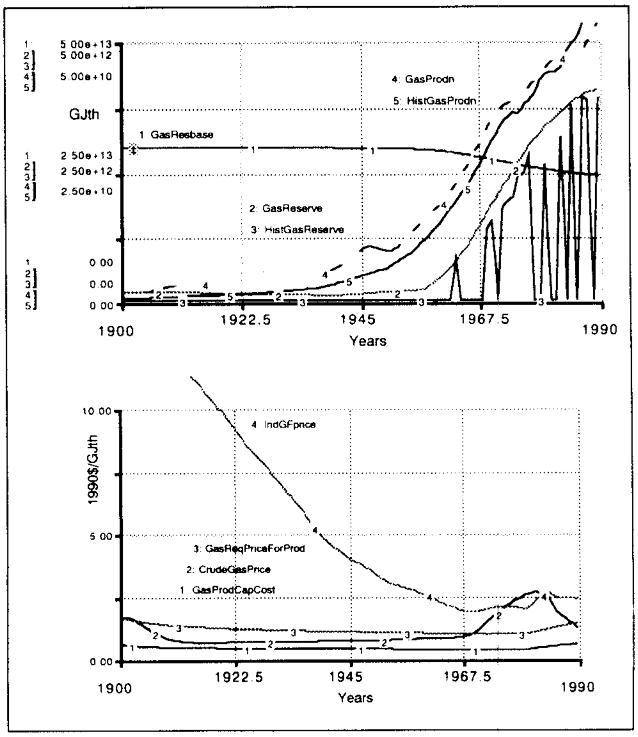
Gaseous Fuel demand comes from the ED-model (Ch.3). In this simulation, too, there are some exogenous events. First, a zero-cost pulse of gas discoveries i.e. exploration successes have been introduced between 1950 and 1980. Secondly, we have introduced an external price pulse in the form of a jump in the factor for royalties and taxes with which the price is multiplied. Unlike for the case of Liquid Fuel, we have not given an R&D-boost to biomass-based gaseous fuels (BGF) and consequently they do not penetrate the market.

Table 5.1: Parameter and functional values in GF-model World

Parameter :	
Initial resource base	**28.000 EJ**
Gas production depletion multiplier	**1(1980) - 12 (∞)**
Gas production Capital Output Ratio (COR) in 1980	**3**
Gas learning factor	**1(1980) - 0.3(∞)**

Figure 5.2 below shows two simulation outcomes. The upper graph, *Figure 5.2a*, shows how the resource base is gradually changing into identified reserves and, later, into cumulated production. It also shows that biofuels are too expensive to pene-

Figure 5.2 a-b: The gas reserve and production development and the path of product costs and prices for the industrial sector. The peaks are due to a limited set of historical world gas reserve estimates.



trate the market; traditional gaseous fuels are not considered. Historical gas reserve estimates and gas production rate are reproduced fairly well in this simulation. Like for oil the reserve-production ratio is not a good indicator of scarcity in a dynamic context like this modelworld.

The graph below, *Figure 5.2b*, shows how prices develop over time. The exploration and production costs are low and declining, because learning-by-doing is presumedly compensating the increasing scarcity of the reserve base. Due to royalties and taxes, plus the OPEC-crisis and other supply-demand imbalances, the crude gas price is higher than the costs. The actual market price for consumers (shown for industry, Ind GF price) is initially much higher than what is calculated from supply-side considerations. This is because of the premium factor which reflects market price distortions - in the case of gas, it should be interpreted as a.o. lack of adequate infrastructure and coupling with oil product prices (cf. paragraph 3.3.3).

6. THE SOLID FUEL (SF) SUBMODEL

This submodel describes the exploitation of coal. It describes separately underground and surface coal-mining and their cost-related shares. Coal [products] for non-energy use and production of synthetic oil or gas from coal are not considered.
The goal of the submodel is to provide a plausible and transparant description of the exploitation of the world's abundant coal resources. Demand for solid fuels in the rest of the [model]world is satisfied (output); for this investment goods and labour are required from the economy sector (input).

6.1 Introduction

Coal is a relatively abundant resource in comparison with the liquid and gaseous carbon occurrences. In comparison with other elements, however, it is a rather exceptional concentration, by biogeochemical processes, of an element which is largely dispersed throughout the earth crust. Exploration of coal deposits has a long history. Therefore, and for geological reasons, not many new discoveries have been made in the last decades or are expected in the future.

Coal production rates have exponentially risen since the Industrial Revolution (*Figure 1.1*). It soared in Britain soon to be followed by France, Germany, the United States and Russia. In 1913 Great Britain, Germany and the USA accounted for 81% of world output; by 1950 it had dropped to 62% (Woytinsky and Woytinsky 1953). Since the middle of the 20th century, coal's share in the commercial energy market has been declining. The main reasons have been : the penetration of oil in factories and for transport (ships, railroad) and more efficient energy use especially in steelmaking (scrap use). The coal industry was in the 1950's one of the major industries in the world, employing 1.6 million people and investing 520 million 1952-$ in Western Europe alone in 1952 (Gordon 1970).

Over the last 80 years extensive assessments of coal reserves have been made (see e.g. Fettweis (1979) for a detailed discussion). Several elaborate classification schemes have been worked out for coal. The key axes are :

- probability of occurrence (proven, probable/indicated, possible/inferred)
- geological characteristics, mainly seam thickness and depth
- physical-chemical characteristics, mainly quality in terms of the content of inorganic material (ash, sulphur) and of C-H-ratio (anthracite, bituminous, subbituminous, lignite).

Any reserve estimate has to be explicit on the probability that the coal is actually in place, on which fraction can be mined technically and/or economically, and on the need for and cost of upgrading/beneficiation of coal in view of market requirements.

A certain amount of coal-in-place can be mined in various ways. Traditional ways are underground mining with room-and-pillar methods (50-60% recoverable) and with mechanized long- and shortwall-mining (60-90% recoverable). Opencast (or surface) coal mining has become more important due to technological progress, lower labour requirements and economies of scale in surface mining techniques. Recoverability is high (>90%); environmental impacts are severe without proper restoration afterwards. Around 1973 its share was 47% in the USA and 30% in the former USSR (Fettweis 1979). An analysis by Astakhov and Grübler (1984) shows that the penetration of opencast mining in the former USSR follows the logistic substitution pattern between 1940 and 1985; around 1985 surface mining accounted for almost 40% of production.

There is a general formula for the economically acceptable overburden A for surface mining to be more profitable than underground mining : $A=(c_u - c_s)/ c_o$ (in m), with c cost per unit and u underground, s surface and o overburden removal (Fettweis 1979). The formula simply expresses the fact that the cost of removing the overburden ($=A\ c_o$) should not exceed the cost advantage of surface mining over underground mining ($c_u - c_s$). In practice, there is seldom competition between underground and opencast mining because a deposit which can be surface-mined is usually not profitable for underground mining. However, due to cost developments, the limit for economic exploitation - as compared to the alternative of underground mining - expressed as an overburden/coal ratio has been increasing[16]. This so-called stripping-ratio is presently about 30/1.

In the present SF-model, we assume that the dynamics of coal exploitation is largely governed by three factors :

- with increasing cumulative coal output, the reserves which are economically recoverable require more capital and labour per unit of output;
- the substitution of labour by capital in underground mining, thus increasing the labour productivity and reducing the costs in a situation of rising labour wages;
- the increase of capital productivity in opencast mining, and consequently a cheaper way of exploiting reserves less than 400-600 m below the surface.

The latter two trends offset the first, cost-increasing trend of declining geological and physical-chemical attractiveness. In the model there is only one generic type of coal, at 29 GJ/ton, henceforth referred to as solid fuel. That is to say, we do not distinguish between various types and grades of coal, in terms of calorific content c.q. C-H-ratio or sulphur- and ash-content. Also, other solid fuels which are largely non-commercial (fuelwood, dung a.o.) are not taken into account, at least not directly[17].

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 solid fuel use. Also, the present model version does not allow for the conversion of coal to liquid or gaseous fuels. Several technologies for liquefaction and gasification have been developed in the past, mostly under warlike circumstances. After the oil crises in 1970's, the prospects for these conversion processes were thought to be good. It was claimed that at oil prices in the order of 30-40 1979-US $/bbl would allow commercial coal liquefaction; gas from coal could become available at prices of 8-9 $/GJ if coal is available at mine-mouth cost of about 1 $/GJ (Edmonds and Reilly 1985). However, as with the cost estimates of oil from shales and tar sands, the estimates tended to rise over time while the world oil prices have dropped significantly. It also became evident that coal conversion processes have large negative environmental impacts which will further drive up costs. Apparently, only integrated systems of coal gasification and combined-cycle electric power generation offer prospects for large-scale introduction within the next few decades. This can be dealt with in the electric power generation (EPG) submodel.

The requirements for land and water due to coal production are not calculated. They may be significant and will be topic of further study in the next TARGETS-model version. Carbon-dioxide emissions are discussed in a sequel report. Other coal-related environmental pressures are not yet incorporated in the model. They do occur : land degradation, solid waste generation, emission of sulphur- and nitrogen-oxides to mention a few. They, too, will be dealt with in the next model version.

Several modelling concepts and relationships in the SF-model are analogous to those in the LF- and GF-model. More specifically, the SF-model formulation has borrowed from the Coal-model as described in Naill (1977) which is also a part of the Fossil-2 model used for the U.S. by the Department of Energy (AES 1990).

6.2 Submodel representation

Figure 6.1 is a representation of the SF-submodel at the information level. It is similar to the structure of the LF- and GF-models with two major differences :

- exploration is largely driven exogenously as most coal deposits are known and exploration has mainly to do with improving estimates of recoverable coal and its cost; and
- two different mining techniques are distinguished because they have quite different production factor inputs : underground and surface coal mining.

The physical flows picture the conversion from an [unknown] resource into an identified reserve, which is produced, transported and then - in combustion processes - converted into CO_2. At present we omit the use of coal [products] as feedstock[18]. To keep this exploitation process going, investment

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[16] A major cost reduction in opencast mining has resulted from economies of scale. For instance, bucket capacity for excavators has increased 9-fold between 1945 and 1970 (Atkinson 1977).

[17] Indirectly they are taken into account by the relationship between sectoral activity and end-use energy demand (cf. Chapter 3), assuming that most of these fuels will gradually be replaced by commercial fuels.

[18] For coal, this has been quite important in the past century but coal use for feedstock has significantly given in to the use of oil and gas, even in the important iron and steel industry.

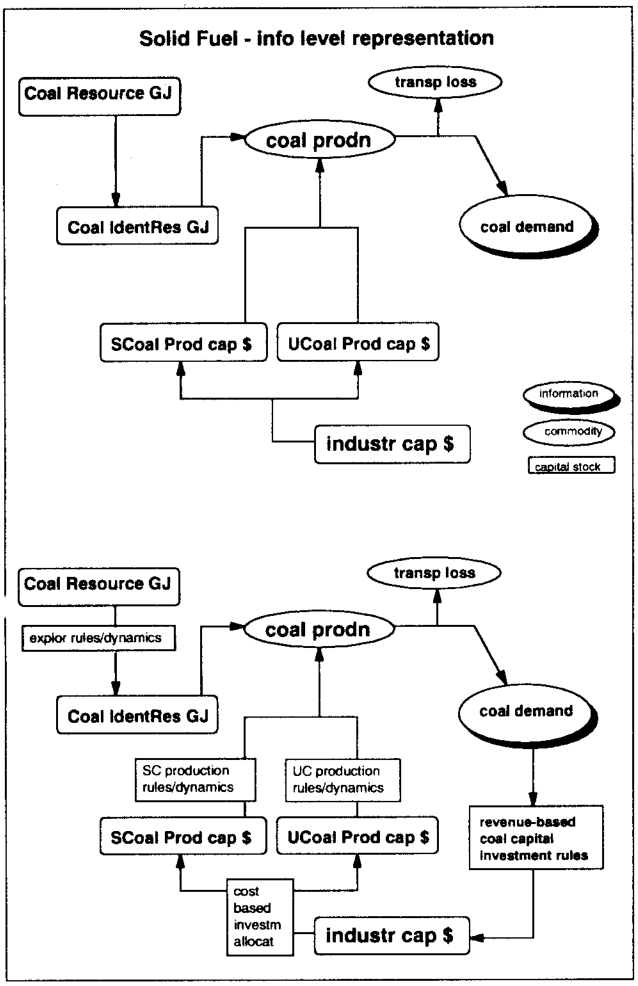


Figure 6.1: Info-level representation of the SF-model. The upper scheme indicates physical flows; the lower scheme shows the added-on behavioural/ informational structures

goods are required for the coal mining and upgrading capital stock.

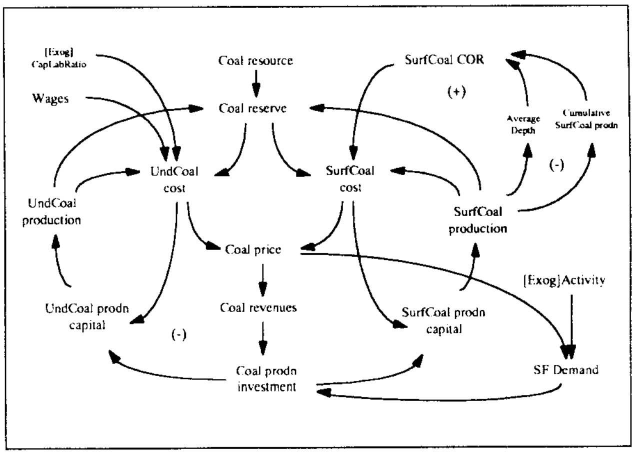
The lower scheme shows the information flows and the decisional rules. On the basis of energy c.q. coal demand, industrialists and governments invest on the basis of anticipated required capacity. Coal production is governed by a production function, which represents both the impacts of declining marginal resource quality and capital-productivity increase due to learning-by-doing. The reserve-production ratio is kept at some desired level through an exogenous discovery rate. The investors also wish to maintain a certain profit level in terms of revenues over costs; otherwise they will direct their capital into other [non-specified] activities.

The other way of representing the SF-submodel is in terms of causal loop diagrams. The major loops are shown in *Figure 6.2*. The most important short-term loop is the demand - investment - production - price loop. Given a demand for solid fuels (from the ED-model), the anticipated demand generates investments into new production capacity. These investments are a fraction of the revenues, depending on the price-to-cost ratio. The investments are allocated among underground and surface coal mining on the basis of their relative cost-ratio. An important longer-term loop is that, due to coal production, the solid fuel price is changing in response to depletion and learning dynamics, which in turn affects coal demand as calculated in the ED-model. In the present submodel, price is calculated by adding the capital costs for upgrading and transport.

A third way to represent the submodel is the interactive one (cf. *Figure 6.3*). This shows which are the in- and outputs to and from the rest of the world as well as the most important parameter assumptions, those outputs which are thought to have an indicator function and the decision levers. The most important inputs from the rest of the world are the investment goods (from the Economy submodel) and the demand for solid fuels c.q. coal. The outputs are the flows of [upgraded] coal [products], the required investment goods and coal prices. The latter is informational i.e. it serves to induce certain decisions and resulting physical fluxes in other submodels.

There are many assumptions, both with regard to structure and parameter values, in a model like this. It appears that the most relevant ones have to do with the [relative] rate at which depletion and learn-

Figure 6.2 The demand - investment - price loop in the SF-submodel. The left part is the demand-driven exploitation loop for Underground Coal (UC) with depletion and capital-labour substitution; the right part is the same for Surface Coal (SC) with depletion and learning.



Inputs from the rest of the [model]world

physical	Investment goods
informational	[Past] SolidFuel demand

Outputs to the rest of the [model]world

physical	SolidFuel [Coal] supply	
informational	Required investment goods	SolidFuel [Coal] price

Relevant parameter assumptions

Depletion cost multiplier UC/SC exploitation	Initial C resource base
Learning rate SC exploitation capacity	

Performance indicators

SolidFuel [Coal] price	Required investment goods
Reserve-Production Ratio	SolidFuel [Coal] cost

Decision levers

carbon/energy tax on SolidFuel [Coal]

Figure 6.3: Interactive representation of the SF-submodel

ing are taking place and with the degree and rate at which surface mining will replace underground mining. Regarding performance indicators - there are many and only some of the more obvious ones are indicated in *Figure 6.3*. One can interactively change many parameters; key ones are policy actions to influence the price of coal through e.g. tax regimes, and to introduce safety- and health measures in underground mining.

6.3 Submodel description

6.3.1 Investment in coal exploitation

As with liquid and gaseous fuels, demand for solid fuels, D_{SF}, is generated in the rest of the [model]world. Every ton of marketable solid fuel requires more than one ton of coal, to cover exploitation and mining and beneficiation energy use and losses. In view of widely diverging mining and upgrading processes, this has not been taken into account. The major consequence is that oil, gas and electric power use purchased by the coal industry are not accounted for. Demand for solid fuel in any given year is D_{SF} GJ/yr. Impacts on demand from competing fuels and from price changes are dealt with in the Energy Demand submodel. On the basis of anticipated demand for solid fuel, coal companies decide to invest in coal producing capacity.

As in other submodels, this anticipated demand is a trend extrapolation over a time horizon of TH years of the form $(1+r)^{TH}$ with r the annual growth rate in the past 5-10 years. Thus, D_{SF} is replaced by $AD_{SF} = (1+r)^{TH} * D_{SF}$. If the reserve-production ratio (RPR) is below a desired level (RPR_d), coal exploration will take place, but exploration costs are not taken into consideration because these are minor in view of the extensive assessments in the past (cf. eqn. 6.5).

The key investment decision to be made is how much to invest in coal production capacity and how to allocate these investments among underground and surface coal mining. As in the case of liquid and gaseous fuels, we assume that the investments into the coal industry are based on profit considerations. Given a market price for solid fuels, p_{SF}, and an average coal cost, c_{SF}, the return on investment, ROI, is calculated as :

$$ROI = (p_{SF} - c_{SF}) * P_{SF} / (UC + SC) \qquad [6.1]$$

with P_{SF} the coal production rate, $p_{SF} * P_{SF}$ the revenues from coal sales and UC, SC the underground resp. surface coal producing capital stock. Depending on the ROI-value, a certain fraction FR of these revenues is re-invested in the industry. This fraction is taken from Naill (1977), who used it in the Coal/Fossil2 model for the USA. One consequence of this way of modelling the investment decision is that it is not a realistic description of what happened in [more] centrally-planned - and important coal-producing - countries like the former USSR, India and China. This formulation also makes clear that the present model formulation does not trace money flows : where the revenues not re-invested are going to is not specified.

The available investments for coal mining are $FR * p_{SF} * P_{SF}$. This investment flow is the physical link between the SF-submodel and the rest of the [model]world. The share of it going into underground mining depends on the cost ratio between underground and surface mined coal. As in the case of BLF and BGF, this allocation is determined on the basis of a multinomial logit function (cf. Appendix A) :

$$IMSI_{UC} = C_{UC}^{-k} / (C_{UC}^{-k} + C_{SC}^{-k}) \qquad [6.2]$$

with $IMSI_{UC}$ the indicated share of investments going into underground mining and k the multinomial logit constant. With a delay, the actual market share μ_{UC} will grow towards this indicated value. Exploitation investments take some years before they are actually producing coal. The remaining share of the investments goes into surface coal mining. The resulting state equations are now in analytical form :

$$dUC/dt = \mu_{UC} * FR * p_{SF} * P_{SF} - UC/\lambda_{UC} \qquad \$/yr \quad [6.3]$$

$$dSC/dt = (1 - \mu_{UC}) * FR * p_{SF} * P_{SF} - SC/\lambda_{SC} \qquad \$/yr \quad [6.4]$$

with λ capital stock lifetime and μ_i the actual share of option i in the investments.

6.3.2 Depletion, substitution and learning dynamics in coal exploitation

The life-cycle of coal is based on the distinction between the resource base (X), identified reserves (R) and cumulated production (Y). The first represents the ultimately recoverable coal at same technological and cost cut-off level. The second represents those parts of the resource base that have been discovered as part of the exploration process and are identified by the industry as technically recoverable. The main solid fuel considered is coal; oil and gas [products] from coal and other solid fuels are not explicitly taken into account. The third, cumulated production, is physically speaking only relevant inasfar as it enters the atmosphere as CO_2; it is however also used as a depletion and learning indicator.

The resource base X is explored and discovered, i.e. converted into identified reserves R. The coal exploration rate leads to a coal discovery rate (CDR) which is governed by the equation :

$$CDR = (RPR_d - RPR) * P_{SF} + CDR_{ex} \qquad GJ/yr \quad [6.5]$$

with P_{SF} total annual production of solid fuels, i.e. coal, RPR the Reserve-Production Ratio. To reproduce the historical development of reserves plus cumulated production, an exogenous time-series called Coal Discovery Rate (CDR_{ex}) is used.

The key factor in the cost of coal is the capital-output ratio, γ_{prod}. The change over time of this ratio should represent three trends :

a) as exploration proceeds, newly discovered deposits tend to be of lower quality i.e. deeper, smaller and more distant. This is represented by a depletion cost multiplier which rises as a function of the ratio between cumulated production plus identified reserves, and the initial resource base;

b) in the labour-intensive underground coal mining, labour productivity increases over time as more capital per labourer is used; this substitution of labour by capital has been an important trend in the past;
c) over time, [capital] costs to find and produce one unit of coal tend to decline due to technical progress of all forms. This is for underground mining implicit in the capital-labour substitution but for surface mining it is modelled on the basis of loglinear learning (cf. Appendix A).

These three trends have been observed in the past in various degrees and combinations.

The underground mining capital stock UC has a capital-output ratio, $\gamma_{prod,UC}$. Hence, its production capacity is $PC_{UC} = UC / \gamma_{prod,UC}$ GJ/yr in any year. The productivity of this capital stock is described according to a two-factor Cobb-Douglas-type production function in combination with a depletion multiplier (cf. Naill 1977). In formula form, the above dynamics are expressed as follows :

$$PC_{UC} = PC_{UC,1900} * f_{UC}[(Y + R)/X] * (UC/UC_0)^{\alpha} * (L/L_0)^{1-\alpha} * SHM \quad \text{GJ/yr} \quad [6.6]$$

with f_{UC} the depletion multiplier for underground coal production and α the substitution coefficient between capital UC and labour L. The functional f_{UC} is driven by the fraction of reserves remaining, $(Y + R)/X$. For α we have taken the value used by Naill for the U.S. : $\alpha = 0.47$. Following Naill (1977) the labour requirement is based on an exogenous time-series of the capital-labour ratio; it is not driven by relative factor prices. It is adapted from estimates for Western Europe and the USA (Gordon 1970, 1987; Naill 1977), to take into account that mechanisation in underground coal mining was lagging behind in other regions in the world. SHM is a multiplier which accounts for the introduction of measures to improve safety and health of coal miners; its value is set at one unless a specific policy target is explored. It will not be discussed here.

In the case of surface coal mining, labour costs are much smaller and taken to be a fixed and small fraction of the capital costs. In the SF-model it is assumed that all discoveries are added to the reserves. The decline in the fraction of reserves remaining, $(Y + R)/X$, will cause larger average deposit depth, which in turn increases the capital-output ratio for surface coal mining. Also, analogous to oil- and gas-production, the capital productivity for surface coal mining increases with cumulated production. Consequently, the expression for the capital-output ratio reads :

$$\gamma_{prod,SC} = \gamma_{prod,SC,1900} * g_{SC}(ADD/ADD_{1900}) * (Y/Y_{tL,SC})^{-\pi} \quad \$/GJ/yr \quad [6.7]$$

with ADD the average deposit depth of the reserve, g_{sc} an increasing functional, tL the year in which learning dynamics start and π the learning coefficient.

The resulting expression for the total coal producing capacity is :

$$PC_{SF} = UC / \gamma_{prod,UC} + SC / \gamma_{prod,SC} \quad \text{GJ/yr} \quad [6.8]$$

The actual coal production equals coal production capacity, unless the ratio between coal demand and coal production capacity exceeds 0.9 in which case less coal is produced than the capacity. Thus, capacity shortage allows a further production increase up to a certain point.

6.3.4. Coal costs and prices

The capital costs of coal are calculated as an annuity factor times the production capital stock, divided by the annual production (see also Appendix A). However, for underground mining also the labour costs have to be included. The exogenous time-series for the capital-labour ratio allows the calculation of the required labour force, which is assumed to become available with a delay. The wage rate has been set equal to some fixed factor times the average consumption per caput. The cost of underground-mined coal is then calculated as the sum of annuitized capital costs and the product of labour force and wage rate. Given the cost of underground and surface coal, c_{UC} and c_{SC}, the average coal cost c_{avg} is determined as a weighted average.

It is assumed, as with the LF- and GF-model, that the coal price is also affected by the ratio between demand and supply. This Supply Demand Multiplier (SDM), generating a cobweb-like dynamics, expresses the fact that the price increases when the ratio between demand and potential production, i.e. production capacity PC_{SF}, approaches or exceeds one. The market price for coal is calculated now as :

$$p_{SF} = SDM * c_{avg} \qquad \$/GJ \quad [6.9]$$

The next step is to incorporate the capital requirements and resulting add-on costs for transport and upgrading of coal. This is modelled in a very simple way in the form of a fixed multiplier, presently set at 1.4. Conversion losses are accounted for by this same factor. It is assumed that 90% of these additional costs are in the form of annuity payments for investments. Energy, mostly Heavy Liquid Fuel, for coal transport is not included here but is implicit in the energy demand for transport; it may be up to 3-4% of the coal calorific content (Vries and Nieuwlaar 1981). If the price changes in response to an excess or shortage of capacity, this decreases or increases revenues which in turn with a delay generates lower resp. higher investments.

6.4 Submodel calibration

6.4.1 Parameter values

As has been discussed in Chapter 1, calibration and validation are only possible at a lower aggregation level. For the SF-model we have not done yet a systematic calibration. Historical data on reserves, production and prices have been collected for the period 1900-1990. The data base is still incomplete. Wherever possible we have followed the calibration procedure as described in Appendix E. A number of parameters and functionals have been chosen in agreement with Naill's model (1977). Over-all, we are confident that the longer-term dynamics is plausible but some major topics like the availability and cost of labour and the quality characteristics of the reserves deserve closer scrutiny. As with the LF- and GF-model, some parts of the model dynamics - and consequently the associated parameters and functionals - have no proper meaning at a world level. In fact, even more than with oil and gas, the investment- and price-based rules cannot correctly describe a world in which a large part of solid fuel production is under various forms of government controls.

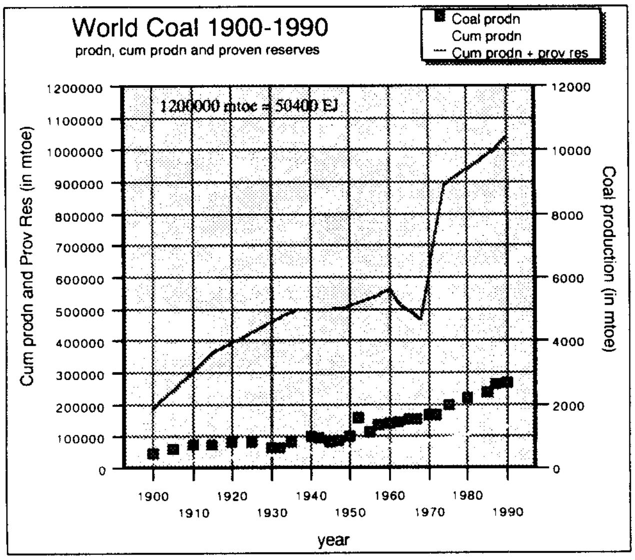
We will now discuss the various parameters and relationships in some detail. Although calibration is our first concern here, we also discuss some parameters which are crucial in scenario construction. First, the model requires an estimate of the long-term coal supply cost curve, i.e. the expected cost increase due to depletion as a function of cumulative coal production. Estimates of the ultimately recoverable world coal resources abound. *Figure 6.4* shows the world coal production and estimates of proved reserves over the period 1900-1990. Two things are worth noting (cf. *Figure 1.1*) :

- coal production has risen much less than oil and gas production, and coal reserve estimates have increased but also much less than oil and gas reserve estimates. This is in agreement with the longer-term substitution dynamics as hypothesized by e.g. King Hubbert (1967) and Marchetti and Nakicenovic (1978)
- present estimates of proved coal reserves - which excludes more speculative or presently unrecoverable occurrences - exceed present estimates of proved oil and gas reserves with a factor of 4 à 5. Only a small fraction of the resource base has been produced so far although coal is the first commercially, on a large scale exploited fossil fuel.

Another difference with oil and gas reserves is that the coal resource base has a different geographical distribution . Of the proved reserves about one third is in the USA, 20% in the former USSR and 10% in China. Of total resources as estimated by the World Energy Conference (WEC 1993) these shares are an estimated 26%, 42% and 13% respectively. The dip in the reserve estimates seems to be caused by reassessments for the former USSR and China.

Proved reserves plus cumulated production are an estimated 1500 EJ in 1900 and about 4600 EJ in 1990, based on an estimate of 620 EJ between 1600

Figure 6.4: Development of solid fuel (coal and lignite) production, cumulated production and proven reserves, world 1900-1990



and 1900 (Gordon 1970). Estimates of proved, technically and economically recoverable reserves of coal and lignite range from 45000 (WEC 1993) to 169000 EJ (Edmonds and Reilly 1986) to 241000 EJ (WEC 1989). The estimate of the ultimately recoverable coal and lignite depends a.o. on the reserve categories included (Fettweis 1979). The official view is that the total coal resource base as of 1980 amounts to some 380000 EJ (WEC 1978). Other estimates are 142000 EJ (Häfele et al. 1981, WEC 1993) and 131000+ EJ (WEC 1989). We use a value of 230000 EJ, or 7880 billion tons of coal equivalent at 29.3 GJ/ton, for the resource base as of 1900.

For a supply cost curve one also needs estimates of the exploitation costs. Such estimates are rare.The two estimates found in the literature are shown in *Figure 6.5,* together with the one used in the SF-model (Edmonds and Reilly 1986, Kaya et al. 1991). It is seen that solid fuel costs at the mine-mouth and not considering quality are expected to rise non-linearly. Not shown are the large uncertainties in each of these estimates. For our estimate we have also used Naill's estimate for the estimated 21000 EJ in the USA.

The situation is different from the LF- and GF-model because the SF-model assumes two competing mining technologies. For both scarcity is driven by a declining fraction of reserves remaining (cf. Eqn. [6.5], [6.6]). For underground coal mining this shows up in the costs by way of a depletion multiplier; this is the one shown in *Figure 6.6*. For those deposits which are shallow and large enough to be surface mined, it shows up in increasing depth. This relation is shown in *Figure 6.6* and entered into the cost function of Eqn. [6.7] as $g_{SC}(ADD/ADD_{1900}) = 1 + 3 * (ADD/ADD_{1900})$.

For this function c.q. cost function we have not found empirical justification so far. Consequently, the penetration of surface mined production of coal and lignite had to be simulated by using the guestimate of *Figure 6.6* and calibrating the surface-mined coal costs with help of initial capital-output ratio and learning multiplier in such a way that historical output levels are reproduced. The resulting choice is that the initial capital-output ratio $\gamma_{prod,SC,1900} = 0.75$ \$/GJ/yr and that the learning multiplier has been operating from 1900 onwards (tL = 1900) in such a way that it equals one in 1980. As is discussed in the next paragraph, this procedure allowed a good reproduction of past production rates. It also revealed a large sensitivity for the initial value of $\gamma_{prod,SC,1900}$. A drop with one third requires much faster learning, a rise with 20% requires much slower learning.

A second set of calibrations concerns the capital stock and labour requirements for underground mining. We assume that all coal mined in 1900 was underground and that the initial capital-labour ratio for UC in 1900 equals two third of the 1970-estimate for the U.S. by Naill (1977). That is : $\gamma_{prod,UC,1900} = 0.21$ 1970-\$/GJ/yr. The Capital-Labour ratio is assumed to increase from 2500 in 1900 to 57000 \$/manyear/yr in 1990. From this, the initial capital stock UC is calculated as 4.3 billion \$. We used literature estimates of labour productivity : for W-Europe and the USSR values of 150-280 tce per person employed are given for 1913, while the USA has higher values (Gordon 1970). We use 200 tce/person for the world at large in 1900.

The rising capital-labour ratio reflects the mechanisation trend in underground coal mining and is, as stated previously, adapted from Naill's estimate for the U.S. for the period 1950-2010. For scenario's, we assumed that productivity estimates for Western Europe and the U.S. will with a 20-year delay become world averages. Because there are only a few reliable data, this needs further research. The time-series used for the reference scenario is shown in *Figure 6.7*. For surface-mined coal, we had to rely on an equally sparse data set. As discussed in the previous paragraph, the capital-output ratio has been chosen in such a way that the historical world production estimates are reproduced satisfactorily.

Among the data used for this calibration is a regression analysis for the former USSR, which shows that the penetration of surface mining is well described by the ratio of average labour productivity in surface mining over underground mining (Astakhov and Grübler 1984). *Figure 6.8* shows these productivities; the large productivity rise after 1940 is remarkable. Similar productivity increases for surface mining occurred in the USA and Western and Eastern Europe (lignite). In underground mining in the former USSR and Western Europe, they have risen much less despite the increasing mechanisation. Throughout Europe and the former USSR they ranged in 1968 between 1.3 and 2.2 ton/man-shift[20].

Once the capital and labour requirements are calculated, coal costs can be calculated. These costs are extraction costs only. The inclusion of upgrading and transport costs have been accounted for by multiplication with a factor 1.4. This approach is too

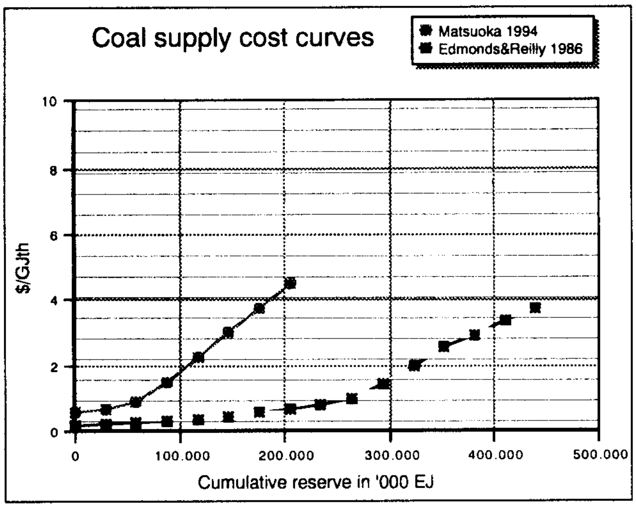


Figure 6.5: Literature values for the solid fuel (coal and lignite) supply cost curve

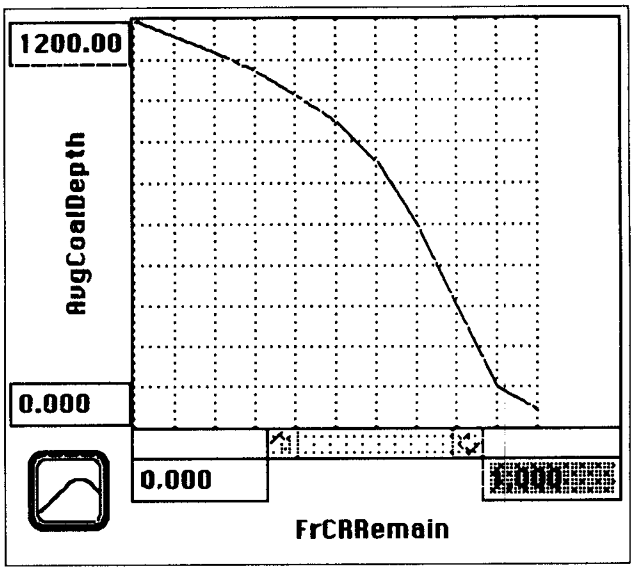


Figure 6.6: The assumed relationship between depletion of solid fuel resource base and the average depth of surface-mined deposits, ADD (in meter)

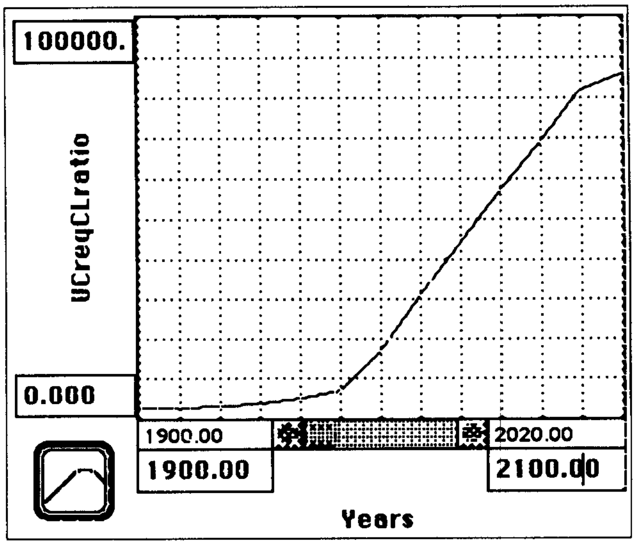
simple and needs more research. There are good reasons to assume that upgrading and transport costs may increase as the distance between mine and consumer increases and stricter quality standards are introduced (ash, sulphur). In fact, this development is part of the over-all dynamics according to which the lowest cost deposits are [surface-]mined first.

The supply-demand multiplier SDM (eqn. [6.9]) is adapted from Naill (1977) and the LF- and GF-model. It is shown in *Figure 6.9*. As can be seen from this graph, the price exceeds the cost with 50% if coal demand equals coal producing capacity. The cobweb-dynamics occurs when overcapacity lowers the price/cost ratio e.g. to 1.2 for 20% overcapacity; a capacity shortage will increase it, e.g. to 1.8 at 20% capacity shortage. Because the price/cost ratio affects revenues and therefore the investments, it is a negative feedback loop. To incorporate the effects of the 1972- and 1979-oil crises, coal prices have been multiplied with a multiplier larger than one between 1970 and 1985.

Ideally, the SDM-relationship has to be derived from investigating coal cost and price fluctuations. However, coal cost and price data are not easily collected : they differ for regions and markets because of geographical, geological and economic reasons, even without any government interference. In real terms, wholesale coal prices in Western Europe have risen less than 20% between 1955 and 1968. Pithead prices in Western Europe 1959-1968 were in the order of 13-17 $/ton excl. tax and transport; delivered prices varied between 15 and 26 $/ton (Gordon 1970). This is 0.5-0.9 $/GJ which is the range for which the SF-model has been calibrated.

After 1960 the [European] coal industry faced increasing competition from oil and gas. Governments responded with subsidies, for strategic and employment reasons. Per GJ these subsidies amounted to 0.1 $/GJ in 1976 but increased to 0.35 $/GJ in 1981 up to 0.9 $/GJ in 1985. Despite these subsidies we had to introduce in the ED-submodel premium factors for coal larger than 1, i.e. markets

Figure 6.7: The assumed development of the capital-labour ratio in underground mining, world 1900-2020



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[20] Gordon (1970) gives 13.67 ton/manshift for undergrond mining in the USA - much higher, presumedly because of cheaper mining methods which are not applicable in European coalfields.

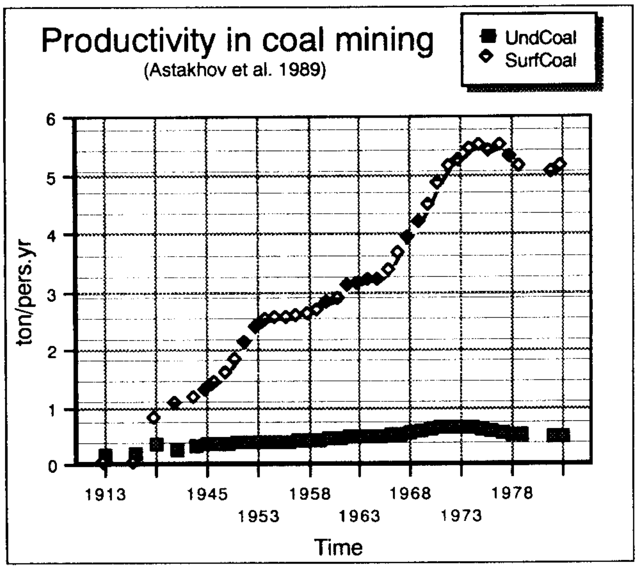

Figure 6.8: Increase in labbour productivity in the former USSR (Astakhov et al. 1989)

responded more to the actual costs than to market prices. Only in the electric power generation market coal remained competitive thanks to these subsidies. *Table 6.1* gives a brief summary of the assumptions used in the simulations presented here

6.4.2 Calibration results

As with the LF- and SF-model we present results for a simulation experiment in which the demand for coal is determined in the ED-model and driving the coal supply sector. To run the model for the world at large we have to initialize the state variables and assess values to a number of parameters and relationships; these initialisation and parameter values have been discussed in the previous paragraph.

Figure 6.9: Supply Demand Multiplier (SDM)

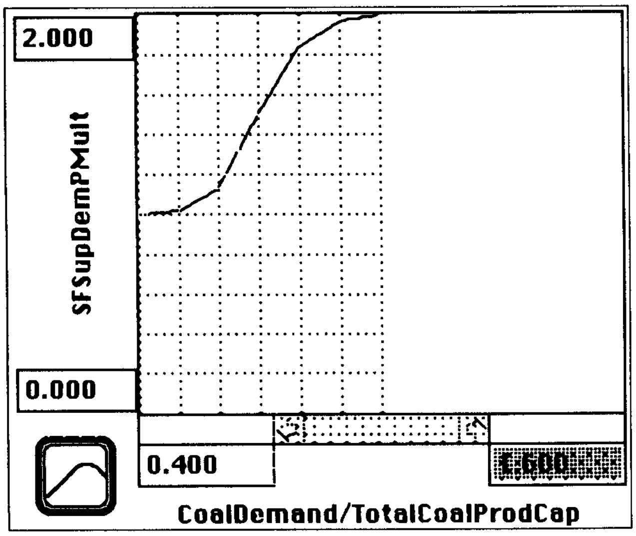

Table 6.1 Parameter and functional values in SF-model World

Initial resource base	230.000 EJ
UC production depletion multiplier (f_{UC})	1(1)-0(0)
SC production depletion multiplier	4(50m)- 73(1200m)
SC learning multiplier coefficient (α)	3.8(1900)-1(1970)- 0.8(1990)
UC Capital Labour substitution	0.53
SC Capital Output Ratio (COR) in 1980	0.75 $/GJ/yr
UC-SC substitution multinomial logit parameter (k)	0.8

As has been discussed before, the penetration dynamics of surface mining technology is difficult to make on empirically based assessments. Consequently, our initial estimate of capital costs and depletion and learning parameters have illustrative value only; they are chosen to ensure a fair reproduction of historical data. As explained before, we have added one external event into the simulation : an external price pulse in the form of a factor with which coal cost is multiplied to simulate the two oil price crises.

Figure 6.10 below shows two simulation outcomes. The upper graph, *Figure 6.10a*, shows how total coal production closely follows the historical output. This is also the case for the share of surface-mined coal; historical data for the world are not shown.

The graph below, *Figure 6.10b*, shows how prices develop over time. The costs of underground-mined coal are in the order of 1 $/GJ with minor fluctuations. Because the cost of surface-mined coal has kept decreasing due to learning, its share gradually increases to the present 40-50% (cf. *Figure 6.10a*). The coal price is higher and reflects the fixed upgrading and transport costs as well as the fluctuations due to over- or underutilisation of the mining capital stock . From a long-term perspective, one can observe that the model generates rising underground-mined coal costs due to labour costs and depletion, which is partly mitigated by the introduction of lower-cost surface-mined coal. For comparison, also the path of the major competing fuel, Heavy Liquid Fuel (HLF), is shown.

The investments required to meet the [exogenous] demand for solid fuels are initially dominating

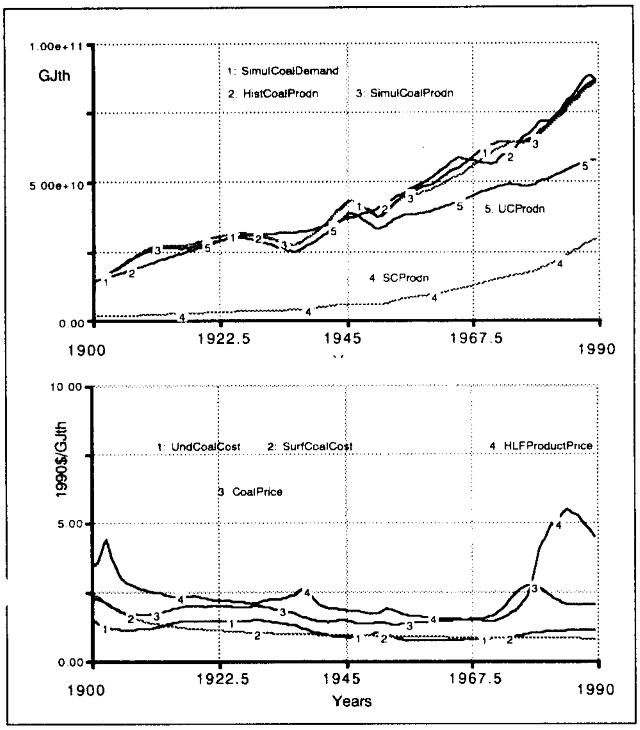

Figure 6.10a-b: The coal reserve and production development and the path of product costs and prices

total investments in fossil fuel supply. After the second world war, however, their share drops to below 30%.

7. THE ELECTRIC POWER GENERATION (EPG) SUBMODEL

This submodel represents the generation of electricity by way of thermal, non-thermal and hydro generating capacity. Non-thermal is viewed as a competing alternative (nuclear, solar...) which penetrates the market. The goal of the submodel is to provide a transparant and plausible description of how fossil-fuelled electric power generation is gradually replaced by a non-thermal alternative. The demand for electricity in the rest of the [model]world is satisfied (output); to do this a flow of fossil fuels from the energy supply models and of investment goods from the economy model are used (inputs).

7.1 Introduction

Electric power generation is an important and growing part of the energy supply system. Construction of power plants and the transmission and distribution network absorbs a sizeable fraction of a nation's investments, especially in the build-up stage.[21] Operation of thermal electric power plants requires large amounts of fossil fuel. In the industrialized countries the share of electricity in total final energy use has risen from less than 7% around 1950 to more than 17% around 1990 (Nakicenovic 1989). From the perspective of CO_2-emissions, electric power generation is of great importance. It not only is a large emitter but it has also an interesting array of emission-reduction options. Prominent among these are the non-thermal electric power plants based on hydropower, nuclear fission heat, wind- and solar power and biofuels. Large-scale distribution of waste heat (district heating) and combined heat-and-power schemes (cogeneration), further increases of the thermal-to-electric conversion efficiency (STAG-cycle, fuel cells) and removal of CO_2 from exhaust gases are among the other options. Electric power generation is also an important, in many countries the most important emitter of acidifying compounds like SO_2 and NO_x; interesting mitigation options are conversion into partly usable solid waste flows through flue-gas desulphurisation and fuel cleaning.

The concepts used in the present models are partly based on previous modelling efforts, notably on work by Baughman (1972), Naill (1977) and AES (1990). Some model parts are similar to the corresponding parts in the supply models, e.g. the learning multiplier formulation.

7.2 Submodel representation

As has been discussed, the EPG-model is situated within the larger framework of TARGETS. *Figure 7.1* is a representation of the EPG-submodel in terms of the info-levels discussed in Chapter 1. The physical flows, indicated in the upper scheme, are summarily indicated. There are three electricity generating capital stocks, in which physical investment flows from the industrial capital stock and fossil fuels from the fossil-fuel capital stock are combined. The electricity produced flows towards consumers i.e. to the Economy submodel.

The lower scheme shows the information flows and decisional rules which determine the dynamics of the physical flows. On the basis of electricity demand, orders are given for electricity generating capacity. Whether this is for thermal or non-thermal capacity is based on their respective generation costs. For hydropower it is an exogenously planned expansion. How much electricity is produced with the existing capital stocks is determined by the system operating rules. Whether thermal capacity is fuelled with solid, liquid or gaseous fuels depends on their respective prices.

From a systems dynamics perspective the EPG-submodel is a set of interconnected causal loops. The most important one is the demand - investment - price loop in connection with the submodels Economy and the LGF- and SF-submodels (*Figure 7.2*). This loop simulates the planning process in which a future demand is anticipated from which the

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[21] For the developing countries an estimated US $ 100 billion annual investments are required for the electric power sector in the decade of the 90's, making up 12% of total domestic investments. For India, for example, capital may become a major constraint in realizing its power expansion planning.

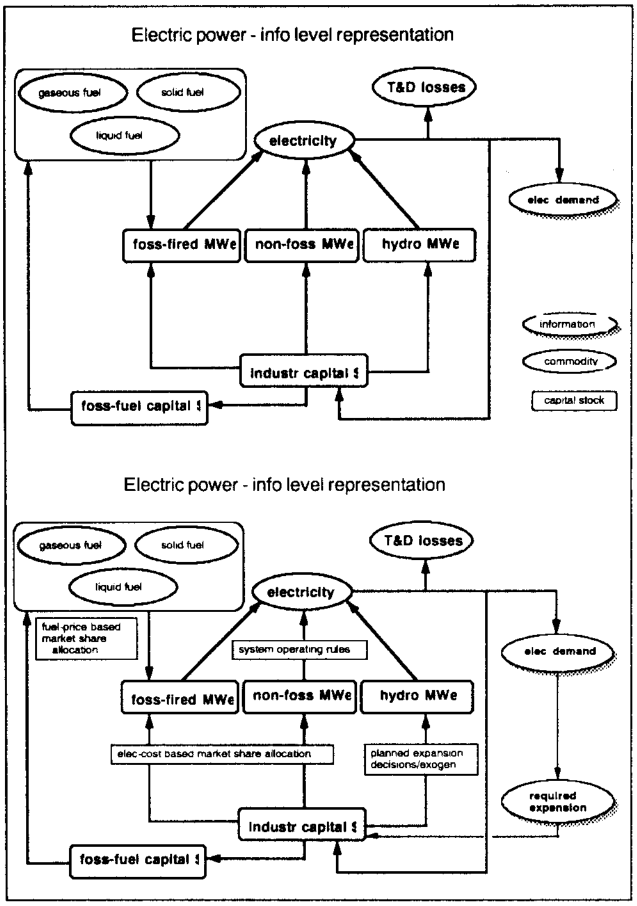


Figure 7.1: Information level representation of the EPG-model. The upper scheme indicates physical flows; the lower scheme shows the added-on informational structures.

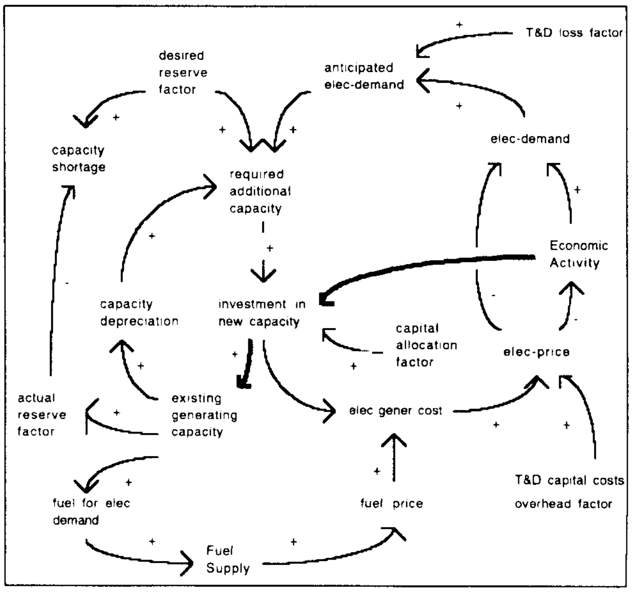
required new capacity is derived. This amount of new capacity is ordered if there are no capital or other constraints (allocation factor equal to one); this results in an investment flow and new capacity coming into operation. In combination with fuel costs, this influences the electricity generating costs and, through transmission and distribution costs and an overhead factor, electricity prices. This in turn affects the demand for electricity (ED-submodel). If there is a capacity shortfall, economic activity is below its potential. This is not modelled in the present model version: activity levels are exogenous.

One of the key parts of the EPG-submodel are the investment decisions. In most countries electric power generation is done by large, state-owned or state-regulated companies. Often, the government is also [one of] the major investor[s] and investment decisions are made on the basis of various criteria e.g. economic, strategic and environmental

Therefore, we model the investment decisions in the form of an actor with the following characteristics :

- the investor anticipates a growth in electricity demand; in combination with a preferred reserve factor and time horizon, this indicates how much capacity has to be added to the system. The resulting expansion plan is implemented by ordering new units of one of the three categories of electricity producing capital stock, which come into operation with a construction delay;
- expansion of hydropower capacity is based on an exogenous time-path. It is constrained by a fixed potential which can be exploited at increasing marginal specific investment costs;
- investments in new capacity (excluding hydropower) is allocated to thermal resp. non-thermal on the basis of the cost differential of thermal resp. non-thermal electricity. An explicit target for the fraction of non-thermal electricity in the total electricity generated or an RD&D-program based construction pulse can be implemented to interfere with the cost-based market penetration dynamics;
- thermal capacity will be used for the upper part of the load-duration curve; each of the three fuels (solid, liquid, gaseous) gets a market share in the total fuel required on the basis of the cost differential of the fuels. The implicit assumption is that, with a delay, all thermal capacity is multi-firing.

Figure 7.2: The demand - investment - price loop. The influence of electricity price on economic activity is absent in the present model version.



Inputs from the [model]world

physical	Fuels	Investment goods
informational	[Past] Electricity demand	Fuel prices (solid, liquid, gaseous)

Outputs to the rest of the [model]world

physical	Electricity	
informational	Required investment goods	Electricity price

Relevant parameter assumptions

Learning rate non-thermal capacity
Time trend in non-thermal base-load factor
Time trend conv efficiency thermal capacity
Fuel shadow price factors

Performance indicators

Electricity price
Actual reserve factor
Required investment goods
Fuel inputs (solid, liquid, gaseous)

Decision levers

Expansion targets hydropower (constrained) (Mwe, year)
R&D program Non-Thermal Electric

Figure 7.3: Interactive representation of the EPG-model

One fourth option links the EPG- to the Energy Demand submodel : Combined Heat and Power (CHP). This, however, has not yet been included.

Another representation is user-oriented : a black box with inputs from and outputs to the rest of the [model]world, complemented with a specific set of model parameter assumptions, model output performance indicators and decision levers. *Figure 7.3* gives this overview for the EPG-model.

The major physical interactions with the rest of the modelworld are the input of fuels and investment goods and the output of electricity. The informational signals which govern these flows are the [anticipated] demand for electricity and the fuel prices. The electricity price as a demand-affecting signal is part of the Economy submodel.

An important assumption has to do with the learning rate and market penetration rate of the non-thermal alternative. In the allocation of fuels, the existence of premium factors is an exogenous assumption. Another important assumption concerns the change over time of the thermal conversion efficiency and of the non-thermal base-load factor. These are as of yet explicit functions of time. The reason is, for thermal efficiency, that the insights about what influences its increase are inadequate. For the base-load factor for non-thermal generating option, the main reason is that it is an aggregate of nuclear fission [or even fusion] power, solar photovoltaics, wind, wave and tidal power a.o. As long as this is not disaggregated, an endogenous calculation of the base-load factor is not meaningful.

Important performance indicators are the electricity price and the reserve factor, from a systems operation point-of-view, but also the capital needs and the use of fossil fuels because they can be important constraints and/or be of great strategic importance.

Finally, we chose to focus the decisions on the expansion targets for hydropower and on the targets and RD&D-programs for the non-thermal alternative, as these are major elements in most [government-oriented] expansion programs for electric power (cf. Appendix A).

7.3 Submodel description

7.3.1 System operating rules

In the real-world operation of electric power systems is done on the basis of rather sophisticated operational rules (see e.g. Vries and Benders 1994). Let exogenous net demand for electricity be END (in GJelectric or GJe). We assume that demand is anticipated over a time horizon of TH years on the basis of a trend factor of the form (1+r)TH with r the annual growth rate in the past TH years. Thus, END is replaced by AEND = (1+r)TH * END and this is converted into gross demand (EGD) :

$$EGD = (1 + TDL) * AEND \qquad \text{GJe} \quad [7.1]$$

with TDL the transmission and distribution losses which are estimated from historical data.

In the EPG-submodel, we have simplified the short-term operation of the system by assuming that gross demand is generated in two fractions : base-load and peak-load. The fraction of gross demand generated in base-load is indicated with BF. *Figure 7.4* illustrates the approach. It is evident that this is a rather crude approximation of the real-world operation of the system. However, for the long term it has most of the required dynamic characteristics.

In the EPG-submodel, we distinguish four categories of electricity producing capital stock, expressed in MWe :

- hydro-electric (H), based on a finite hydropower potential;
- thermal electric (TE), fuelled by solid, liquid or gaseous fuels;
- non-thermal electric (NTE), based on geothermal and nuclear fission/fusion heat, solar heat/light, wind/wave power etc.
- combined-heat-and-power (CHP), which refers to that part of TE-capacity that is also used to provide useful heat (not yet implemented).

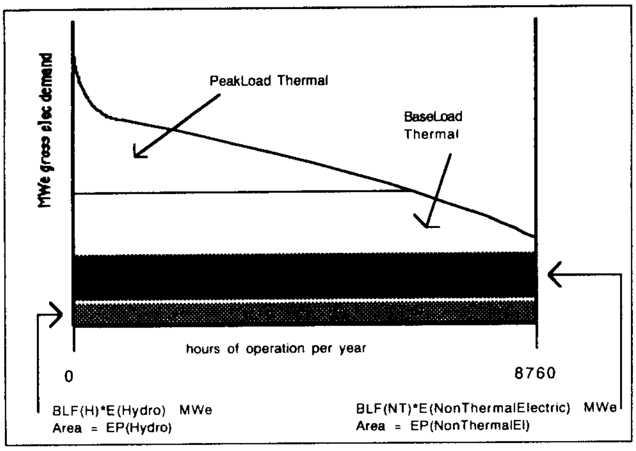


Figure 7.4: Two-block approximation of the [annual] load duration curve

The total producing stock E equals $\sum_i E_i = E_H + E_{TE} + E_{NTE}$. Each of the three capital stocks is assumed to depreciate at a rate of E_i/TL_i with TL_i the technical lifetime of stock E_i. Each produces electricity which is determined by how the system is operated. This is expressed in the load factor of stock i, LF_i, which indicates the ratio of actual and potential electricity generation per unit of capacity : $LF_i = EP_i/(\beta * E_i)$ with EP_i the actual production of stock i and $\beta = 8760*3.6$ [22]. Thus, total electricity production EP in any given year equals :

$$EP = \sum_i EP_i = \sum_i LF_i * E_i * \beta \qquad \text{GJe/yr} \quad [7.2]$$

The LF_i are calculated from a set of rules which approximate the system's operation. First, we assume that hydro-electric power (H) and non-thermal electric power capacity (NTE) are operated in base-load at fixed load factors BLF_H resp. BLF_{NTE} [23]. This is also shown in *Figure 7.4*. Thermal electric power capacity (TE) is operated both in base- and peak-load. In base-load it has a fixed load factor BLF_{TE}. The amount of electricity produced in thermal capacity in base-load is given by base-load demand minus the production of H- and NTE-units :

$$EP_{bT} = BF*EGD - \beta*(E_H*BLF_H + E_{NTE}*BLF_{NTE}) \qquad \text{GJe} \quad [7.3a]$$

It may occur that the production of hydro- and non-thermal electricity exceeds the base-load demand; then, EP_{bT} is set to 0.

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[22] One year has 8760 hours; 1 MWe producing during 1 hour generates 1 MWhe or 3.6 GJe.

[23] For the world at large, this is not unrealistic; for smaller regions resources like hydro- and windpower with seasonal variations cannot be simulated accurately in this way.

The next step is to determine how peak-load demand is met. First, we define a maximum peak-load factor, PLF_{max} , at which units can operate in peak-load. Also, the actual peak-load factor, PLF, is calculated. This is done by calculating peak-capacity, E_p, as total capacity minus base-load capacity. Then, the PLF is calculated as :

$$PLF = (1 - BF) * EGD / (\beta * E_p) \qquad [7.3b]$$

Now, the peak-load part of electricity generation is $E_p * \beta * MIN\{PLF, PLF_{max}\}$. In this way, a capacity shortage shows up as generating less peak-load electricity than is demanded.

All or part of the peak-load electricity is generated by TE-units. If installed NTE-capacity exceeds what is required to satisfy base-load electricity demand, there is an excess NTE-capacity, $E_{exc,NTE}$. We now calculate the part of peak-load electricity generated by thermal units as :

$$EP_{pT} = [PLF_{max}/PLF^*) * (1\text{-}BF) * EGD - E_{exc,NTE} * \beta * PLF^* \qquad GJe/yr \quad [7.3c]$$

with $PLF^* = PLF_{max}$ if $PLF \leq PLF_{max}$ and $PLF^* = PLF$ if PLF > PLFmax. In this way, a capacity shortage leads to a reduction in thermally produced electricity while the excess NTE-units always produce at the calculated peak-load factor. Note that this biases electricity generation in favour of the non-thermal units.

As a third step, the required capacity for each category is calculated. Given the fixed base-load factors for H, NTE- and TE-units, the required thermal capacity to generate the base-load demand , E_{bT}, is (cf. eqn. 7.3a) :

$$E_{bT} = EP_{bT} /(BLF_T*\beta) \qquad MWe \quad [7.4a]$$

with $E_{bT} \geq 0$. The total required base-load capacity, E_b, is accordingly :

$$E_b = E_H + E_{NTE} + E_{bT} \qquad MWe \quad [7.4b]$$

If EP_{bT} as calculated with eqn. 7.3a is negative, there is excess non-thermal capacity, $E_{exc,NTE}$, which is approximated by assuming the same load-factor as for base-load :

$$E_{exc,NTE} = E_{NTE} - (BF*EGD - E_H*BLF_H) / (\beta * BLF_{NTE}) \qquad MWe \quad [7.4c]$$

The required peak-load capacity, E_p, equals :

$$E_p = (1\text{-}BF) * EGD / (PLF * \beta) \qquad MWe \quad [7.4d]$$

Total required installed capacity is $E_r = (E_b + E_p)$, assuming that a reserve margin to guarantee a desired level of reliability is included in the load-factor estimates.

This set of rules determines what happens when the installed capacity is not matching the required capacity. If there is overcapacity, it will show up as increasing costs, a phenomenon which has been modelled in detail (see e.g. Ford 1981). If there is undercapacity, a rule has to be inserted which represents that there is unmet demand. Such a situation is characterized by a decreasing system reliability which shows up as so-called brown-outs and black-outs, curtailing schemes etc. In the EPG-submodel such a situation can result from unexpectedly fast demand increase in combination with long construction periods or delays, or from an economy which cannot or does not sustain the required investment flows.

The ratio between the actually installed and the required system capacity is used as a feedback signal. If this ratio[24] drops below one, the anticipated required electricity capacity is divided by this ratio . Such a shortfall in electricity affects industrial and agricultural production, and also in more indirect ways the residential and commercial sector. So far, we have not included these feedbacks on economy and welfare in our model. Implicitly, it is assumed that the shortage in transmission and distribution is proportional to the shortage in generation capacity, as will be discussed later.

7.3.2 *Market penetration of fuels and non-thermal generation*

A part of the longer-term dynamics in the EPG-submodel has to do with the market penetration dynamics of the fuels (solid, liquid, gaseous) and the non-thermal electric power technology (nuclear, solar a.o.). *Figure 7.6* shows the relationships which govern the market share dynamics. The market penetration dynamics for fuels is based on a multinomial logit function which determines the indicated mar-

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[24] This assumption may introduce errors in case of rationing schemes e.g. non-delivery to industrial consumers during certain days of the week. See e.g. Thukral (1990).

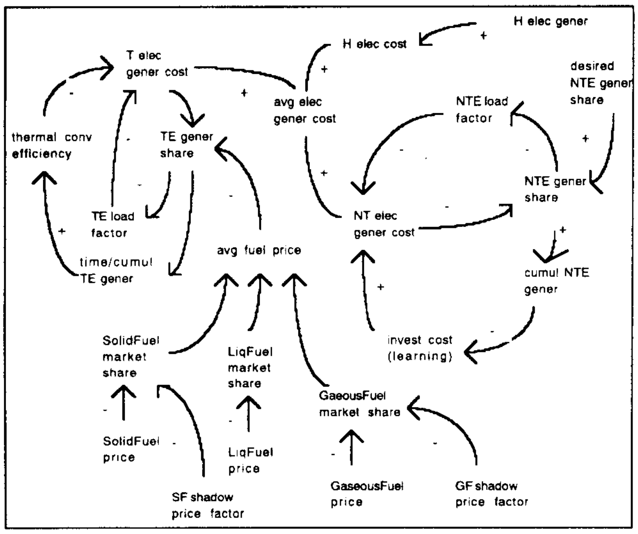

Figure 7.6: The fuel and non-thermal capacity market penetration dynamics

ket share of fuel j, IMS_j, for the thermal electricity generating capital stock :

$$\text{IMS}_j = p_j^{-k} / \sum_i p_i^{-k} \qquad [7.5]$$

with p_j the price of fuel i for electric power utilities (with i = coal, HFL, gas; cf. Appendix A). With a delay, the actual market share, μ_j, becomes equal to this indicated market share. This delay is represented by an adjustment time. The existing capital stock changes from one fuel to another, either because of multi-fuel firing capacity or because of newly built capacity in the course of the adjustment period.

Fuel prices are the driving force for this substitution process. It appears that actual market prices do not correctly represent consumer preferences, an observation which has led to the notion of shadow prices. For example, Moxnes (1989) finds for electricity generation in OECD-Europe that coal has gotten a premium equivalent to a price discount of 29% as of 1983 whereas natural gas has been discriminated against at the equivalent of a 12% price increase. The factors behind this are many e.g. the environmental and legislational aspects of coal handling and storing, the perception of shortages, the protection of the [coal] industry for reason of employment and the lack of a [natural gas] infrastructure.

In the EPG-submodel this has been accounted for by the introduction of a premium factor, as has been discussed in Chapter 3. This factor is a representation of the empirical fact that consumers incorporate aspects of various fuels which are not reflected by actual market prices.

The second substitution process concerns the allocation of the required c.q. available investments among thermal and non-thermal capacity (excluding those for hydropower expansion). Here, too, we use the multinomial logit model to calculate the indicated fraction of investments allocated to non-thermal electric power capacity, and the actual, delayed one, μ_N (cf. Appendix A). Consequently, the ratio of the generating cost of thermal and non-thermal capacity determines this investment allocation.

We have included the option to set a target for the fraction of total electricity generated by non-thermal capacity in some future year. If this target exceeds the market-indicated fraction, a larger share of investments is allocated to non-thermal capacity - we refer to it as the politically desired share, PMS_N, as opposed to the economically indicated market share, IMS_N.

7.3.3 Costing rules and learning-by-doing

The driving force for the penetration of the non-thermal capacity thus depends on its generating costs relative to the generating costs of thermal capacity. How are these costs to be calculated ? There are a few widely used rules in calculating the costs of electricity produced (see e.g. Kahn 1988, Vries et al. 1994). Basically, two cost elements have to be considered :

- investment costs for generation and for transmission and distribution i.e. the costs of capital and the rate of capital depreciation; and
- operational costs which include fuel inputs as the major item but include also labour, materials etc.

Investment costs are dependent on the power generation technologies which are used e.g. low-investment Diesel-engines vs. high-investment solar cells, and on the availability of capital. Operational costs are also quite different for the various generation technologies : for an inefficient coal-fired power plant they may amount to 70% of total costs whereas for nuclear power plants it may be less than 20%. However, most large-scale high-tech power plants are relatively labour-extensive and operate at comparable costs throughout the world if fuel prices do not differ.

In the EPG-submodel we use a general cost formula which converts the costs of the existing capital stocks into annual capital costs with the annuity formula and which calculates fuel costs from thermal efficiencies and fuel prices. The cost of electricity produced with stock E_i is :

$$c_i = (a_i * I_i * E_i + EP_i * AFP / \varepsilon_i)/EP_i \quad \$/GJe \quad [7.7]$$

with a the annuity factor[25], I the specific investment costs, EP the electricity production, AFP the average fuel price and ε_i the thermal-to-electric conversion efficiency for capital stock E_i. The second term only applies for thermal-electric capacity. Operation and maintenance costs are assumed to be a fixed fraction of capital costs. Note that we use a single capital stock for thermal electricity, i.e. we neglect the differences in investment costs and fuel efficiencies between solid, liquid and gaseous fuels. In case of major fuel switches and divergent technologies, this may induce a rather serious error.

Using the economic lifetime EL and not the technical lifetime TL (EL<TL) for the calculation of the annuity and annuitizing the total capital stock tends to overestimate the capital costs, especially in periods of low or negative capacity growth. The use of the present investment costs tends to overestimate capital costs in a situation of declining specific investment costs (which is the dominant expectation for NTE-capacity). This issue is dealt with in some more detail in Appendix A.

The price of electricity is set equal to the average generation cost plus the capital cost of transmission and distribution, multiplied by some pricing factor χ which may depend on e.g. the category of consumers :

$$p = \chi * [\textstyle\sum_i c_i + a_{TD} * I_v * E / EP] \quad \$/GJe \quad [7.8]$$

with a_{TD} the annuity factor applied for the transmission and distribution capital stock and I_v the required transmission and distribution capital per unit of generating capacity. In first instance we assume that the value of I_v is constant, irrespective of system reliablity and transmission and distribution losses - which is not the case in the real world (see e.g. Munasinghe 1979).

There are two additional dynamic elements which are also depicted in *Figure 7.6*. First, both thermal and non-thermal capacity have a *learning* element which tends to improve their productivity in the form of increasing thermal efficiency resp. decreasing specific investment costs. For non-thermal capacity this is a positive loop because the rate at which specific investment costs decrease is related to cumulative production (cf. Appendix A). For thermal capacity we have in first instance assumed an exogenous improvement in thermal efficiency over time which is an average for coal-, oil- and gas-fired power stations. This assumption is realistic inasfar as coal- and oil-gasification will increasingly be integrated in STAG-units in the pursuit of higher conversion efficiencies.

Secondly, the load factor for thermal and non-thermal capacity decreases if their share in total capacity increases. As soon as the sum of H- and NT-capacity exceeds the required base-load capacity, NTE-capacity will start operating in the peak-load regime whenever TE-capacity is less than the required peak-load capacity[25]. As a consequence the NTE-load factor will drop which in turn increases its cost and thus slows down its penetration rate.

The total annual investment flow which are required within the EPG-model is given by :

$$IE = \textstyle\sum_i (MAX\{dE_i/dt,0\} * I_i) \quad \$/yr \quad [7.9]$$

i.e. it is either the linear product of capacity additions and specific investment costs or zero. This is, together with the fuel inputs, the only physical input to the EPG-sector from the rest of the [model]world (cf. *Figure 7.3*).

In various parts of the world, there is a large unmet demand for electricity. Estimates for India and China indicate that this may be in the order of 5-15% in the present situation. The main reason for this is a shortage of capital in combination with extremely high demand growth rates and lead times longer than expected. The latter may be caused by a.o. environmental consideration in the case of hydropower. Also the fairly low reliability of power stations and transport systems contribute to capacity shortages and unserved electricity.

We explored the response of the system to capital shortages by assuming an exogenous flow of available investments which is below the required investments. The results show that the present model formulation is a viable way of simulating real-world discrepancies between electricity supply and an effectively curbed demand.

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[25] It is assumed that hydropower will never exceed the required base-load capacity.

7.4 Submodel calibration

7.4.1 Parameter values

As has been discussed in Chapter 1, calibration and validation are only possible at a lower aggregation level. Here too, we have chosen the USA 1950-1990 to calibrate the EPG-model, because it has the best historical data base, has a large and diversified electric power system, and is also the region considered in the models by other authors. The calibration procedure is described in Appendix E. In the present case, the historical generation of electricity has been equated to demand so unmet (or latent) demand is not considered. Historical data have been collected for thermal, hydro and non-thermal i.e. nuclear capacity. Also, estimates of electricity generating costs, prices and investments have been collected as well as some parameters relating to load and load factors.

The results of this calibration are reported elsewhere (Berg 1994). The results have been used to make minor changes in the model formulation and parametrisation. For instance, it turned out that costs of nuclear electricity could only be reproduced by assuming a negative learning rate for the period 1965-1990; this reflects the fact that nuclear power plant costs have actually increased as additional safety measures led to higher investment costs and longer construction periods. It also turned out to be quite difficult to reproduce the fuel shares correctly, indicating that the fuel-price based substitution mechanism is too simple a description of the rules governing fuel choice. The analysis also indicated that the choice of the load parameters (BLF, PLF, BF) and the forecasting horizon are interrelated, as one would expect.

Over-all, the analysis for the USA has given us confidence that the structural representation of this sector, and the relevance of the various parameters which allow calibration, are fairly good.

Next, we have calibrated the EPG-model for the world 1900-1990 at large in similar fashion. Here, however, the historical time-series are less available and the ones which are published are probably less reliable. Also, as with the fuel supply models, some parts of the model dynamics - and consequently the associated parameters and functionals - have no proper meaning at a world level. Especially the investment- and price-based rules, derived and calibrated for the USA, are too narrowly defined to give an adequate representation of the real-world decision-making processes regarding the electric power sector which is subject to various forms of government control in important regions of the world.

We will now discuss the various parameters and relationships in some detail. Although calibration is our first concern here, we also discuss some parameters which are crucial in scenario construction. First, given the demand for end-use electricity as calculated in the ED-model, we have to split this demand into base- and peak-load demand. The demand profile is characterized by a set of parameters which have been set at the following values :

BF	Base-load Fraction elec-demand	0.9
PLF_{max}	maximum value of Peak Load Fraction	0.5

Then, one has to specify how certain characteristics of the capital stocks and their characteristrics change [over time]. The load factors are based on historical time-series and set at :

BLF_{NTE}	0.52(before 1980); 0.67 (>1980)
BLF_H	0.43
BLF_{TE}	0.55

Indicating thermal with TE, hydro with H and non-thermal with NTE, the choices for the model parameters are given in *Table 7.1*.

The economic lifetime, the interest rate and the specific investment costs are the major determinants of the kWhe-generation costs. The fuel premium factors affect the relative fuel shares. The multinomial logit parameter which equals the cross-price elasticity and determines the degree to which investments are channeled towards either TE- or NTE-capacity, is set at 0.8. The future share of NTE is rather sensitive for this choice, as one would expect; the actual penetration of nuclear power until 1990 is largely simulated with an exogenous RD&D-pulse. The learning multiplier for NTE has been operating from 1960 onwards (tL = 1960) in such a way that it equals one in 1980. However, we made the parameter time-dependent to be able to reproduce the initial rise in nuclear power specific capital costs.

7.4.2 Calibration results

To run the model for the world at large we have to initialize the state variables and assess values to a number of parameters and relationships. Demand for electricity is from the ED-model. Estimates of the three capital stocks have been based on world data on electric power generation in combination with

Table 7.1: Parameter and functional values in EPG-model World

	Thermal TE	Hydro H	NonThermal NTE	T&D
Economic LifeTime (yr)	15	15	15	40
Technical LifeTime (yr)	25	100	30	50
Interest Rate (%)	10	10	10	10
TE Thermal Efficiency	0.04(1900)-0.35 (1990)[a]			
NTE Learning rate param.			0.85 (1960)-1.1(1990)	
Spec Investment Cost ('000 $/MWe)	2000(1900) -590(1990)	1500[b]	1000[b]	600[c]
GF Premium Factor	(1900)-1.45 (1965-70) -1.2 (1995)			
SF Premium Factor	1.7(1900)- 0.4 (after 1965)			
Construction delay (yr)	3	5	8	na
TE-NTE cross-pr-elast	0.8	na	0.8	na

a) afterwards increase towards 0.45 as default assumption
b) excluding depletion and learning, i.e. 1980-[initial] value; starts at 700 in 1900
c) investment per MWe of installed peak capacity

1980-values for the specific investment costs, I (in $/kWe, the equivalent of the capital output ratio if divided by ß).

As explained before, the efficiency of thermal capacity is assumed to increase over time from a low 4 % in 1900 to 35 % in 1990. For the prices of fossil fuels, coal, oil and gas, we have taken reasonable estimates of the historical values - actually non-existent for the world at large. These should of course come from the Fuel Supply models. However, to reproduce the historical coal input we had to use a cost reduction factor for coal of 0.4 after 1965. This can be interpreted as, first; lower coal prices for large-scale utility users and, secondly, a coal preference in the form of strategic, employment or environmental aspects. The latter is often in the form of government subsidies or plans. The system operating rules and their parameter choices have been discussed in paragraph 7.3.1.

Figure 7.7-7.10 show a few results. Electricity demand after AEEI and PIEEI is met by electricity production which is higher because it includes transmission and distribution losses (*Figure 7.7*). Historical production is shown for comparison. *Figure 7.8* shows how electricity has been generated. Comparison with historical data for 1970-1990 on thermal electricity generation show a fair calibraton. *Figure 7.9* shows the development of installed capacity. The historical estimates for thermal (TE) and non-thermal (NTE) capacity around 1980-1985 are added for comparison. To simulate the build-up of non-thermal capacity, an RD&D-pulse is given which peaks at 900 MWe/yr in 1980-1985 while at the same time the learning coefficient rises from 0.85 in 1960 to 1.1 in 1990. The latter reflects the observed rise in nuclear power specific investment costs due to additional safety measures, construction delays etc. This historical match is based on data for the USA. Hydropower capacity, also shown in *Figure 7.9*, is expanded according to a preset exogenous scheme which matches historical capacity expansion.

The introduction of nuclear [NTE-]capacity has caused a slow-down in the growth of fossil fuel use-after 1970. This is shown in *Figure 7.10* which contains the simulated use of oil, coal and total fossil fuel input and a comparison with the estimated historical values[26]. This graph also shows how, as a consequence of varying time-paths for the coal, oil and gas prices, around 1980 oil (LF) was loosing market share but regained its importance after 1980.

Finally, *Figure 7.11* shows the simulated and historical costs of thermal (TE) and non-thermal (NTE) electricity. The decline in specific investments costs and fuel prices and the rise in conversion efficiency

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[26] It should be noted that accurate and reliable historical data for these variables are not available, so we had to rely on estimates and inferences from incomplete sets.

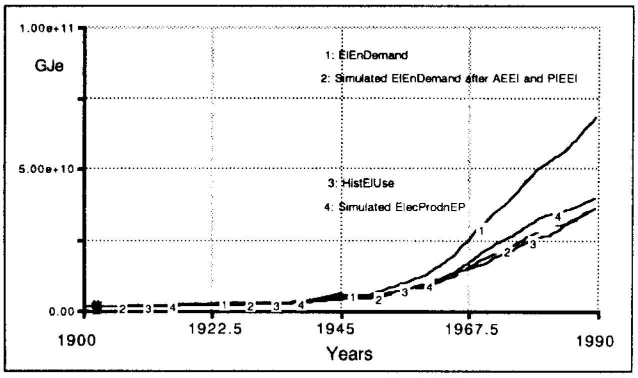


Figure 7.7: Historical and simulated electricity demand c.q. production before and after AEEI and PIEEI

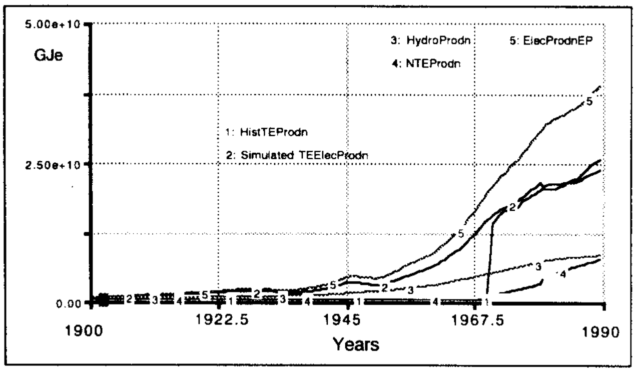


Figure 7.8: Historical and simulated generation mix for electricity production

all have contributed to declining electricity generation costs in thermal power plants. For non-thermal electricity generation, that is, nuclear power, cost developments in the USA suggest a drastic increase which we calibrated by adjusting the learning coefficient. As for the future, the key question is whether nuclear power costs will come down and/or whether alternative non-thermal options will become cost-competitive.

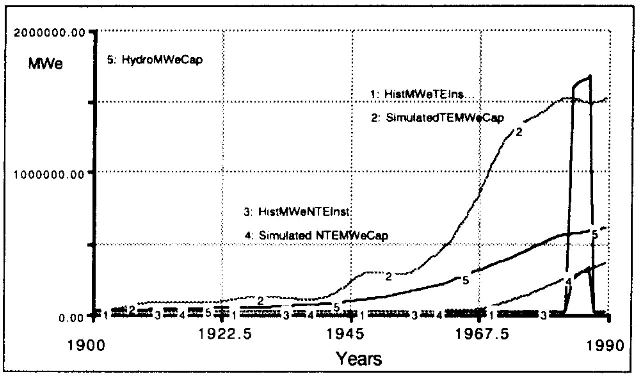


Figure 7.9: Historical and simulated installed capacity generating mix for electricity production

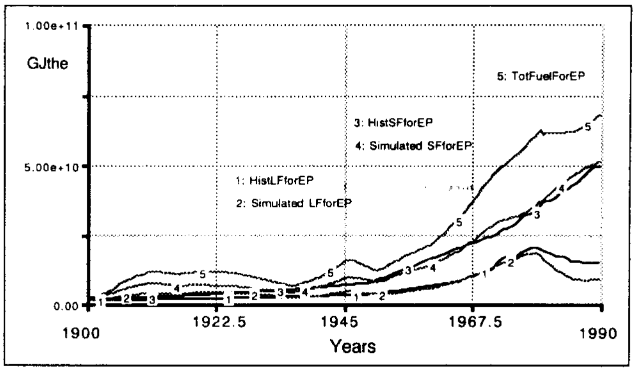


Figure 7.10: Historical and simulated fossil fuel input for electricity production

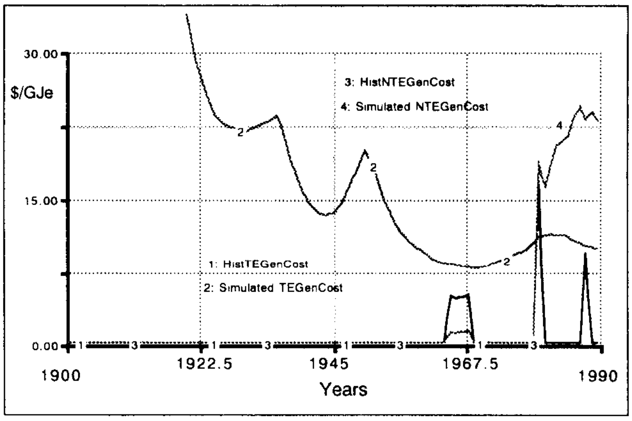


Figure 7.11: Historical and simulated electricity generation costs. The peaks are for the few historical estimates available.

APPENDIX A: GENERIC MODEL ELEMENTS

A.1 The multinomial logit model

The substitution mechanism described by the multinomial logit model is based on the formula :

$$IMS_i = \exp(-\lambda * c_i) / \sum_j \{\exp(-\lambda * c_j)\} \qquad [A1.a]$$

with IMS_i the indicated market share of product/process i, λ the logit parameter and c_i the cost c.q. the price of the products/processes i. This formula can be rewritten and approximated by dividing upper and lower part by $\exp(-\lambda * c_i)$ and expanding each exponent into its two first terms :

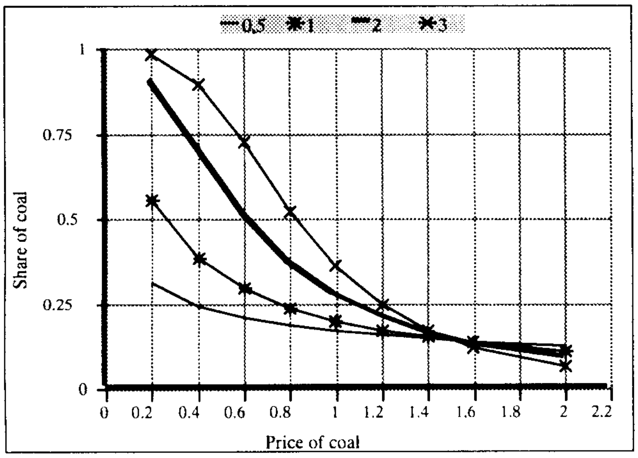
$$IMS_i = 1 / [1 + \sum_{j \neq i} (1 - \lambda(c_j - c_i) + \lambda^2(c_j - c_i)^2)/2] \qquad [A1.b]$$

This form shows that for equal cost c.q. price all market shares become 1/n in case of n products/processes. For small λ-values, indicated market shares tend to become inelastic i.e. independent of cost c.q. price.

An alternative formulation of eqn. [A1.a] is based on the cost ratio $\gamma_{i1} = C_i/C_1$:

$$IMS_i = C_i^{-\lambda} / \sum_i C_j^{-\lambda} = 1 / [1 + \sum_{i>1} \gamma_{i1}^{-\lambda}] \qquad [A1.c]$$

Figure A.1: Equilibrium market share of coal as a function of the relative price of coal in the case of a substitution elasticity of 0.5, 1, 2 and 3 %; prices of all other energy carriers are set equal to 1.5 in this example.



In this case, the parameter λ equals the cross-price elasticity. This formulation is used in the TIME-model

In most applications it is assumed that the actual market share MS_i is lagging behind the value which is indicated by the cost c.q. price differences or ratio's. This delayed response is described by the equation :

$$d\,MS_i / dt = (IMS_i - MS_i) / ADJT \qquad [A1.d]$$

with ADJT the adjustment time representing the system's resistance to [rapid] changes. It has been shown that the multinomial logit model is consistent with the existence of a large group of consumers/producers which aspire minimum cost as given with a translog production function (Edmonds and Reilly 1986). If the model is used to simulate the introduction of completely new and different technologies, the indicated market share most adequately refers to the new capacity c.q. investment. This ensures a slow penetration of the new product/process.

As an illustration of eqn. A1.c, *Figure A.1* shows an application for secondary energy carriers. If prices of n secondary energy carriers are equal, each of them has a market share equal to 1/n . In *Figure A.1* this is at 1.5. The higher the cross-price elasticity, the steeper the curve, i.e., the more responsive the market share is to a price difference. If the parameter λ is set at 3 and the coal price level is set at 0.5 (one third that of the other secondary fuels), the market share of coal in equilibrium will be about 80%. For λ = 1, it is only 30%.

A.2 Technological learning

It is well known that the cost and performance characteristics of a given technology change over time due to various dynamical factors. One of them is the ability of people to learn by doing. This phenomenon, variously called the learning curve, learning-by-doing, organizational learning a.o., has been investigated in detail and for a variety of products and processes. Hirschmann (1964) gives it the status of a natural law. Its formulation is that a cost meas-

Table A1: Representative learning variables

product/process	y	x
aircraft manufacturing	direct man-hours per lb	cumulative amount of planes
petroleum refining	days per 10000 bbl processed	cumulative amount of bbls processed
	direct manhours per bbl refined	cumulative bbls refined
catalytic cracking	cost per bbl of capacity	total capacity
power plant manufacturing	cost per kWe capacity	total capacity installed
power plant maintenance	average time per replacement	cumulative number of replacements
nuclear power	unplanned loss factor	years of operation
basic steel production	manhours per unit produced	cumulative units produced
solar photovoltaics cells	investment cost per kWe	cumulative kWe produced

ure y tends to decline as a power function of an accumulated learning measure x :

$$y = y(tL)\, x^{-\pi} \quad \text{or} \quad \log y = \log y(tL) - \pi \log x$$

with tL the time at which learning is supposed to start.

Often, the learning rate is expressed by the progress ratio p which indicates the factor with which the cost measure y decreases on a doubling of experience x. It is easily seen that $p = 2^{-\pi}$. Many illustrations of this law have been found and published, as *Table A1* shows.

Most data are for the United States and it has been found that the progress ratio in almost all cases investigated is between 0.65 and 0.95 with a median value of 0.82 (Argote and Epple 1990). There are several reasons why it varies. Hirschmann (1964) suggests that because it are humans that are capable of learning, the progress ratio is higher for activities with a high labour content. He also notices the relationship between learning rate on the one hand and targets and expectations on the other hand.[a] Knowledge from learning may also depreciate, in which case more weight should be given to recent production rates.

A.3 Capital costing methods

There are various ways to convert investment flows into the cost of a product. A very simple way, used in the TIME-model, is to equate the capital cost of a product in year t, c_{ct}, to the annuitized investments over the total producing capital stock :

$$c_{ct} = a_t\, I_t\, C_t / P_t \qquad \$/\text{unit.yr} \quad [\text{A3.a}]$$

with a_t the annuity factor, I_t the specific investment costs, C_t the installed production capacity and P_t the production, all at time t [A1]. This is a rough approximation, especially when investment costs are developing over time and when production per unit capacity varies.

The degree of approximation can be assessed in the following example. Let us assume that capacity and production both expand at a rate of 100*g % per year and that both annuity and specific investment costs are constant over time. Then, the investment INV_t flow consists of two parts. One accounts for the depreciation of the capital stock :

$$INV_{dt} = I\, C_t / LT \qquad \$/\text{yr} \quad [\text{A3.b}]$$

with LT the technical lifetime. The other part accounts for the expansion investments :

$$INV_{et} = I\, (C_t - C_{t-1}) \qquad \$/\text{yr} \quad [\text{A3.c}]$$

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[a] "...merely expecting progress does not bring it about. It is not ordained by fate... but must be continuously, vigorously, and resourcefully sought. Such drive is usually the result of need. In the case of animals, the need is usually hunger - the desire to survive... This same need underlies national and industrial progress... Survival is also the drive in industry... The threat of economic extinction is like any other threat of death" (Hirschmann 1964 pp. 137). See also Wilkinson's Poverty and Progress (1971) on the drives behind technological progress.

[A1] Defined in the usual way as a = r/(1-(1+r)**(-ELT)) with r the discount rate c.q. interest rate and ELT the economic lifetime of the investment.

Using that $C_t = (1+g)\ C_{t-1}$, one gets for the annuitized sum of the investments over the first n years :

$$SUMINV_n = a\ I\ C_0\ (g + 1/LT)\ \sum_n \{1 + (1+g) + (1+g)^2 \ldots (1+g)^n\} \quad \$/yr \quad [A3.d]$$

which gives, using the geometric series sum formula, for the capital cost :

$$c_c = (a\ I\ C_0 / P_0) * (g + 1/LT) * ((1+g)^n - 1)/(g * (1+g)^n) \quad \$/unit.yr \quad [A3.e]$$

Note that the first term equals the simplified cost expression, $\mathbf{c}_c$. Also note that this approach neglects the capital costs due to past investments (t<0); its value will only be reached after LE years.

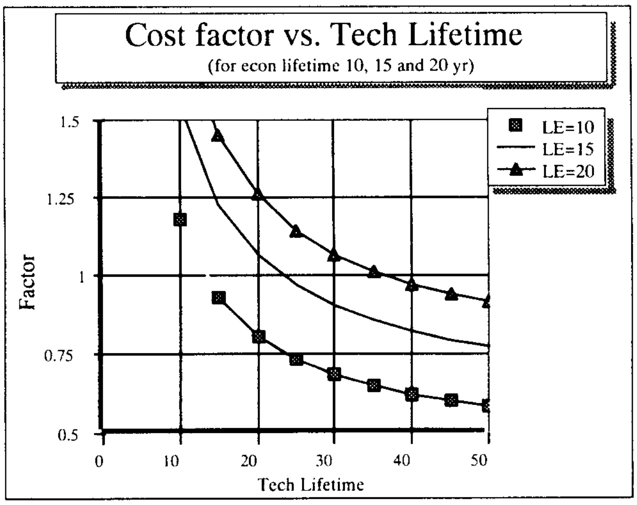
In the above equation, no account is given to the fact that after the economic lifetime, LE, the annuitized investment flow becomes zero. After subtracting the value of $SUMINV_{n-LE}$, we get for the capital cost :

$$c_c = \mathbf{c}_c\ (1 + 1/(g\ LT))\ (\ 1 - (1+g)^{-LE}\ ) \quad \$/unit.yr\ [A3.f]$$

This equation shows that the approximation in using the simplified expression is dependent on the rate of capacity c.q. production growth and on the technical and economic lifetime. *Figure A.2* below shows how the ratio between c_c and $\mathbf{c}_c$ varies.

From the graph it can be seen that the discrepancy between the simplified and the somewhat more elaborate cost expression is within about 10%, if the technical lifetime is between 20% (LE=10) to 150% (LE=20) higher than the economic lifetime. In the EPG-model, the discrepancy for thermal capacity (LT=25, LE=15) is small. This may no longer be the case if a utility uses higher LT-values of up to 40 years. For hydropower (LT=50, LE=15) it may be signficant. For non-thermal capacity it is small for the usual assumptions for nuclear power (LT=25, LE=15), but it may be significant when one assumes much longer (nuclear : LT=50) or shorter (solar : LT=15) technical lifetimes without corresponding changes in the economic lifetimes used.

Fig A.2



A.4 Target-based policy action

In a variety of ways decisionmakers would like to interact with the world - in the present case with the modelworld with its own autonomous dynamics. Many of the policy interactions can best be viewed as attempts to influence the "business-as-usual" course of events. Often, the latter can be equated to the market- and technology-driven processes which the world at large as well as separate regions have experienced in the past. Two important generic ones have been discussed in the previous paragraphs : the cost c.q. price based substitution mechanics as described mathematically with the multinomial logit model, and the mechanics of learning-by-doing as expressed in a power function.

To allow the model-user to interfere with these autonomous developments, we have constructed a generic model with the following elements. First, the actor attempts to speed up the penetration of certain technologies e.g. biofuels, nonthermal electric power or mineral recycling. This can be done by formulating a target e.g. a desired markets share, in some target year. Based on this target plan, market shares will differ from those indicated by the prevailing market costs c.q. prices. The politically desired market share which is assumed to be realized with a delay and as a result of all sorts of supporting policy measures (price regulation, subsidies etc.), in its turn speeds up the learning process. This in turn will tend to reduce the discrepancy between the market-indicated and the politically indicates market shares.

The second option for an actor is to introduce a pulse program for a new process or technology. This has been done for nuclear power and for liquid biofuels (BLF) between the years 1970 and 1990, to get them going. In the model it is not specified where the funding for such programs comes from, but it could be related to e.g. income from a carbon tax.

A.5 The determination of load factors

To implement the approximate estimation of the plant load factors in the EPG-model, we rely on the average system load factor as derived from global or regional data on operating capacity E and on electricity generated EP for the period under concern. This historical system load factor SLF is defined as the ratio of actual and potential production :

$$SLF = EP/(\beta * E) \qquad GJe/GJe \quad [A5.a]$$

Assuming that electricity production equals gross electricity demand, i.e. no shortfall, and using eqn. [7.3b] the desired system load factor is :

$$SLF_d = (BF/BLF + (1\text{-}BF)/PLF)^{-1} \qquad GJe/GJe \quad [A5.b]$$

In this way the choice of BF, BLF and PLF can be calibrated to the historical SLF-values. Figure A.3 illustrates which values for BLF and PLF are to be used for a given choice of SLF and BF. Given the value of SLF_d, for a given choice of BF and BLF the value of PLF can be calculated. We have chosen BF and BLF to be constant over time, whereas PLF is calculated to gauge demand and production under the condition $PLF \leq PLF_{max}$:

$$PLF = (1 - BF) * EGD / (Ep * \beta) \qquad GJe/GJe \quad [A5\ c]$$

One may wish to simulate measures to increase SLF_d (e.g. through load management) by increasing PLF_{max}. Alternatively, one may incorporate other characteristics for NTE-options by a change of BLF over time (e.g. lower values if photovoltaics have a larger share).

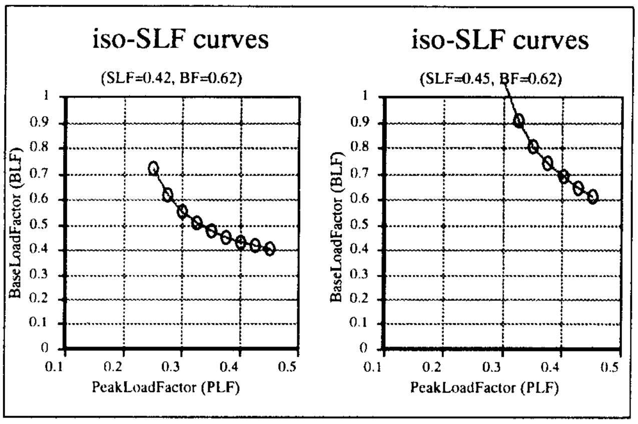


Figure A.3 Possible choices of BLF and PLF for a given value of the system load factor SLF and the base fraction of demand BF

APPENDIX B: THREE LEVELS OF [MODELLING] REALITY

One of the issues in model-based explorations into sustainable development strategies is to deal adequately with the varying grades of knowledge, ignorance and complexity. The world is moving along some [quasi-]evolutionary path with its own, "autonomous" dynamics. The underlying dynamic "laws" can be stratified from geo- and ecosphere to technosphere and sociosphere (Vries 1993). Environmental problems, often of a long-term and complex nature, have physico-chemical, eco- and biological and socio-economic aspects. For some of these, detailed scientific understanding is available; for other aspects, strong knowledge is not or never will be available [b].

The context for interaction in the form of policy processes with the "autonomous" developments is one of actors with bounded rationality and biased information (Morecroft and Sterman 1992). The dynamics of global change and, up to a certain level of complexity, the behaviour of actors therein can be mapped into a world of formal statements : a model. Such a model can serve the broader goal of futures exploration e.g. in the framework of a policy exercise.

In dealing with this problem, it helps to distinguish three levels (cf. *Figure B.1*). The background to this approach is that the models should be used in an interactive way to communicate and support the policy debate, and allow for the inclusion of new approaches to deal with cultural perspectives and real-world complexity. This approach is used in the context of the Global Environmental Strategic Planning Exercise (GESPE) project (Vries et al. 1993), in CO_2-emission allocation (Janssen and Rotmans 1994) and in dealing with the issue of demographic fertility issues (Vianen et al. 1995).

One may think of these three levels as representing ascending order of intentionality, complexity, consciousness. At the first level are the physical stocks and flows which constitute observable reality. Model variables, at this level, have an explicit and formal correspondence with real-world observables. The laws of physical and engineering science hold, e.g. conservation of mass and energy. This is the geosphere, ecosphere and technosphere. It is here that modern science and technology have been successful by combining formal analysis with controlled experiment. The development path of strong knowledge can be traced by the analogues and metaphors it has provided us : the planets as a celestial clock, the heart as a mechanical pump, the brain as a computer.

The next level maps the behavioural and informational structures which govern human interference in the underlying physical environment [c]. Such behaviour is described by information-dependent sets of rules : about how to get food, construct shelter, invest in energy supply etc. The rules describe [human] actors, varying from the rather rigid farmer in Sri Lanka performing age-old agricultural practices, to multinational companies relying on sophisticatedly supported entrepreneurial rules. How many actors should be modelled explicitly depends on the modeller's purpose. Many of the prevailing controversies e.g. in economic theory, reflect the existence of a large variety of such actors and the ongoing conflict of interests and ideas among them. Usually, models of actors are rather condensed - rigid equations which represent observations within quite limited sets of space, time and populations. More insightful but less easily endogenized approaches are to use generic archetypes or rule-based ensembles.

At the third level are the values, beliefs and ideas which both reflect and motivate people's behaviour. It is here that cultural perspectives are reinforced and mutually affected by what happens in the two levels underneath. At this level, policy issues arise and are discussed and macro-oriented policy measures are designed [d]. Generally speaking, this level is not part of [simulation] models. In fact, at this level

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[b] I use the adjectives "strong" and "weak" to indicate the degree to which the object of study can be known in the sense of the physical sciences which can analyse its object in the isolated environment of laboratory experiments. Many systems which are of interest from an environmental point-of-view can not or not satisfactorily be subjected to repeated experimentation; nor can many living entities like ecosystems, economic and social systems. See Vries 1989.

[c] Separating human actors is because of the anthropocentric background of most modelling exercises. Indeed, there is a continuous spectrum and, in view of their rich behaviour, animals high up in ecosystem webs could be separated in similar fashion.

[d] Like between the first and the second level, one should actually speak of a spectrum. Severely constrained actors are at the very bottom of the second level, while well-organized anticipatory interest groups are up into the third level, especially if they have control over information flows.

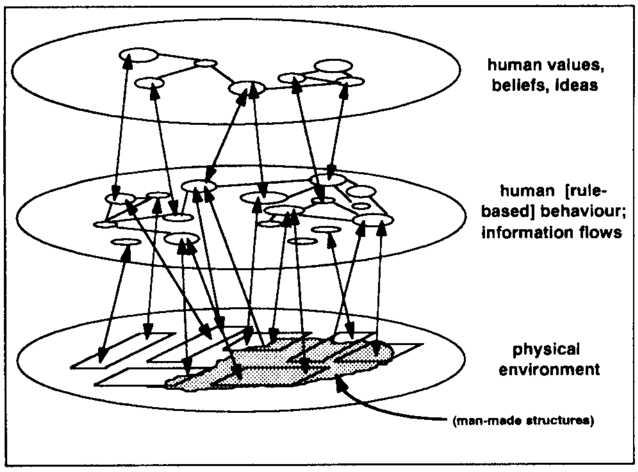


Figure B.1: Three interacting levels of modelling reality

simulation models are only tools for strategic evaluation. The more a model incorporates behavioural dynamics, the more it is linked to this third level and the less universality it can claim.

APPENDIX C: THE PSIR (Pressure-State-Impact-Response) - FRAMEWORK

In modelling [parts of] the real world, one constructs from experiences in the real world aggregate, abstract classes of physical objects. These are not observables as such. They have a characteristic unit of measurement e.g. number of people, ha of land, money value of capital stocks ($), m^3 of water, tons of carbon etc. These aggregate classes are usually subdivided according to one or more relevant characteristics : subclasses. They have the same unit of measurement as classes. Their relevance is determined by model objectives, empirical evidence and all sorts of judgments and inferences. Important subclasses in the TARGETS1.0 model are : age cohorts and disease burden subclasses for human population, temperature and soil productivity subclasses for land, type of output subclasses for capital stocks, physical quality and compartment and/or functional use subclasses for water and physical form and compartment subclasses for carbon.

The collection of elements in a class-subclass, measured in its characteristic unit, is associated with a system state. Changes in state refer to :

- inflow from outside into the system or outflow out of the system;
- transitional flows among subclasses.

Important flows are : births and deaths and ageing and declining health for human population, erosion and deforestation for land, and investments and depreciation for capital stocks. Within each subclass, a set of [relevant] properties is distinguished [for modelling purposes]. The key to their relevance is whether they are a [important] determinant of the [sub]class occupation c.q. dynamics. Relevant properties in TARGETS1.0 are : risk exposure, food per caput, water and sanitation availability and income distribution for human population, crop productivity and management mode for land, capital-output ratio and learning-by-doing for capital stocks, and pollutant level and distribution for water.

The rate equations behind these changes in the system states are based on gradients within the system which generate driving forces :

- in natural systems, the gradients are mostly physical;
- in human systems, the gradients take the form of a difference between the actual/perceived and desired [properties of the] system state.

We call the associated dynamics the autonomous system dynamics. It expresses the inherent non-equilibrium nature of real-world processes, which shows up as a discrepancy between desired and actual perceived health/food, a difference between actual and required food production, a difference in actual and aspired capital productivity and economic output etc. These gradients lead to the system's natural response at micro-level (response). The driving forces [that lead to additional interference with natural cycles] generate the micro-pressures on the system.

In a macro-context, those driving forces are associated with Pressure. When some class occupations and properties in the system State are labeled as less desirable, micro-pressures are translated into macro-Pressure. Some weighing algorithm is used for the conversion. Pressure thus is a subset and combination of pressures.

To formulate the rate equations, either as differential or as difference equation, the modeller has to choose which gradients-driving forces are relevant. This is the most crucial modelling step. It requires a translation of gradients and driving forces into variables which are thought to drive the micro-pressure and -response dynamics. I call these variables signifiers (to avoid confusion with indicators, which could be another name).

The notion of more or less desirable system states is derived from an implicit notion of quality of human life (e.g. sustainability) which has a correspondence with functions of the earth as life-support system. If certain system states are changing [the potential of] these functions, the changes in the system can be said to have Impacts. If the micro-responses take the form of collective [human] [government] action in response to such a [anticipated] change in life-support functions, it is associated with policy.

Conceptually, the above is represented in *Figure C.1* below. The key point is the distinction between the "autonomous dynamics" [micro] [psir] cycle and the "policy reinforcement & feedback" [macro] [PSIR] cycle. One of the consequences of this view is that "policy" as a collective [government-based] response has to be modelled as an interference into the autonomous dynamics. Within the sub-models, the key state variables, their driving forces and the associated signifiers are summarized in *Table 1.2*.

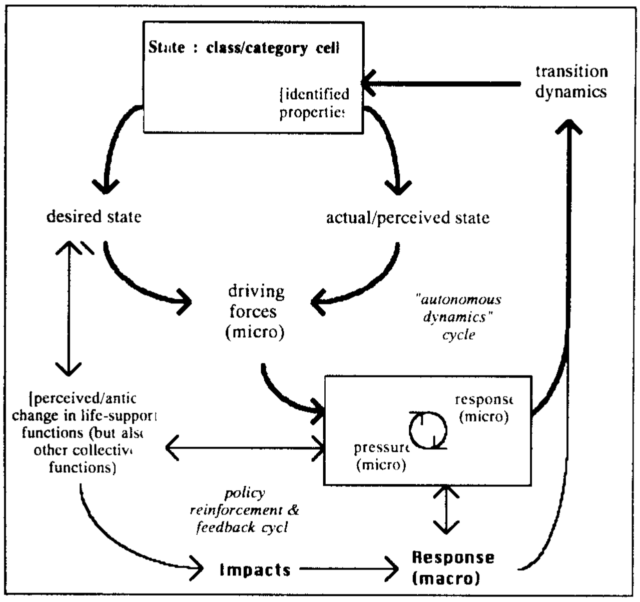


Figure C.1: Conceptualizing the PSIR at micro- and at macro-level

APPENDIX D: DATA BASE USED FOR CALIBRATION

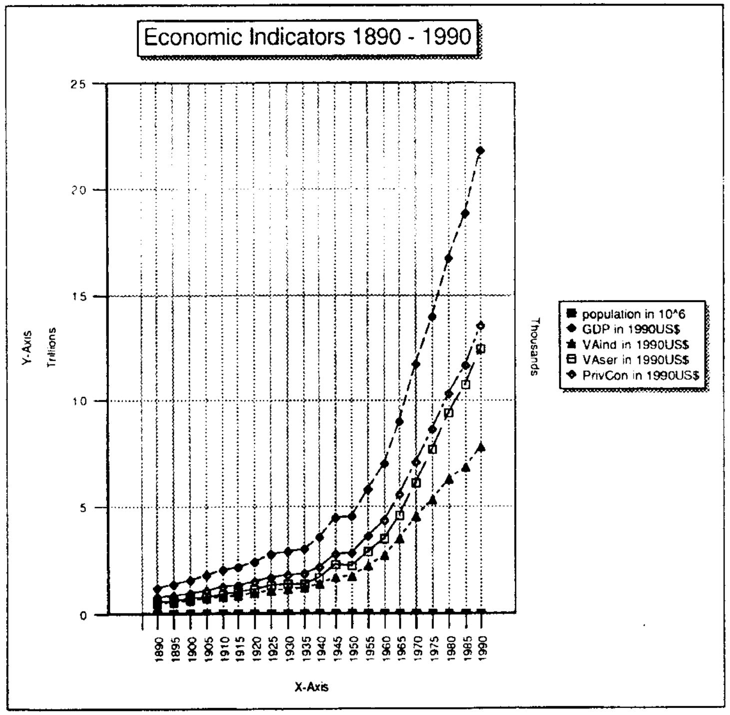
The data for the calibration are based on the IEA-statistics and on various other sources (see references). For completeness they are given here, for the world, in the form of spreadsheets and graphs.

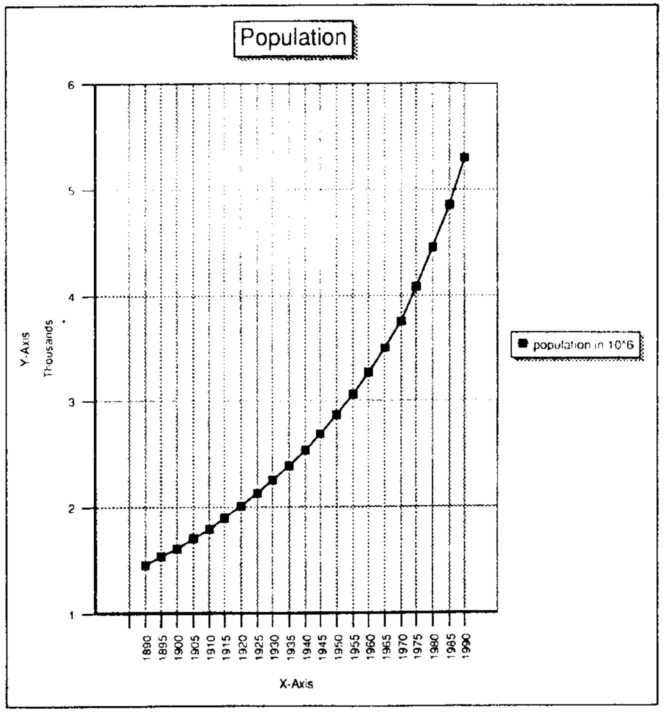
Data on biomass, windpower and photovoltaic power are collected from a variety of studies (see references). A compilation of those data is also included in spreadsheet form.

GLOBAL economic indicators 1890-1990

	1890	1895	1900	1905	1910	1915	1920	1925	1930	1935	1940
population in 10^6	1461	1538	1619	1708	1803	1904	2012	2130	2256	2390	2534
GDP in 1990US$	1.23E+12	1.38E+12	1.56E+12	1.79E+12	2.03E+12	2.19E+12	2.44E+12	2.76E+12	2.92E+12	3.00E+12	3.55E+12
VAind in 1990US$	5.06E+11	5.68E+11	6.31E+11	7.16E+11	8.10E+11	8.75E+11	9.71E+11	1.09E+12	1.15E+12	1.20E+12	1.41E+12
VAser in 1990US$	5.30E+11	6.00E+11	6.95E+11	8.13E+11	9.36E+11	1.01E+12	1.15E+12	1.32E+12	1.40E+12	1.39E+12	1.69E+12
PrivCon in 1990US$	7.60E+11	8.49E+11	9.66E+11	1.11E+12	1.26E+12	1.35E+12	1.51E+12	1.71E+12	1.81E+12	1.86E+12	2.20E+12

	1940	1945	1950	1955	1960	1965	1970	1975	1980	1985	1990
population in 10^6	2534	2695	2868	3059	3266	3499	3754	4080	4448	4851	5297
GDP in 1990US$	3.55E+12	4.46E+12	4.52E+12	5.78E+12	7.01E+12	8.98E+12	1.17E+13	1.40E+13	1.68E+13	1.88E+13	2.18E+13
VAind in 1990US$	1.41E+12	1.69E+12	1.75E+12	2.24E+12	2.74E+12	3.50E+12	4.55E+12	5.28E+12	6.26E+12	6.82E+12	7.80E+12
VAser in 1990US$	1.69E+12	2.29E+12	2.24E+12	2.91E+12	3.52E+12	4.61E+12	6.10E+12	7.65E+12	9.39E+12	1.07E+13	1.24E+13
PrivCon in 1990US$	2.20E+12	2.79E+12	2.82E+12	3.60E+12	4.36E+12	5.58E+12	7.09E+12	8.62E+12	1.03E+13	1.16E+13	1.35E+13





			1900	1910	1920	1930	1940	1950	1960	1970	1980	1990
Primary energy consumption (million toe)												
HYDE-database												
WORLD	TOTAL	coal	861	904.3	1115.2	1271.6	1399	1603.6				
WORLD	TOTAL	oil	137.7	263.1	505.5	764.9	1049.3	1511.4				
WORLD	TOTAL	gas	33.5	69.8	176.5	272.7	428.8	638.5				
WORLD	TOTAL	hydroelectr.	6.9	16	30.4	41.4	60.2	78.8				
WORLD	TOTAL	total	1039.1	1253.2	1827.6	2350.6	2937.3	3832.3				
Primary energy consumption (PJ)												
HYDE-database/Nakicenovic						(1925)	(1938)				(1965)	
WORLD	TOTAL	coal	15768			36048	37861	46691	58573		67140	
WORLD	TOTAL	oil	788			5765	11015	21164	43932		63279	
WORLD	TOTAL	gas	315			1403	2922	7390	17953		26733	
WORLD	TOTAL	hydroelectr.	9			289	670	1273	2520		3299	
WORLD	TOTAL	total				43505	52469	76518	122979		160451	
Primary energy consumption (million metric tons of coal eq.)												
HYDE-database						(1929)					1965	
WORLD	TOTAL	electricity				145		367			1037.3	
WORLD	TOTAL	hydro-electr				14.7		43.4			112.6	
WORLD	TOTAL	fuel-electr				130.3		323.6			924.7	
Primary energy consumption (PJ.)												
HYDE-database						1925					1965	
WORLD	TOTAL	electricity				4249		10753			30393	
WORLD	TOTAL	hydro-electr				431		1272			3299	
WORLD	TOTAL	fuel for electr				3818		9481			27094	
WORLD	TOTAL	coal for electr				2672	4372	6637	14856		18966	
WORLD	TOTAL	oil for electr				954	1561	2370	5306		6773	
WORLD	TOTAL	gas for elect				191	312	474	1061		1355	
WORLD	**TOTAL**	**coal-heat**	**15768**			**33376**	**33490**	**40054**	**43717**		**48174**	
WORLD	**TOTAL**	**oil-heat**	**788**			**4811**	**9454**	**18794**	**38626**		**56506**	
WORLD	**TOTAL**	**gas-heat**	**315**			**1212**	**2610**	**6916**	**16892**		**25378**	
Secondary energy consumption (1000 million kWh)												
HYDE-database			1900			(1925)	(1938)				(1965)	
WORLD	TOTAL	electricity				187.5	446.9	945	2274.3		3339.8	
Secondary energy consumption (PJ)												
HYDE-database						1925	1938	1950	1960		1965	
WORLD	**TOTAL**	**electricity**	**20**			**675**	**1609**	**3402**	**8187**		**12023**	
WORLD	**TOTAL**	**wood**	**8515**					**4415**				

Notes and references

- Scaling factor differences HYDE-Darmstadter/ IEA (1965/1971) set at 0.8
- Traditional biofuels: 1971-1990 according to definition IEA-diskette; 1900&1950 wood only (Nakicenovic)
- Coal, oil, gas for electricity production based on share in year 1965.
- Data for in-between years from interpolation (cf. IMAGE2.1 database)

Source 1971-1990	IMAGE 2.1 database (Alcamo et al. 1995)
Source 1925-1965	HYDE-database (Klein Goldewijk and Battjes 1995)
Source 1900	Nakicenovic, Technological Progress, Structural Change and Efficient Energy Use: Trends World Wide and in Austria, International Part, IIASA, Laxenburg, November 1989.

Secondary Energy Consumption; final data for IMAGE2.1 (from IEA data on diskette; in GJ /yr.); modified for difference Hyde-IEA and new definition sector others (IEA) in 19

IMAGE	SECTOR	CARRIER	1900	1901	1902	1903	1904	1905	1906	1907	1908	1909
WORLD	TOTAL	coal	1.26E+10	1.32E+10	1.37E+10	1.43E+10	1.49E+10	1.54E+10	1.60E+10	1.66E+10	1.71E+10	1.77E+10
WORLD	COMMERCIAL	coal	1.19E+09	1.24E+09	1.29E+09	1.35E+09	1.40E+09	1.45E+09	1.50E+09	1.56E+09	1.61E+09	1.66E+09
WORLD	INDUSTRY	coal	8.57E+09	8.96E+09	9.34E+09	9.72E+09	1.01E+10	1.05E+10	1.09E+10	1.13E+10	1.16E+10	1.20E+10
WORLD	OTHERS	coal	4.79E+08	5.00E+08	5.21E+08	5.43E+08	5.64E+08	5.85E+08	6.07E+08	6.28E+08	6.50E+08	6.71E+08
WORLD	RESIDENTIAL	coal	1.75E+09	1.83E+09	1.91E+09	1.98E+09	2.06E+09	2.14E+09	2.22E+09	2.30E+09	2.37E+09	2.45E+09
WORLD	TRANSPORT	coal	6.28E+08	6.56E+08	6.84E+08	7.12E+08	7.40E+08	7.68E+08	7.96E+08	8.25E+08	8.53E+08	8.81E+08
WORLD	TOTAL	electricity	2.00E+07	4.62E+07	7.24E+07	9.86E+07	1.25E+08	1.51E+08	1.77E+08	2.03E+08	2.30E+08	2.56E+08
WORLD	COMMERCIAL	electricity	3.17E+06	7.33E+06	1.15E+07	1.56E+07	1.98E+07	2.39E+07	2.81E+07	3.23E+07	3.64E+07	4.06E+07
WORLD	INDUSTRY	electricity	1.07E+07	2.47E+07	3.88E+07	5.28E+07	6.58E+07	8.08E+07	9.48E+07	1.09E+08	1.23E+08	1.37E+08
WORLD	OTHERS	electricity	8.44E+05	1.95E+06	3.06E+06	4.16E+06	5.27E+06	6.37E+06	7.48E+06	8.58E+06	9.69E+06	1.08E+07
WORLD	RESIDENTIAL	electricity	4.77E+06	1.10E+07	1.73E+07	2.35E+07	2.98E+07	3.60E+07	4.23E+07	4.86E+07	5.48E+07	6.11E+07
WORLD	TRANSPORT	electricity	5.05E+05	1.17E+06	1.83E+06	2.49E+06	3.15E+06	3.81E+06	4.47E+06	5.13E+06	5.79E+06	6.45E+06
WORLD	TOTAL	gas	2.52E+08	2.81E+08	3.10E+08	3.38E+08	3.67E+08	3.96E+08	4.24E+08	4.53E+08	4.82E+08	5.10E+06
WORLD	COMMERCIAL	gas	2.99E+07	3.33E+07	3.67E+07	4.01E+07	4.35E+07	4.69E+07	5.03E+07	5.37E+07	5.72E+07	6.06E+07
WORLD	INDUSTRY	gas	1.42E+08	1.59E+08	1.75E+08	1.91E+08	2.07E+08	2.23E+08	2.39E+08	2.56E+08	2.72E+08	2.88E+08
WORLD	OTHERS	gas	1.33E+07	1.48E+07	1.63E+07	1.78E+07	1.93E+07	2.08E+07	2.23E+07	2.38E+07	2.53E+07	2.69E+07
WORLD	RESIDENTIAL	gas	6.64E+07	7.40E+07	8.15E+07	8.91E+07	9.66E+07	1.04E+08	1.12E+08	1.19E+08	1.27E+08	1.34E+08
WORLD	TRANSPORT	gas	3.21E+05	3.57E+05	3.94E+05	4.30E+05	4.67E+05	5.03E+05	5.40E+05	5.76E+05	6.13E+05	6.49E+05
WORLD	TOTAL	oil	6.31E+08	7.59E+08	8.88E+08	1.02E+09	1.15E+09	1.27E+09	1.40E+09	1.53E+09	1.66E+09	1.79E+09
WORLD	COMMERCIAL	oil	3.71E+07	4.47E+07	5.22E+07	5.98E+07	6.74E+07	7.50E+07	8.25E+07	9.01E+07	9.77E+07	1.05E+08
WORLD	INDUSTRY	oil	1.37E+08	1.65E+08	1.92E+08	2.20E+08	2.48E+08	2.76E+08	3.04E+08	3.32E+08	3.60E+08	3.88E+08
WORLD	OTHERS	oil	4.95E+07	5.96E+07	6.97E+07	7.98E+07	8.99E+07	1.00E+08	1.10E+08	1.20E+08	1.30E+08	1.40E+08
WORLD	RESIDENTIAL	oil	8.23E+07	9.91E+07	1.16E+08	1.33E+08	1.49E+08	1.66E+08	1.83E+08	2.00E+08	2.17E+08	2.33E+08
WORLD	TRANSPORT	oil	3.25E+08	3.92E+08	4.58E+08	5.24E+08	5.91E+08	6.57E+08	7.23E+08	7.90E+08	8.56E+08	9.22E+08
WORLD	TOTAL	trad biofuel	8.51E+09	8.43E+09	8.35E+09	8.27E+09	8.19E+09	8.10E+09	8.02E+09	7.94E+09	7.86E+09	7.78E+09
WORLD	COMMERCIAL	trad biofuel	5.15E+05	5.10E+05	5.05E+05	5.00E+05	4.96E+05	4.91E+05	4.86E+05	4.81E+05	4.76E+05	4.71E+05
WORLD	INDUSTRY	trad biofuel	1.79E+09	1.78E+09	1.76E+09	1.74E+09	1.72E+09	1.71E+09	1.69E+09	1.67E+09	1.66E+09	1.64E+09
WORLD	OTHERS	trad biofuel	1.82E+06	1.81E+06	1.79E+06	1.77E+06	1.75E+06	1.74E+06	1.72E+06	1.70E+06	1.68E+06	1.67E+06
WORLD	RESIDENTIAL	trad biofuel	6.72E+09	6.65E+09	6.59E+09	6.53E+09	6.46E+09	6.40E+09	6.33E+09	6.27E+09	6.20E+09	6.14E+09
WORLD	TRANSPORT	trad biofuel	2.71E+04	2.69E+04	2.66E+04	2.63E+04	2.61E+04	2.58E+04	2.56E+04	2.53E+04	2.50E+04	2.48E+04
WORLD	TOTAL-ALL SI	All fuels	2.20E+10	2.27E+10	2.33E+10	2.39E+10	2.46E+10	2.52E+10	2.58E+10	2.65E+10	2.71E+10	2.78E+10
WORLD	TOTAL-ALL SI	Fuels without	1.35E+10	1.42E+10	1.49E+10	1.57E+10	1.64E+10	1.71E+10	1.78E+10	1.85E+10	1.93E+10	2.00E+10

Energy consumption for electricity production (GJ/yr)

IMAGE	SECTOR	CARRIER	1900	1901	1902	1903	1904	1905	1906	1907	1908	1909
WORLD	elec generati	coal	2.17E+08	3.15E+08	4.13E+08	5.12E+08	6.10E+08	7.08E+08	8.06E+08	9.04E+08	1.00E+09	1.10E+09
WORLD	elec generati	oil	7.70E+07	1.12E+08	1.47E+08	1.82E+08	2.17E+08	2.52E+08	2.87E+08	3.23E+08	3.58E+08	3.93E+08
WORLD	elec generati	gas	1.40E+07	2.11E+07	2.82E+07	3.52E+07	4.23E+07	4.94E+07	5.65E+07	6.36E+07	7.06E+07	7.77E+07
WORLD	elec generati	hydro	9.00E+06	2.02E+07	3.14E+07	4.26E+07	5.38E+07	6.50E+07	7.62E+07	8.74E+07	9.86E+07	1.10E+08
WORLD	elec generati	non-thermal	0	0	0	0	0	0	0	0	0	0
WORLD	elec generation											

Notes:

source 1971-1990: IMAGE 2.1; hydro includes geothermal, solar etc.; non-thermal is nuclear

- Coal, oil, gas for electricity production based on share in year(1965?).

Source 1925-1965 HYDE

Source 1900 Nakicenovic, Technological Progress, Structural Change and Efficient Energy Use: Trends World Wide and in Austria, International Part, IIASA, Laxenburg, November 1989.

1900 hydro: 9 PJ (Nakicenovic); elec prod by fuels (Nakicenovic): 11 PJ; efficiency 3.6% (HYDE)

Efficiency hydro = 1.00

Efficiency nuclear = 0.33

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1910	1911	1912	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927
1.82E+10	1.88E+10	1.94E+10	1.99E+10	2.05E+10	2.11E+10	2.16E+10	2.22E+10	2.28E+10	2.33E+10	2.39E+10	2.44E+10	2.50E+10	2.56E+10	2.61E+10	2.67E+10	2.67E+10	2.67E+10
1.72E+09	1.77E+09	1.82E+09	1.87E+09	1.93E+09	1.98E+09	2.03E+09	2.09E+09	2.14E+09	2.19E+09	2.25E+09	2.30E+09	2.35E+09	2.40E+09	2.46E+09	2.51E+09	2.51E+09	2.51E+09
1.24E+10	1.28E+10	1.32E+10	1.36E+10	1.39E+10	1.43E+10	1.47E+10	1.51E+10	1.55E+10	1.58E+10	1.62E+10	1.66E+10	1.70E+10	1.74E+10	1.78E+10	1.81E+10	1.82E+10	1.82E+10
6.92E+08	7.14E+08	7.35E+08	7.56E+08	7.78E+08	7.99E+08	8.21E+08	8.42E+08	8.63E+08	8.85E+08	9.06E+08	9.27E+08	9.49E+08	9.70E+08	9.92E+08	1.01E+09	1.01E+09	1.01E+09
2.53E+09	2.61E+09	2.69E+09	2.76E+09	2.84E+09	2.92E+09	3.00E+09	3.08E+09	3.15E+09	3.23E+09	3.31E+09	3.39E+09	3.47E+09	3.55E+09	3.62E+09	3.70E+09	3.70E+09	3.70E+09
9.09E+08	9.37E+08	9.65E+08	9.93E+08	1.02E+09	1.05E+09	1.08E+09	1.11E+09	1.13E+09	1.16E+09	1.19E+09	1.22E+09	1.25E+09	1.27E+09	1.30E+09	1.33E+09	1.33E+09	1.33E+09
2.82E+08	3.08E+08	3.34E+08	3.61E+08	3.87E+08	4.13E+08	4.39E+08	4.65E+08	4.92E+08	5.18E+08	5.44E+08	5.70E+08	5.96E+08	6.23E+08	6.49E+08	6.75E+08	7.47E+08	8.19E+08
4.47E+07	4.89E+07	5.30E+07	5.72E+07	6.13E+07	6.55E+07	6.97E+07	7.38E+07	7.80E+07	8.21E+07	8.63E+07	9.04E+07	9.46E+07	9.87E+07	1.03E+08	1.07E+08	1.18E+08	1.30E+08
1.51E+08	1.65E+08	1.79E+08	1.93E+08	2.07E+08	2.21E+08	2.35E+08	2.49E+08	2.63E+08	2.77E+08	2.91E+08	3.05E+08	3.19E+08	3.33E+08	3.47E+08	3.61E+08	4.00E+08	4.38E+08
1.19E+07	1.30E+07	1.41E+07	1.52E+07	1.63E+07	1.74E+07	1.85E+07	1.96E+07	2.07E+07	2.19E+07	2.30E+07	2.41E+07	2.52E+07	2.63E+07	2.74E+07	2.85E+07	3.15E+07	3.45E+07
6.73E+07	7.36E+07	7.98E+07	8.61E+07	9.23E+07	9.86E+07	1.05E+08	1.11E+08	1.17E+08	1.24E+08	1.30E+08	1.36E+08	1.42E+08	1.49E+08	1.55E+08	1.61E+08	1.78E+08	1.95E+08
7.11E+06	7.77E+06	8.44E+06	9.10E+06	9.76E+06	1.04E+07	1.11E+07	1.17E+07	1.24E+07	1.31E+07	1.37E+07	1.44E+07	1.50E+07	1.57E+07	1.64E+07	1.70E+07	1.88E+07	2.07E+07
5.39E+08	5.68E+08	5.96E+08	6.25E+08	6.54E+08	6.83E+08	7.11E+08	7.40E+08	7.69E+08	7.97E+08	8.26E+08	8.55E+08	8.83E+08	9.12E+08	9.41E+08	9.69E+08	1.06E+09	1.14E+09
6.40E+07	6.74E+07	7.08E+07	7.42E+07	7.76E+07	8.10E+07	8.44E+07	8.78E+07	9.12E+07	9.46E+07	9.80E+07	1.01E+08	1.05E+08	1.08E+08	1.12E+08	1.15E+08	1.25E+08	1.35E+08
3.04E+08	3.20E+08	3.37E+08	3.53E+08	3.69E+08	3.85E+08	4.01E+08	4.17E+08	4.34E+08	4.50E+08	4.66E+08	4.82E+08	4.98E+08	5.15E+08	5.31E+08	5.47E+08	5.96E+08	6.44E+08
2.84E+07	2.99E+07	3.14E+07	3.29E+07	3.44E+07	3.59E+07	3.74E+07	3.89E+07	4.04E+07	4.19E+07	4.34E+07	4.50E+07	4.65E+07	4.80E+07	4.95E+07	5.10E+07	5.55E+07	6.00E+07
1.42E+08	1.49E+08	1.57E+08	1.65E+08	1.72E+08	1.80E+08	1.87E+08	1.95E+08	2.02E+08	2.10E+08	2.17E+08	2.25E+08	2.33E+08	2.40E+08	2.48E+08	2.55E+08	2.78E+08	3.00E+08
6.86E+05	7.22E+05	7.59E+05	7.95E+05	8.32E+05	8.68E+05	9.05E+05	9.41E+05	9.78E+05	1.01E+06	1.05E+06	1.09E+06	1.12E+06	1.16E+06	1.20E+06	1.23E+06	1.34E+06	1.45E+06
1.92E+09	2.05E+09	2.18E+09	2.30E+09	2.43E+09	2.56E+09	2.69E+09	2.82E+09	2.95E+09	3.08E+09	3.21E+09	3.33E+09	3.46E+09	3.59E+09	3.72E+09	3.85E+09	4.13E+09	4.42E+09
1.13E+08	1.20E+08	1.28E+08	1.36E+08	1.43E+08	1.51E+08	1.58E+08	1.66E+08	1.73E+08	1.81E+08	1.89E+08	1.96E+08	2.04E+08	2.11E+08	2.19E+08	2.26E+08	2.43E+08	2.60E+08
4.16E+08	4.43E+08	4.71E+08	4.99E+08	5.27E+08	5.55E+08	5.83E+08	6.11E+08	6.39E+08	6.67E+08	6.94E+08	7.22E+08	7.50E+08	7.78E+08	8.06E+08	8.34E+08	8.96E+08	9.58E+08
1.50E+08	1.61E+08	1.71E+08	1.81E+08	1.91E+08	2.01E+08	2.11E+08	2.21E+08	2.31E+08	2.41E+08	2.51E+08	2.62E+08	2.72E+08	2.82E+08	2.92E+08	3.02E+08	3.24E+08	3.47E+08
2.50E+08	2.67E+08	2.84E+08	3.01E+08	3.17E+08	3.34E+08	3.51E+08	3.68E+08	3.85E+08	4.01E+08	4.18E+08	4.35E+08	4.52E+08	4.69E+08	4.85E+08	5.02E+08	5.39E+08	5.77E+08
9.89E+08	1.06E+09	1.12E+09	1.19E+09	1.25E+09	1.32E+09	1.39E+09	1.45E+09	1.52E+09	1.59E+09	1.65E+09	1.72E+09	1.79E+09	1.85E+09	1.92E+09	1.98E+09	2.13E+09	2.28E+09
7.69E+09	7.61E+09	7.53E+09	7.45E+09	7.37E+09	7.28E+09	7.20E+09	7.12E+09	7.04E+09	6.96E+09	6.87E+09	6.79E+09	6.71E+09	6.63E+09	6.55E+09	6.46E+09	6.38E+09	6.30E+09
4.66E+05	4.61E+05	4.56E+05	4.51E+05	4.46E+05	4.41E+05	4.36E+05	4.31E+05	4.26E+05	4.21E+05	4.16E+05	4.11E+05	4.06E+05	4.01E+05	3.96E+05	3.91E+05	3.86E+05	3.81E+05
1.62E+09	1.60E+09	1.59E+09	1.57E+09	1.55E+09	1.53E+09	1.52E+09	1.50E+09	1.48E+09	1.47E+09	1.45E+09	1.43E+09	1.41E+09	1.40E+09	1.38E+09	1.36E+09	1.34E+09	1.33E+09
1.65E+06	1.63E+06	1.61E+06	1.60E+06	1.58E+06	1.56E+06	1.54E+06	1.53E+06	1.51E+06	1.49E+06	1.47E+06	1.46E+06	1.44E+06	1.42E+06	1.40E+06	1.39E+06	1.37E+06	1.35E+06
6.07E+09	6.01E+09	5.94E+09	5.88E+09	5.81E+09	5.75E+09	5.68E+09	5.62E+09	5.55E+09	5.49E+09	5.43E+09	5.36E+09	5.30E+09	5.23E+09	5.17E+09	5.10E+09	5.04E+09	4.97E+09
2.45E+04	2.43E+04	2.40E+04	2.37E+04	2.35E+04	2.32E+04	2.29E+04	2.27E+04	2.24E+04	2.22E+04	2.19E+04	2.16E+04	2.14E+04	2.11E+04	2.09E+04	2.06E+04	2.03E+04	2.01E+04
2.84E+10	2.90E+10	2.97E+10	3.03E+10	3.10E+10	3.16E+10	3.22E+10	3.29E+10	3.35E+10	3.42E+10	3.48E+10	3.54E+10	3.61E+10	3.67E+10	3.73E+10	3.80E+10	3.83E+10	3.86E+10
2.07E+10	2.14E+10	2.21E+10	2.29E+10	2.36E+10	2.43E+10	2.50E+10	2.58E+10	2.65E+10	2.72E+10	2.79E+10	2.86E+10	2.94E+10	3.01E+10	3.08E+10	3.15E+10	3.19E+10	3.23E+10

1910	1911	1912	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927
1.20E+09	1.30E+09	1.40E+09	1.49E+09	1.59E+09	1.69E+09	1.79E+09	1.89E+09	1.98E+09	2.08E+09	2.18E+09	2.28E+09	2.38E+09	2.48E+09	2.57E+09	2.67E+09	2.80E+09	2.93E+09
4.28E+08	4.63E+08	4.98E+08	5.33E+08	5.68E+08	6.03E+08	6.38E+08	6.73E+08	7.08E+08	7.44E+08	7.79E+08	8.14E+08	8.49E+08	8.84E+08	9.19E+08	9.54E+08	1.00E+09	1.05E+09
8.48E+07	9.19E+07	9.90E+07	1.06E+08	1.13E+08	1.20E+08	1.27E+08	1.34E+08	1.41E+08	1.49E+08	1.56E+08	1.63E+08	1.70E+08	1.77E+08	1.84E+08	1.91E+08	2.00E+08	2.10E+08
1.21E+08	1.32E+08	1.43E+08	1.55E+08	1.66E+08	1.77E+08	1.88E+08	1.99E+08	2.11E+08	2.22E+08	2.33E+08	2.44E+08	2.55E+08	2.67E+08	2.78E+08	2.89E+08	3.18E+08	3.48E+08
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

1928	1929	1930	1931	1932	1933	1934	1935	1936
2.67E+10	2.67E+10	2.67E+10	2.67E+10	2.67E+10	2.68E+10	2.68E+10	2.68E+10	2.68E+10
2.51E+09	2.51E+09	2.51E+09	2.51E+09	2.52E+09	2.52E+09	2.52E+09	2.52E+09	2.52E+09
1.82E+10	1.82E+10	1.82E+10	1.82E+10	1.82E+10	1.82E+10	1.82E+10	1.82E+10	1.82E+10
1.01E+09	1.01E+09	1.01E+09	1.01E+09	1.01E+09	1.02E+09	1.02E+09	1.02E+09	1.02E+09
3.70E+09	3.71E+09	3.71E+09	3.71E+09	3.71E+09	3.71E+09	3.71E+09	3.71E+09	3.71E+09
1.33E+09	1.33E+09	1.33E+09	1.33E+09	1.33E+09	1.33E+09	1.33E+09	1.33E+09	1.33E+09
8.91E+08	9.62E+08	1.03E+09	1.11E+09	1.18E+09	1.25E+09	1.32E+09	1.39E+09	1.47E+09
1.41E+08	1.53E+08	1.64E+08	1.75E+08	1.87E+08	1.98E+08	2.10E+08	2.21E+08	2.32E+08
4.77E+08	5.15E+08	5.54E+08	5.92E+08	6.30E+08	6.69E+08	7.07E+08	7.46E+08	7.84E+08
3.76E+07	4.06E+07	4.36E+07	4.67E+07	4.97E+07	5.27E+07	5.58E+07	5.88E+07	6.18E+07
2.13E+08	2.30E+08	2.47E+08	2.64E+08	2.81E+08	2.98E+08	3.15E+08	3.33E+08	3.50E+08
2.25E+07	2.43E+07	2.61E+07	2.79E+07	2.97E+07	3.15E+07	3.33E+07	3.51E+07	3.70E+07
1.23E+09	1.31E+09	1.40E+09	1.49E+09	1.57E+09	1.66E+09	1.74E+09	1.83E+09	1.92E+09
1.46E+08	1.56E+08	1.66E+08	1.76E+08	1.86E+08	1.97E+08	2.07E+08	2.17E+08	2.27E+08
6.93E+08	7.41E+08	7.90E+08	8.38E+08	8.87E+08	9.35E+08	9.84E+08	1.03E+09	1.08E+09
6.46E+07	6.91E+07	7.36E+07	7.82E+07	8.27E+07	8.72E+07	9.17E+07	9.63E+07	1.01E+08
3.23E+08	3.46E+08	3.68E+08	3.91E+08	4.14E+08	4.36E+08	4.59E+08	4.82E+08	5.04E+08
1.56E+06	1.67E+06	1.78E+06	1.89E+06	2.00E+06	2.11E+06	2.22E+06	2.33E+06	2.44E+06
4.71E+09	4.99E+09	5.28E+09	5.56E+09	5.85E+09	6.13E+09	6.42E+09	6.71E+09	6.99E+09
2.77E+08	2.94E+08	3.10E+08	3.27E+08	3.44E+08	3.61E+08	3.78E+08	3.95E+08	4.11E+08
1.02E+09	1.08E+09	1.14E+09	1.21E+09	1.27E+09	1.33E+09	1.39E+09	1.45E+09	1.51E+09
3.69E+08	3.92E+08	4.14E+08	4.36E+08	4.59E+08	4.81E+08	5.04E+08	5.26E+08	5.48E+08
6.14E+08	6.51E+08	6.89E+08	7.26E+08	7.63E+08	8.00E+08	8.38E+08	8.75E+08	9.12E+08
2.43E+09	2.57E+09	2.72E+09	2.87E+09	3.02E+09	3.16E+09	3.31E+09	3.46E+09	3.60E+09
6.22E+09	6.14E+09	6.05E+09	5.97E+09	5.89E+09	5.81E+09	5.73E+09	5.64E+09	5.56E+09
3.76E+05	3.71E+05	3.66E+05	3.62E+05	3.57E+05	3.52E+05	3.47E+05	3.42E+05	3.37E+05
1.31E+09	1.29E+09	1.28E+09	1.26E+09	1.24E+09	1.22E+09	1.21E+09	1.19E+09	1.17E+09
1.33E+06	1.32E+06	1.30E+06	1.28E+06	1.26E+06	1.24E+06	1.23E+06	1.21E+06	1.19E+06
4.91E+09	4.84E+09	4.78E+09	4.71E+09	4.65E+09	4.58E+09	4.52E+09	4.45E+09	4.39E+09
1.98E+04	1.96E+04	1.93E+04	1.90E+04	1.88E+04	1.85E+04	1.82E+04	1.80E+04	1.77E+04

3.89E+10	3.92E+10	3.95E+10	3.98E+10	4.01E+10	4.04E+10	4.07E+10	4.10E+10	4.12E+10
3.27E+10	3.30E+10	3.34E+10	3.38E+10	3.42E+10	3.45E+10	3.49E+10	3.53E+10	3.57E+10

1928	1929	1930	1931	1932	1933	1934	1935	1936
3.06E+09	3.20E+09	3.33E+09	3.46E+09	3.59E+09	3.72E+09	3.85E+09	3.98E+09	4.11E+09
1.09E+09	1.14E+09	1.19E+09	1.23E+09	1.28E+09	1.33E+09	1.37E+09	1.42E+09	1.47E+09
2.19E+08	2.28E+08	2.38E+08	2.47E+08	2.56E+08	2.65E+08	2.75E+08	2.84E+08	2.93E+08
3.77E+08	4.06E+08	4.36E+08	4.65E+08	4.94E+08	5.23E+08	5.53E+08	5.82E+08	6.11E+08
0	0	0	0	0	0	0	0	0

1928	1929	1930	1931	1932	1933	1934	1935	1936
2.67E+10	2.67E+10	2.67E+10	2.67E+10	2.67E+10	2.68E+10	2.68E+10	2.68E+10	2.68E+10
2.51E+09	2.51E+09	2.51E+09	2.51E+09	2.52E+09	2.52E+09	2.52E+09	2.52E+09	2.52E+09
1.82E+10	1.82E+10	1.82E+10	1.82E+10	1.82E+10	1.82E+10	1.82E+10	1.82E+10	1.82E+10
1.01E+09	1.01E+09	1.01E+09	1.01E+09	1.01E+09	1.02E+09	1.02E+09	1.02E+09	1.02E+09
3.70E+09	3.71E+09	3.71E+09	3.71E+09	3.71E+09	3.71E+09	3.71E+09	3.71E+09	3.71E+09
1.33E+09	1.33E+09	1.33E+09	1.33E+09	1.33E+09	1.33E+09	1.33E+09	1.33E+09	1.33E+09
8.91E+08	9.62E+08	1.03E+09	1.11E+09	1.18E+09	1.25E+09	1.32E+09	1.39E+09	1.47E+09
1.41E+08	1.53E+08	1.64E+08	1.75E+08	1.87E+08	1.98E+08	2.10E+08	2.21E+08	2.32E+08
4.77E+08	5.15E+08	5.54E+08	5.92E+08	6.30E+08	6.69E+08	7.07E+08	7.46E+08	7.84E+08
3.76E+07	4.06E+07	4.36E+07	4.67E+07	4.97E+07	5.27E+07	5.58E+07	5.88E+07	6.18E+07
2.13E+08	2.30E+08	2.47E+08	2.64E+08	2.81E+08	2.98E+08	3.15E+08	3.33E+08	3.50E+08
2.25E+07	2.43E+07	2.61E+07	2.79E+07	2.97E+07	3.15E+07	3.33E+07	3.51E+07	3.70E+07
1.23E+09	1.31E+09	1.40E+09	1.49E+09	1.57E+09	1.66E+09	1.74E+09	1.83E+09	1.92E+09
1.46E+08	1.56E+08	1.66E+08	1.76E+08	1.86E+08	1.97E+08	2.07E+08	2.17E+08	2.27E+08
6.93E+08	7.41E+08	7.90E+08	8.38E+08	8.87E+08	9.35E+08	9.84E+08	1.03E+09	1.08E+09
6.46E+07	6.91E+07	7.36E+07	7.82E+07	8.27E+07	8.72E+07	9.17E+07	9.63E+07	1.01E+08
3.23E+08	3.46E+08	3.68E+08	3.91E+08	4.14E+08	4.36E+08	4.59E+08	4.82E+08	5.04E+08
1.56E+06	1.67E+06	1.78E+06	1.89E+06	2.00E+06	2.11E+06	2.22E+06	2.33E+06	2.44E+06
4.71E+09	4.99E+09	5.28E+09	5.56E+09	5.85E+09	6.13E+09	6.42E+09	6.71E+09	6.99E+09
2.77E+08	2.94E+08	3.10E+08	3.27E+08	3.44E+08	3.61E+08	3.78E+08	3.95E+08	4.11E+08
1.02E+09	1.08E+09	1.14E+09	1.21E+09	1.27E+09	1.33E+09	1.39E+09	1.45E+09	1.51E+09
3.69E+08	3.92E+08	4.14E+08	4.36E+08	4.59E+08	4.81E+08	5.04E+08	5.26E+08	5.48E+08
6.14E+08	6.51E+08	6.89E+08	7.26E+08	7.63E+08	8.00E+08	8.38E+08	8.75E+08	9.12E+08
2.43E+09	2.57E+09	2.72E+09	2.87E+09	3.02E+09	3.16E+09	3.31E+09	3.46E+09	3.60E+09
6.22E+09	6.14E+09	6.05E+09	5.97E+09	5.89E+09	5.81E+09	5.73E+09	5.64E+09	5.56E+09
3.76E+05	3.71E+05	3.66E+05	3.62E+05	3.57E+05	3.52E+05	3.47E+05	3.42E+05	3.37E+05
1.31E+09	1.29E+09	1.28E+09	1.26E+09	1.24E+09	1.22E+09	1.21E+09	1.19E+09	1.17E+09
1.33E+06	1.32E+06	1.30E+06	1.28E+06	1.26E+06	1.24E+06	1.23E+06	1.21E+06	1.19E+06
4.91E+09	4.84E+09	4.78E+09	4.71E+09	4.65E+09	4.58E+09	4.52E+09	4.45E+09	4.39E+09
1.98E+04	1.96E+04	1.93E+04	1.90E+04	1.88E+04	1.85E+04	1.82E+04	1.80E+04	1.77E+04

3.89E+10	3.92E+10	3.95E+10	3.98E+10	4.01E+10	4.04E+10	4.07E+10	4.10E+10	4.12E+10
3.27E+10	3.30E+10	3.34E+10	3.38E+10	3.42E+10	3.45E+10	3.49E+10	3.53E+10	3.57E+10

1928	1929	1930	1931	1932	1933	1934	1935	1936
3.06E+09	3.20E+09	3.33E+09	3.46E+09	3.59E+09	3.72E+09	3.85E+09	3.98E+09	4.11E+09
1.09E+09	1.14E+09	1.19E+09	1.23E+09	1.28E+09	1.33E+09	1.37E+09	1.42E+09	1.47E+09
2.19E+08	2.28E+08	2.38E+08	2.47E+08	2.56E+08	2.65E+08	2.75E+08	2.84E+08	2.93E+08
3.77E+08	4.06E+08	4.36E+08	4.65E+08	4.94E+08	5.23E+08	5.53E+08	5.82E+08	6.11E+08
0	0	0	0	0	0	0	0	0

1937	1938	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954
2.68E+10	2.68E+10	2.72E+10	2.77E+10	2.81E+10	2.85E+10	2.90E+10	2.94E+10	2.99E+10	3.03E+10	3.07E+10	3.12E+10	3.16E+10	3.20E+10	3.24E+10	3.28E+10	3.32E+10	3.36E+10
2.52E+09	2.52E+09	2.56E+09	2.60E+09	2.64E+09	2.68E+09	2.72E+09	2.77E+09	2.81E+09	2.85E+09	2.89E+09	2.93E+09	2.97E+09	3.01E+09	3.05E+09	3.09E+09	3.12E+09	3.16E+09
1.82E+10	1.82E+10	1.85E+10	1.88E+10	1.91E+10	1.94E+10	1.97E+10	2.00E+10	2.03E+10	2.06E+10	2.09E+10	2.12E+10	2.15E+10	2.18E+10	2.20E+10	2.23E+10	2.26E+10	2.28E-10
1.02E+09	1.02E+09	1.03E+09	1.05E+09	1.07E+09	1.08E+09	1.10E+09	1.12E+09	1.13E+09	1.15E+09	1.17E+09	1.18E+09	1.20E+09	1.22E+09	1.23E+09	1.25E+09	1.26E+09	1.27E+09
3.71E+09	3.71E+09	3.77E+09	3.84E+09	3.90E+09	3.96E+09	4.02E+09	4.08E+09	4.14E+09	4.20E+09	4.26E+09	4.32E+09	4.38E+09	4.44E+09	4.50E+09	4.55E+09	4.60E+09	4.66E+09
1.33E+09	1.33E+09	1.36E+09	1.38E+09	1.40E+09	1.42E+09	1.44E+09	1.46E+09	1.49E+09	1.51E+09	1.53E+09	1.55E+09	1.57E+09	1.60E+09	1.62E+09	1.63E+09	1.65E+09	1.67E+09
1.54E+09	1.61E+09	1.76E+09	1.91E+09	2.06E+09	2.21E+09	2.36E+09	2.51E+09	2.65E+09	2.80E+09	2.95E+09	3.10E+09	3.25E+09	3.40E+09	3.84E+09	4.27E+09	4.71E+09	5.14E+09
2.44E+08	2.55E+08	2.79E+08	3.03E+08	3.26E+08	3.50E+08	3.74E+08	3.97E+08	4.21E+08	4.45E+08	4.68E+08	4.92E+08	5.16E+08	5.40E+08	6.08E+08	6.77E+08	7.46E+08	8.15E+08
8.23E+08	8.61E+08	9.41E+08	1.02E+09	1.10E+09	1.18E+09	1.26E+09	1.34E+09	1.42E+09	1.50E+09	1.58E+09	1.66E+09	1.74E+09	1.82E+09	2.05E+09	2.29E+09	2.52E+09	2.75E+09
6.49E+07	6.79E+07	7.42E+07	8.05E+07	8.68E+07	9.31E+07	9.94E+07	1.06E+08	1.12E+08	1.18E+08	1.25E+08	1.31E+08	1.37E+08	1.44E+08	1.62E+08	1.80E+08	1.99E+08	2.17E+08
3.67E+08	3.84E+08	4.20E+08	4.55E+08	4.91E+08	5.27E+08	5.62E+08	5.98E+08	6.34E+08	6.69E+08	7.05E+08	7.41E+08	7.76E+08	8.12E+08	9.16E+08	1.02E+09	1.12E+09	1.23E+09
3.88E+07	4.06E+07	4.44E+07	4.81E+07	5.19E+07	5.57E+07	5.94E+07	6.32E+07	6.70E+07	7.07E+07	7.45E+07	7.83E+07	8.20E+07	8.58E+07	9.68E+07	1.08E+08	1.19E+08	1.30E+08
2.00E+09	2.09E+09	2.38E+09	2.66E+09	2.95E+09	3.24E+09	3.52E+09	3.81E+09	4.10E+09	4.38E+09	4.67E+09	4.96E+09	5.25E+09	5.53E+09	6.13E+09	6.73E+09	7.32E+09	7.92E+09
2.38E+08	2.48E+08	2.82E+08	3.16E+08	3.50E+08	3.84E+08	4.18E+08	4.52E+08	4.86E+08	5.20E+08	5.54E+08	5.88E+08	6.22E+08	6.56E+08	7.27E+08	7.98E+08	8.69E+08	9.40E+08
1.13E+09	1.18E+09	1.34E+09	1.50E+09	1.66E+09	1.83E+09	1.99E+09	2.15E+09	2.31E+09	2.47E+09	2.64E+09	2.80E+09	2.96E+09	3.12E+09	3.46E+09	3.80E+09	4.13E+09	4.47E+09
1.05E+08	1.10E+08	1.25E+08	1.40E+08	1.55E+08	1.70E+08	1.85E+08	2.00E+08	2.16E+08	2.31E+08	2.46E+08	2.61E+08	2.76E+08	2.91E+08	3.22E+08	3.54E+08	3.85E+08	4.17E+08
5.27E+08	5.50E+08	6.25E+08	7.01E+08	7.76E+08	8.52E+08	9.27E+08	1.00E+09	1.08E+09	1.15E+09	1.23E+09	1.31E+09	1.38E+09	1.46E+09	1.61E+09	1.77E+09	1.93E+09	2.09E+09
2.55E+06	2.66E+06	3.02E+06	3.39E+06	3.75E+06	4.12E+06	4.48E+06	4.85E+06	5.21E+06	5.58E+06	5.94E+06	6.31E+06	6.67E+06	7.04E+06	7.80E+06	8.56E+06	9.32E+06	1.01E+07
7.28E+09	7.56E+09	8.19E+09	8.81E+09	9.43E+09	1.01E+10	1.07E+10	1.13E+10	1.19E+10	1.25E+10	1.32E+10	1.38E+10	1.44E+10	1.50E+10	1.65E+10	1.80E+10	1.95E+10	2.10E+10
4.28E+08	4.45E+08	4.82E+08	5.18E+08	5.55E+08	5.91E+08	6.28E+08	6.65E+08	7.01E+08	7.38E+08	7.75E+08	8.11E+08	8.48E+08	8.84E+08	9.73E+08	1.06E+09	1.15E+09	1.24E+09
1.58E+09	1.64E+09	1.77E+09	1.91E+09	2.04E+09	2.18E+09	2.31E+09	2.45E+09	2.58E+09	2.72E+09	2.85E+09	2.99E+09	3.12E+09	3.26E+09	3.58E+09	3.91E+09	4.23E+09	4.56E+09
5.71E+08	5.93E+08	6.42E+08	6.91E+08	7.40E+08	7.89E+08	8.37E+08	8.86E+08	9.35E+08	9.84E+08	1.03E+09	1.08E+09	1.13E+09	1.18E+09	1.30E+09	1.42E+09	1.53E+09	1.65E+09
9.50E+08	9.87E+08	1.07E+09	1.15E+09	1.23E+09	1.31E+09	1.39E+09	1.47E+09	1.56E+09	1.64E+09	1.72E+09	1.80E+09	1.88E+09	1.96E+09	2.16E+09	2.35E+09	2.55E+09	2.75E+09
3.75E+09	3.90E+09	4.22E+09	4.54E+09	4.86E+09	5.18E+09	5.50E+09	5.83E+09	6.15E+09	6.47E+09	6.79E+09	7.11E+09	7.43E+09	7.75E+09	8.53E+09	9.30E+09	1.01E+10	1.09E+10
5.48E+09	5.40E+09	5.32E+09	5.23E+09	5.15E+09	5.07E+09	4.99E+09	4.91E+09	4.83E+09	4.74E+09	4.66E+09	4.58E+09	4.50E+09	4.42E+09	5.85E+09	7.28E+09	8.72E+09	1.02E+10
3.32E+05	3.27E+05	3.22E+05	3.17E+05	3.12E+05	3.07E+05	3.02E+05	2.97E+05	2.92E+05	2.87E+05	2.82E+05	2.77E+05	2.72E+05	2.67E+05	3.54E+05	4.41E+05	5.28E+05	6.14E-05
1.15E+09	1.14E+09	1.12E+09	1.10E+09	1.09E+09	1.07E+09	1.05E+09	1.03E+09	1.02E+09	9.99E+08	9.82E+08	9.64E+08	9.47E+08	9.30E+08	1.23E+09	1.53E+09	1.84E+09	2.14E-09
1.17E+06	1.16E+06	1.14E+06	1.12E+06	1.10E+06	1.09E+06	1.07E+06	1.05E+06	1.03E+06	1.02E+06	9.99E+05	9.81E+05	9.64E+05	9.46E+05	1.25E+06	1.56E+06	1.87E+06	2.18E-06
4.33E+09	4.26E+09	4.20E+09	4.13E+09	4.07E+09	4.00E+09	3.94E+09	3.87E+09	3.81E+09	3.74E+09	3.68E+09	3.61E+09	3.55E+09	3.48E+09	4.62E+09	5.75E+09	6.88E+09	8.01E+09
1.75E+04	1.72E+04	1.69E+04	1.67E+04	1.64E+04	1.62E+04	1.59E+04	1.56E+04	1.54E+04	1.51E+04	1.48E+04	1.46E+04	1.43E+04	1.41E+04	1.86E+04	2.32E+04	2.78E+04	3.23E+04

4.15E+10	4.18E+10	4.31E+10	4.44E+10	4.56E+10	4.69E+10	4.82E+10	4.94E+10	5.07E+10	5.20E+10	5.32E+10	5.45E+10	5.58E+10	5.70E+10	6.10E+10	6.49E+10	6.88E+10	7.27E+10
3.61E+10	3.64E+10	3.78E+10	3.91E+10	4.05E+10	4.18E+10	4.32E+10	4.45E+10	4.59E+10	4.72E+10	4.86E+10	4.99E+10	5.13E+10	5.26E+10	5.51E+10	5.76E+10	6.01E+10	6.26E+10

1937	1938	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954
4.24E+09	4.37E+09	4.56E+09	4.75E+09	4.94E+09	5.13E+09	5.32E+09	5.50E+09	5.69E+09	5.88E+09	6.07E+09	6.26E+09	6.45E+09	6.64E+09	7.46E+09	8.28E+09	9.10E+09	9.93E+09
1.51E+09	1.56E+09	1.63E+09	1.70E+09	1.76E+09	1.83E+09	1.90E+09	1.97E+09	2.03E+09	2.10E+09	2.17E+09	2.24E+09	2.30E+09	2.37E+09	2.66E+09	2.96E+09	3.25E+09	3.54E+09
3.03E+08	3.12E+08	3.26E+08	3.39E+08	3.53E+08	3.66E+08	3.80E+08	3.93E+08	4.07E+08	4.20E+08	4.34E+08	4.47E+08	4.61E+08	4.74E+08	5.33E+08	5.92E+08	6.50E+08	7.09E+08
6.41E+08	6.70E+08	7.20E+08	7.71E+08	8.21E+08	8.71E+08	9.21E+08	9.72E+08	1.02E+09	1.07E+09	1.12E+09	1.17E+09	1.22E+09	1.27E+09	1.37E+09	1.46E+09	1.55E+09	1.64E+09
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971
3.40E+10	3.42E+10	3.44E+10	3.46E+10	3.48E+10	3.50E+10	3.57E+10	3.64E+10	3.71E+10	3.78E+10	3.85E+10	3.74E+10	3.63E+10	3.52E+10	3.41E+10	3.30E+10	3.19E+10
3.20E+09	3.21E+09	3.23E+09	3.25E+09	3.27E+09	3.29E+09	3.36E+09	3.42E+09	3.49E+09	3.56E+09	3.62E+09	3.52E+09	3.42E+09	3.31E+09	3.21E+09	3.11E+09	3.00E+09
2.31E+10	2.32E+10	2.34E+10	2.35E+10	2.36E+10	2.38E+10	2.43E+10	2.47E+10	2.52E+10	2.57E+10	2.62E+10	2.54E+10	2.47E+10	2.39E+10	2.32E+10	2.24E+10	2.17E+10
1.29E+09	1.30E+09	1.30E+09	1.31E+09	1.32E+09	1.33E+09	1.35E+09	1.38E+09	1.41E+09	1.43E+09	1.46E+09	1.42E+09	1.38E+09	1.34E+09	1.29E+09	1.25E+09	1.21E+09
4.71E+09	4.74E+09	4.77E+09	4.79E+09	4.82E+09	4.85E+09	4.95E+09	5.05E+09	5.15E+09	5.24E+09	5.34E+09	5.19E+09	5.04E+09	4.88E+09	4.73E+09	4.58E+09	4.43E+09
1.69E+09	1.70E+09	1.71E+09	1.72E+09	1.73E+09	1.74E+09	1.78E+09	1.81E+09	1.85E+09	1.88E+09	1.92E+09	1.86E+09	1.81E+09	1.75E+09	1.70E+09	1.64E+09	1.59E+09
5.58E+09	6.10E+09	6.62E+09	7.14E+09	7.67E+09	8.19E+09	8.95E+09	9.72E+09	1.05E+10	1.13E+10	1.20E+10	1.27E+10	1.33E+10	1.39E+10	1.45E+10	1.52E+10	1.58E+10
8.84E+08	9.67E+08	1.05E+09	1.13E+09	1.22E+09	1.30E+09	1.42E+09	1.54E+09	1.66E+09	1.79E+09	1.91E+09	2.01E+09	2.11E+09	2.21E+09	2.31E+09	2.41E+09	2.51E+09
2.99E+09	3.26E+09	3.54E+09	3.82E+09	4.10E+09	4.38E+09	4.79E+09	5.20E+09	5.61E+09	6.03E+09	6.44E+09	6.77E+09	7.11E+09	7.45E+09	7.78E+09	8.12E+09	8.46E+09
2.35E+08	2.57E+08	2.79E+08	3.01E+08	3.23E+08	3.46E+08	3.78E+08	4.10E+08	4.43E+08	4.75E+08	5.07E+08	5.34E+08	5.61E+08	5.87E+08	6.14E+08	6.40E+08	6.67E+08
1.33E+09	1.46E+09	1.58E+09	1.71E+09	1.83E+09	1.95E+09	2.14E+09	2.32E+09	2.50E+09	2.69E+09	2.87E+09	3.02E+09	3.17E+09	3.32E+09	3.47E+09	3.62E+09	3.77E+09
1.41E+08	1.54E+08	1.67E+08	1.80E+08	1.93E+08	2.07E+08	2.26E+08	2.45E+08	2.65E+08	2.84E+08	3.03E+08	3.19E+08	3.35E+08	3.51E+08	3.67E+08	3.83E+08	3.99E+08
8.52E+09	9.52E+09	1.05E+10	1.15E+10	1.25E+10	1.35E+10	1.49E+10	1.62E+10	1.76E+10	1.89E+10	2.03E+10	2.09E+10	2.15E+10	2.21E+10	2.28E+10	2.34E+10	2.40E+10
1.01E+09	1.13E+09	1.25E+09	1.37E+09	1.48E+09	1.60E+09	1.76E+09	1.93E+09	2.09E+09	2.25E+09	2.41E+09	2.48E+09	2.55E+09	2.63E+09	2.70E+09	2.77E+09	2.85E+09
4.81E+09	5.37E+09	5.93E+09	6.50E+09	7.06E+09	7.62E+09	8.39E+09	9.16E+09	9.92E+09	1.07E+10	1.15E+10	1.18E+10	1.21E+10	1.25E+10	1.28E+10	1.32E+10	1.35E+10
4.48E+08	5.01E+08	5.53E+08	6.06E+08	6.58E+08	7.11E+08	7.82E+08	8.54E+08	9.25E+08	9.97E+08	1.07E+09	1.10E+09	1.13E+09	1.16E+09	1.20E+09	1.23E+09	1.26E+09
2.24E+09	2.51E+09	2.77E+09	3.03E+09	3.29E+09	3.56E+09	3.91E+09	4.27E+09	4.63E+09	4.99E+09	5.34E+09	5.51E+09	5.67E+09	5.83E+09	5.99E+09	6.15E+09	6.31E+09
1.08E+07	1.21E+07	1.34E+07	1.46E+07	1.59E+07	1.72E+07	1.89E+07	2.06E+07	2.24E+07	2.41E+07	2.58E+07	2.66E+07	2.74E+07	2.82E+07	2.89E+07	2.97E+07	3.05E-07
2.25E+10	2.42E+10	2.59E+10	2.76E+10	2.92E+10	3.09E+10	3.38E+10	3.66E+10	3.95E+10	4.23E+10	4.52E+10	5.02E+10	5.51E+10	6.01E+10	6.50E+10	7.00E+10	7.49E+10
1.33E+09	1.42E+09	1.52E+09	1.62E+09	1.72E+09	1.82E+09	1.99E+09	2.15E+09	2.32E+09	2.49E+09	2.66E+09	2.95E+09	3.24E+09	3.53E+09	3.82E+09	4.12E+09	4.41E+09
4.89E+09	5.25E+09	5.61E+09	5.97E+09	6.33E+09	6.69E+09	7.31E+09	7.93E+09	8.55E+09	9.17E+09	9.79E+09	1.09E+10	1.19E+10	1.30E+10	1.41E+10	1.52E+10	1.62E+10
1.77E+09	1.90E+09	2.03E+09	2.16E+09	2.29E+09	2.42E+09	2.65E+09	2.87E+09	3.10E+09	3.32E+09	3.55E+09	3.93E+09	4.32E+09	4.71E+09	5.10E+09	5.49E+09	5.88E+09
2.94E+09	3.16E+09	3.38E+09	3.60E+09	3.81E+09	4.03E+09	4.41E+09	4.78E+09	5.15E+09	5.53E+09	5.90E+09	6.54E+09	7.19E+09	7.84E+09	8.48E+09	9.13E+09	9.77E+09
1.16E+10	1.25E+10	1.33E+10	1.42E+10	1.51E+10	1.59E+10	1.74E+10	1.89E+10	2.04E+10	2.18E+10	2.33E+10	2.59E+10	2.84E+10	3.10E+10	3.35E+10	3.61E+10	3.86E+10
1.16E+10	1.30E+10	1.45E+10	1.59E+10	1.73E+10	1.88E+10	2.02E+10	2.16E+10	2.31E+10	2.45E+10	2.59E+10	2.74E+10	2.88E+10	3.02E+10	3.17E+10	3.31E+10	3.45E+10
7.01E+05	7.88E+05	8.75E+05	9.62E+05	1.05E+06	1.14E+06	1.22E+06	1.31E+06	1.40E+06	1.48E+06	1.57E+06	1.66E+06	1.74E+06	1.83E+06	1.92E+06	2.00E+06	2.09E+06
2.44E+09	2.74E+09	3.04E+09	3.35E+09	3.65E+09	3.95E+09	4.25E+09	4.55E+09	4.86E+09	5.16E+09	5.46E+09	5.76E+09	6.06E+09	6.37E+09	6.67E+09	6.97E+09	7.27E+09
2.48E+06	2.79E+06	3.10E+06	3.40E+06	3.71E+06	4.02E+06	4.33E+06	4.63E+06	4.94E+06	5.25E+06	5.56E+06	5.86E+06	6.17E+06	6.48E+06	6.79E+06	7.09E+06	7.40E+06
9.14E+09	1.03E+10	1.14E+10	1.25E+10	1.37E+10	1.48E+10	1.59E+10	1.71E+10	1.82E+10	1.93E+10	2.05E+10	2.16E+10	2.27E+10	2.39E+10	2.50E+10	2.61E+10	2.72E+10
3.69E+04	4.15E+04	4.60E+04	5.06E+04	5.52E+04	5.97E+04	6.43E+04	6.89E+04	7.35E+04	7.80E+04	8.26E+04	8.72E+04	9.17E+04	9.63E+04	1.01E+05	1.05E+05	1.10E+05

7.66E+10	8.09E+10	8.52E+10	8.95E+10	9.38E+10	9.81E+10	1.05E+11	1.11E+11	1.17E+11	1.24E+11	1.30E+11	1.36E+11	1.42E+11	1.48E+11	1.54E+11	1.59E+11	1.65E+11
6.51E+10	6.79E+10	7.08E+10	7.37E+10	7.65E+10	7.94E+10	8.43E+10	8.93E+10	9.42E+10	9.91E+10	1.04E+11	1.09E+11	1.13E+11	1.17E+11	1.22E+11	1.26E+11	1.31E+11

1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971
1.07E+10	1.16E+10	1.24E+10	1.32E+10	1.40E+10	1.49E+10	1.57E+10	1.65E+10	1.73E+10	1.81E+10	1.90E+10	1.97E+10	2.05E+10	2.12E+10	2.19E+10	2.27E+10	2.34E+10
3.84E+09	4.13E+09	4.43E+09	4.72E+09	5.01E+09	5.31E+09	5.60E+09	5.89E+09	6.19E+09	6.48E+09	6.77E+09	7.55E+09	8.33E+09	9.11E+09	9.88E+09	1.07E+10	1.14E+10
7.68E+08	8.27E+08	8.85E+08	9.44E+08	1.00E+09	1.06E+09	1.12E+09	1.18E+09	1.24E+09	1.30E+09	1.36E+09	2.56E+09	3.77E+09	4.98E+09	6.19E+09	7.40E+09	8.61E+09
1.73E+09	1.89E+09	2.05E+09	2.21E+09	2.36E+09	2.52E+09	2.68E+09	2.83E+09	2.99E+09	3.14E+09	3.30E+09	3.52E+09	3.74E+09	3.97E+09	4.19E+09	4.41E+09	4.64E+09
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.22E+09

1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
3.22E+10	3.23E+10	3.24E+10	3.28E+10	3.35E+10	3.43E+10	3.53E+10	3.44E+10	3.43E+10	3.36E+10	3.38E+10	3.54E+10	3.64E+10	3.69E+10	3.79E+10	3.90E+10	3.86E+10	3.67E+10
3.18E+09	3.31E+09	3.40E+09	3.45E+09	3.59E+09	3.77E+09	3.84E+09	2.97E+09	2.82E+09	2.72E+09	2.63E+09	2.60E+09	2.47E+09	2.41E+09	2.35E+09	2.37E+09	2.36E+09	2.31E+09
2.23E+10	2.24E+10	2.26E+10	2.29E+10	2.35E+10	2.42E+10	2.50E+10	2.34E+10	2.33E+10	2.26E+10	2.27E+10	2.41E+10	2.47E+10	2.50E+10	2.59E+10	2.68E+10	2.70E+10	2.62E+10
1.22E+09	1.23E+09	1.23E+09	1.24E+09	1.27E+09	1.30E+09	1.34E+09	1.30E+09	1.48E+09	1.53E+09	1.71E+09	1.79E+09	1.77E+09	1.94E+09	1.99E+09	2.42E+09	2.79E+09	2.18E+09
4.05E+09	4.03E+09	3.95E+09	3.97E+09	4.04E+09	4.02E+09	4.14E+09	5.61E+09	5.57E+09	5.72E+09	5.71E+09	5.94E+09	6.50E+09	6.65E+09	6.86E+09	6.57E+09	5.58E+09	5.30E+09
1.38E+09	1.30E+09	1.29E+09	1.15E+09	1.11E+09	1.03E+09	9.66E+08	1.10E+09	1.08E+09	1.07E+09	1.03E+09	1.01E+09	9.90E+08	9.10E+08	8.69E+08	8.30E+08	8.07E+08	7.55E+08
1.84E+10	1.90E+10	1.95E+10	2.08E+10	2.18E+10	2.30E+10	2.40E+10	2.46E+10	2.52E+10	2.54E+10	2.64E+10	2.81E+10	2.92E+10	3.01E+10	3.15E+10	3.29E+10	3.40E+10	3.49E+10
2.86E+09	2.97E+09	3.43E+09	3.56E+09	3.77E+09	3.95E+09	4.09E+09	4.23E+09	4.46E+09	4.60E+09	4.81E+09	5.07E+09	5.39E+09	5.66E+09	6.03E+09	6.34E+09	6.53E+09	6.80E+09
9.93E+09	1.03E+10	9.92E+09	1.08E+10	1.12E+10	1.17E+10	1.22E+10	1.25E+10	1.27E+10	1.24E+10	1.29E+10	1.39E+10	1.43E+10	1.46E+10	1.51E+10	1.59E+10	1.63E+10	1.65E+10
7.77E+08	8.02E+08	8.23E+08	8.78E+08	9.21E+08	9.69E+08	1.01E+09	1.04E+09	1.07E+09	1.17E+09	1.15E+09	1.29E+09	1.30E+09	1.38E+09	1.47E+09	1.55E+09	1.74E+09	1.82E+09
4.41E+09	4.52E+09	4.84E+09	5.11E+09	5.47E+09	5.83E+09	6.13E+09	6.23E+09	6.40E+09	6.59E+09	6.93E+09	7.23E+09	7.54E+09	7.85E+09	8.24E+09	8.47E+09	8.69E+09	8.96E+09
4.37E+08	4.52E+08	4.86E+08	4.82E+08	4.92E+08	5.29E+08	5.53E+08	5.74E+08	5.78E+08	5.83E+08	5.94E+08	6.17E+08	6.53E+08	6.69E+08	6.83E+08	7.09E+08	7.24E+08	7.42E+08
2.66E+10	2.72E+10	2.70E+10	2.83E+10	2.87E+10	2.96E+10	3.13E+10	3.23E+10	3.25E+10	3.17E+10	3.21E+10	3.39E+10	3.43E+10	3.46E+10	3.62E+10	3.76E+10	3.91E+10	3.98E+10
3.00E+09	3.01E+09	3.41E+09	3.67E+09	3.61E+09	3.79E+09	4.07E+09	3.99E+09	4.01E+09	4.19E+09	4.15E+09	4.46E+09	4.52E+09	4.64E+09	4.78E+09	5.08E+09	5.26E+09	5.22E+09
1.53E+10	1.56E+10	1.46E+10	1.55E+10	1.60E+10	1.63E+10	1.73E+10	1.78E+10	1.80E+10	1.68E+10	1.71E+10	1.82E+10	1.83E+10	1.82E+10	1.92E+10	1.98E+10	2.07E+10	2.16E+10
1.69E+09	1.81E+09	7.74E+08	9.09E+08	9.73E+08	1.08E+09	1.17E+09	1.21E+09	1.37E+09	1.38E+09	1.46E+09	9.47E+08	8.91E+08	9.64E+08	1.08E+09	1.24E+09	1.25E+09	1.43E+09
6.61E+09	6.71E+09	8.12E+09	8.11E+09	8.00E+09	8.41E+09	8.75E+09	9.19E+09	9.12E+09	9.33E+09	9.28E+09	1.02E+10	1.06E+10	1.06E+10	1.09E+10	1.13E+10	1.17E+10	1.13E+10
3.64E+07	4.22E+07	4.59E+07	5.19E+07	5.32E+07	5.57E+07	5.60E+07	5.65E+07	6.29E+07	6.79E+07	7.28E+07	8.98E+07	1.22E+08	1.68E+08	2.10E+08	2.34E+08	2.54E+08	2.72E+08
8.38E+10	8.17E+10	8.22E+10	8.68E+10	8.97E+10	9.23E+10	9.39E+10	9.07E+10	8.76E+10	8.60E+10	8.50E+10	8.67E+10	8.77E+10	9.02E+10	9.21E+10	9.50E+10	9.66E+10	9.71E+10
4.98E+09	4.62E+09	4.20E+09	5.44E+09	5.42E+09	5.61E+09	4.97E+09	4.71E+09	4.32E+09	4.06E+09	4.13E+09	4.16E+09	4.07E+09	4.35E+09	4.28E+09	4.30E+09	4.10E+09	4.03E+09
1.79E+10	1.76E+10	1.68E+10	1.77E+10	1.88E+10	1.87E+10	2.07E+10	2.04E+10	1.85E+10	1.75E+10	1.61E+10	1.59E+10	1.59E+10	1.59E+10	1.59E+10	1.59E+10	1.63E+10	1.59E+10
6.57E+09	6.41E+09	6.45E+09	6.81E+09	7.04E+09	7.24E+09	7.37E+09	7.11E+09	7.07E+09	7.07E+09	7.02E+09	7.30E+09	7.44E+09	7.24E+09	7.39E+09	7.53E+09	7.28E+09	7.45E+09
1.07E+10	9.79E+09	9.97E+09	1.00E+10	9.91E+09	1.02E+10	9.65E+09	8.67E+09	8.18E+09	7.85E+09	7.79E+09	8.00E+09	8.13E+09	8.16E+09	8.22E+09	8.32E+09	8.33E+09	8.09E+09
4.37E+10	4.33E+10	4.48E+10	4.68E+10	4.86E+10	5.06E+10	5.13E+10	4.98E+10	4.96E+10	4.95E+10	5.00E+10	5.13E+10	5.22E+10	5.46E+10	5.64E+10	5.89E+10	6.06E+10	6.16E+10
3.63E+10	3.67E+10	3.77E+10	3.87E+10	3.94E+10	4.04E+10	4.19E+10	4.29E+10	4.46E+10	4.49E+10	4.52E+10	4.81E+10	4.72E+10	5.49E+10	4.86E+10	4.93E+10	4.95E+10	4.96E+10
2.09E+06	2.31E+06	2.29E+06	2.28E+06	2.28E+06	2.28E+06	2.29E+06	2.26E+06	2.66E+06	2.68E+06	2.84E+06	2.86E+06	9.32E+06	9.70E+06	9.19E+06	1.00E+07	1.09E+07	1.10E+07
7.59E+09	7.21E+09	7.35E+09	7.56E+09	7.76E+09	7.80E+09	8.10E+09	7.97E+09	8.25E+09	8.13E+09	8.42E+09	8.83E+09	8.71E+09	9.51E+09	9.10E+09	9.19E+09	8.92E+09	8.58E+09
9.49E+06	9.49E+06	7.97E+06	1.03E+07	1.09E+07	1.28E+07	1.71E+07	1.66E+07	1.67E+07	2.85E+07	2.93E+07	3.28E+07	3.35E+07	4.15E+07	5.49E+07	5.37E+07	1.51E+08	9.92E+07
2.87E+10	2.95E+10	3.03E+10	3.11E+10	3.16E+10	3.26E+10	3.38E+10	3.49E+10	3.63E+10	3.67E+10	3.67E+10	3.92E+10	3.85E+10	4.54E+10	3.94E+10	4.00E+10	4.04E+10	4.09E+10
1.20E+05	1.10E+05	1.10E+05	1.00E+05	1.00E+05	1.00E+05	1.00E+05	1.00E+05	1.00E+05	9.00E+04	9.00E+04	8.00E+04	7.00E+04	7.00E+04	7.00E+04	7.00E+04	7.00E+04	7.00E+04
1.79E+11	1.78E+11	1.79E+11	1.87E+11	1.91E+11	1.97E+11	2.02E+11	2.00E+11	1.99E+11	1.96E+11	1.96E+11	2.04E+11	2.06E+11	2.17E+11	2.15E+11	2.21E+11	2.24E+11	2.23E+11
1.43E+11	1.41E+11	1.42E+11	1.48E+11	1.52E+11	1.56E+11	1.60E+11	1.57E+11	1.54E+11	1.51E+11	1.51E+11	1.56E+11	1.58E+11	1.62E+11	1.66E+11	1.72E+11	1.74E+11	1.74E+11

1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
2.60E+10	2.65E+10	2.76E+10	3.00E+10	3.12E+10	3.15E+10	3.30E+10	3.59E+10	3.62E+10	3.72E+10	3.89E+10	4.02E+10	4.19E+10	4.27E+10	4.51E+10	4.67E+10	4.85E+10	4.87E+10
1.56E+10	1.59E+10	1.57E+10	1.73E+10	1.81E+10	1.91E+10	1.90E+10	1.81E+10	1.74E+10	1.63E+10	1.59E+10	1.56E+10	1.41E+10	1.41E+10	1.38E+10	1.38E+10	1.37E+10	1.36E+10
8.86E+09	9.19E+09	9.11E+09	9.44E+09	9.79E+09	1.01E+10	1.10E+10	1.13E+10	1.16E+10	1.22E+10	1.27E+10	1.41E+10	1.50E+10	1.57E+10	1.68E+10	1.75E+10	1.89E+10	1.91E+10
4.99E+09	5.49E+09	5.62E+09	5.62E+09	5.82E+09	6.25E+09	6.65E+09	6.96E+09	7.13E+09	7.31E+09	7.71E+09	8.02E+09	8.24E+09	8.46E+09	8.59E+09	8.84E+09	8.82E+09	8.97E+09
2.24E+09	2.99E+09	4.21E+09	4.84E+09	5.89E+09	6.87E+09	7.11E+09	7.84E+09	9.26E+09	1.00E+10	1.14E+10	1.38E+10	1.64E+10	1.76E+10	1.91E+10	2.07E+10	2.13E+10	2.21E+10

Price of secondary energy carrier (US$-1990 / GJin)

			1900	1905	1910	1915	1920	1925	1930	1935	1940	1945	1950	1955	1960	1965	1971	1975	1980	1985	1990
WORLD	COMMERCIAL	coal	2.43	2.40	2.37	2.34	2.30	2.27	2.24	2.21	2.18	2.15	2.11	2.01	1.90	1.90	1.90	2.14	2.09	2.71	2.80
WORLD	COMMERCIAL	electricity	94.22	87.16	80.09	73.02	65.96	58.89	51.82	44.76	37.69	30.62	23.56	21.78	20.00	18.23	16.45	19.43	20.99	18.60	20.45
WORLD	COMMERCIAL	gas	1.29	1.26	1.23	1.20	1.17	1.14	1.11	1.08	1.05	1.02	0.99	1.28	1.57	1.49	1.40	2.40	4.40	4.81	4.14
WORLD	COMMERCIAL	mod biofuel															ERR	ERR	ERR	ERR	ERR
WORLD	COMMERCIAL	oil	5.73	5.59	5.46	5.33	5.20	5.06	4.93	4.80	4.67	4.54	4.40	4.21	4.01	3.76	3.50	6.10	9.22	7.14	6.67
WORLD	INDUSTRY	coal	1.81	1.78	1.76	1.74	1.71	1.69	1.67	1.64	1.62	1.60	1.57	1.49	1.41	1.41	1.41	1.99	2.04	1.88	2.03
WORLD	INDUSTRY	electricity	66.08	61.12	56.17	51.21	46.25	41.30	36.34	31.39	26.43	21.48	16.52	15.27	14.03	12.78	11.54	14.44	16.07	13.38	15.62
WORLD	INDUSTRY	gas	1.21	1.18	1.15	1.13	1.10	1.07	1.04	1.01	0.99	0.96	0.93	1.20	1.47	1.40	1.32	2.27	3.25	3.21	2.39
WORLD	INDUSTRY	mod biofuel															ERR	ERR	ERR	ERR	ERR
WORLD	INDUSTRY	oil	3.05	2.98	2.91	2.84	2.76	2.69	2.62	2.55	2.48	2.41	2.34	2.24	2.13	2.00	1.86	3.58	5.25	4.30	3.39
WORLD	OTHERS	coal	3.74	3.69	3.64	3.59	3.54	3.49	3.45	3.40	3.35	3.30	3.25	3.09	2.93	2.93	2.93	3.11	3.03	2.82	3.39
WORLD	OTHERS	electricity	87.38	80.82	74.27	67.72	61.16	54.61	48.06	41.50	34.95	28.40	21.84	20.20	18.55	16.90	15.26	15.91	16.73	12.92	15.39
WORLD	OTHERS	gas	0.85	0.83	0.81	0.79	0.77	0.75	0.73	0.71	0.69	0.67	0.65	0.84	1.03	0.98	0.93	5.07	6.51	3.79	3.20
WORLD	OTHERS	mod biofuel															ERR	ERR	ERR	ERR	ERR
WORLD	OTHERS	oil	4.24	4.14	4.04	3.95	3.85	3.75	3.65	3.56	3.46	3.36	3.26	3.12	2.97	2.78	2.59	3.47	5.00	4.44	4.77
WORLD	RESIDENTIAL	coal	6.22	6.14	6.06	5.98	5.90	5.82	5.73	5.65	5.57	5.49	5.41	5.14	4.87	4.87	4.87	6.62	6.23	4.58	6.88
WORLD	RESIDENTIAL	electricity	123.73	114.45	105.17	95.89	86.61	77.33	68.05	58.77	49.49	40.21	30.93	28.60	26.27	23.94	21.60	25.06	26.47	22.05	25.29
WORLD	RESIDENTIAL	gas	1.93	1.89	1.84	1.80	1.75	1.71	1.66	1.62	1.57	1.53	1.48	1.92	2.35	2.23	2.10	3.43	6.15	6.36	6.12
WORLD	RESIDENTIAL	mod biofuel															ERR	ERR	ERR	ERR	ERR
WORLD	RESIDENTIAL	oil	7.95	7.77	7.58	7.40	7.22	7.03	6.85	6.67	6.48	6.30	6.11	5.84	5.57	5.21	4.86	7.61	11.78	8.78	9.29
WORLD	TRANSPORT	coal	3.68	3.63	3.58	3.54	3.49	3.44	3.39	3.34	3.30	3.25	3.20	3.04	2.88	2.88	2.88	3.32	3.35	3.24	3.59
WORLD	TRANSPORT	electricity	72.36	66.93	61.51	56.08	50.65	45.23	39.80	34.37	28.94	23.52	18.09	16.73	15.36	14.00	12.63	14.02	15.48	12.21	16.33
WORLD	TRANSPORT	gas	0.71	0.69	0.68	0.66	0.64	0.63	0.61	0.59	0.58	0.56	0.55	0.70	0.86	0.82	0.77	1.68	1.99	1.09	2.07
WORLD	TRANSPORT	mod biofuel															ERR	ERR	ERR	ERR	ERR
WORLD	TRANSPORT	oil	15.39	15.03	14.68	14.32	13.97	13.61	13.26	12.90	12.55	12.19	11.84	11.31	10.78	10.09	9.40	12.99	17.30	12.53	14.18

DataBiomass at plantations

Biomass production & land use: Battjes

Region	en. balance (GJe/ha)	Electricity production (EJe)		land use (million ha)		Biomass production (EJprimary)	
		BF1	BF2	BF1	BF2	BF1	BF2
Canada	50	1.1	1.1	22	22		
USA	150	6.5	6.5	43	43		
Latin America	200	5.1	6.8	25	34		
Africa	200	0	7.9	0	40		
OECD Europe	100	1.4	1.4	14	14		
Eastern Euro	100	0.9	0.9	9	9		
CIS	50	5.3	5.3	106	106		
Middle East	50	0	0	0	0		
India & S.Eas	150	0	5.3	0	35		
China &CPA	100	0.5	6	5	60		
East Asia	200	0.1	3.8	1	19		
Oceania	150	0.3	0.3	2	2		
Japan	100	0	0	0	0		
Total	118	21.2	45.3	227	384	47	101

Biomass production: Alcamo

amount of biofuel used (PJin)
TRANSPORT: from new required land
REST SECTORS: 60% from crop residues
40% from new required land

	TOTAL WORLD	PLANTATION FACTOR	PLANTATION WORLD
2050			
INDUSTRY	29547	0.4	11819
TRANSPORT	9628	1	9628
RESIDENTIAL	33446	0.4	13378
COMMERCIAL	1498	0.4	599
OTHER	0	0.4	0
TOTAL	74119		**35424**
2100			
INDUSTRY	113031	0.4	45212
TRANSPORT	16761	1	16761
RESIDENTIAL	70153	0.4	28061
COMMERCIAL	8041	0.4	3216
OTHER	0	0.4	0
TOTAL	207987		**93251**

Assumptions

Johansson
- RIGES total primary biomass production: 145 EJ in 2025, 206 EJ in 2050
- RIGES total primary biomass use in 2050:

		Production from biomass	Conversion efficiency	Primary biomass supply (EJ)
Electricity from sugarcane residues	in TWh	1.335	40.0%	12
Electricity from biomass (stand-alone)	in TWh	4.084	57.0%	26
Electricity from methanol	in TWh	0.348	60.0%	2 (methanol use)
Methanol from biomass	in EJ	61.35	62.9%	98
Hydrogen from biomass	in EJ	25.05	71.5%	35
Solid fuel (forests)	in EJ	9.94	100.0%	10
Biogas (dung)	in EJ	14.1	57.0%	25
Biogas (distilleries)	in EJ	0.2	100.0%	0
Ethanol from sugarcane	in EJ	1	60.0%	2
Total excluding electricity from methanol (2/0.629)				206

- share of plantations in total biomass supply: 55% (80 EJ) in 2025, 62% (128 EJ) in 2050
- productivity: 11 ton/ha and 20 GJ/ton; 220 GJ/ha in 2025
  15 ton/ha and 20 GJ/ton; 300 GJ/ha in 2050
  increase in world average productivity due to increase by region,
  so (probably) because of technology & management improvement
- primary biomass supply used for electricity production in 2050: 41 EJ
  of which produced at plantations (62%) 26 EJ

Van Amstel
- Intended to simulate the same amount of biomass supply of plantations of Johansson by IMAGE 2.0
  However, because efficiency of electricity conversion not considered, biomass supply is:
  95 EJ heat, 33 EJ electricity which is 160 EJ primary biomass supply in 2050
  in stead of 128 EJ according to Johansson
  Extra simulation for 2100:
  183 EJ heat and probably 65 EJ electricity which is 350 EJ primary biomass supply in 2100
- considered energy biomass production only from plantations
- biomass productivity: based on an average for elephants grass

Alcamo
- Comparison of conventional wisdom scenario and biofuel crops scenario
  In conventional wisdom scenario primary biomass supply of modem biofuels is 74.1 EJ
  in 2050 and 208 EJ in 2100.
  The conventional wisdom scenario assumes that this biofuels are derived from crop residues
  and other sources that do not require new cropland.
  The biofuel crops scenario has the same assumptions as the conventional wisdom scenario
  except that it assumes that a large fraction of biofuels will be provided by energy crops
  grown on additional cropland. Specifically:

Transport	Latin America, Africa, East Asia:	sugar cane
	other regions:	maize
Other energy sectors:		elephant grass

  The result is an energy biomass production at plantations of 35 EJ in 2050 and 93 EJ in 2100.
- Results: CO2-concentration higher then in Conventional Wisdom scenario due to replacement of forests
  in energy crop plantations.
- Conclusion: "Perhaps this scenario provides a useful estimate of the upper range of land requirements of biofuels"
  because agricultural wastes, plantations on marginal land, and other non-cropland sources
  are not used. Also not the most - for local climate and soil - suitable energy crops are selected.

Battjes
- **All biofuels are used in electricity power generation**
- Only plantations
- Most suitable crops selected: 85% miscanthus (elephant grass), 15% tree crops (Battjes, figure most suitable energy crop)
  productivity: see table on productivity per region
- Most efficient energy conversion selected

energy balance:

Based on land use in the Netherlands	**energy carrier**	**unit**	**eucalyptus**	**miscanthus**	**poplar**	**sugar cane**	**wheat**
co-generation (80% eff.)	elec & heat	(GJe+GJheat)/ha	203	188	130		
electricity generation (45% eff)	electricity	GJe/ha	108	98	67		
heat	heat	GJheat/ha				81	49

Costs of biomass

Electricity (Source: Battjes): Investments in electricity production by energy crops from plantations

	Price of primary energy ($/GJ)			Lower Heating Value GJ/tonne	energy balance feedstock to electricity		electricity power generation costs			electricity power generation investments		
	minimum	maximum	average		GJe/tonne	GJe/ha	total costs $/GJe	capital el.power g. $/GJe	fuel costs $/GJe	total $/GJe	elec. plant $/GJe	fuel inv. 50% of price $/GJe
eucalyptus	2.4		2.4	18	7.2	108	**13**	7	7	**105**	70	35
miscanthus	3.7	11.7	7.7	17	6.5	98	**28**	7	21	**175**	70	105
poplar	3.2	10.8	7	18	6.7	67	**27**	7	19	**165**	70	95

- capital costs of electricity power generation is calculated with the mean of 6% and 12% discount rate and 25 years lifetime of capital stock
- energy balance is based on the Netherlands; world average is 120 GJe/ha according to Battjes
- investments of fuel: assumed is 50% of fuel price is investment, 20% is labour and 30% is other (wheat, the Netherlands, Lysen et al: 300 $/tonne)
- poplar energy balance in GJe per ha based on yield of 10 tonne/ha; CHANGE 22, nov 1994, p10: 14 tonne/ha.
- costs of plantation wood (eucalyptus) in Brazil (Williams & Larson in Johansson 1993): 20% capital; 30% harvest/transport; 50% chipper/conveyor & storage/drying

Ethanol (Source: Battjes): Investments in ethanol production by energy crops from plantations

	Price of feedstock ($/tonne)				energy balance feedstock to ethanol		Price of ethanol				Investments of ethanol from feedstock			
	minimum	maximum	average		GJeth/tonne	GJeth/ha	total costs $/GJeth	capital distillery $/GJeth	fuel costs $/GJeth	revenues (electricity &fodder)	total costs $/GJeth	capital distillery $/GJeth	capital fuel $/GJeth	revenues (electricity &fodder)
sugar cane			10		1.5	81	**8.5**	4.2	6.1	-1.9	**62**	42	30	-10
wheat	130	190	175		7	49	**20.7**	10.7	21.5	-11.8	**155**	107	108	-60

- Price of wheat: given in the table are world prices (SER 1993; NRLO 1990; FAO 1992); The Netherlands is 300 $/tonne (Lysen et al, 1992)
- investments of fuel: assumed is 50% of fuel price is investment, 20% is labour and 30% is other (wheat, the Netherlands, Lysen et al: 300 $/tonne)
- investments saved in electricity (50% of electricity price is capital costs assumed)

Wood cost North East Brazil (Source: J. Woods and D.O. Hall, Bioenergy for development, FAO Environment and Energy Paper 13, Rome, 1994)

Cumulative production (10^6 GJ)	Wood cost (1988$/GJ)
2000	1.1
4000	1.2
11000	1.3
12000	1.8

APPENDIX E: CALIBRATION PROCEDURE

We use a systematic approach for validation which consists of the following three steps (see also Berg 1994).

1. All model variables are organized according to their relationship with real-world observables. The categories used are : exogenous driving forces, directly simulated real-world observables, real-world variables which are themselves estimates from more limited data sets or inference structures, and finally model parameters which have real-world counterparts in technical or economic research resports

2. The calibration procedure is organized by going from exogenous driving forces to the simulation of the real-world observables and determine the variance, by way of least-square regression, between the simulated trajectory and the real-world observable trajectory.

In order to assess the quality of the simulation, some number has to be found that serves as a measure of the similarity between historical fact and simulation. This factor should express the relative difference between history and model outcome over the period of calibration. The factor that serves this purpose best is called the <u>coefficient of variation</u> (CVY), defined as:

$$CVY = \sqrt{\exp(s^2) - 1} \qquad s^2 = \frac{\sum_n (u - \tilde{u})^2}{N-1}$$

In these equations and with u and $\tilde{u}$ respectively representing the historical and the simulated values for each year, and N the number of measurement points. The CVY was used instead of the usual parameter of dispersion, the variance, because the variance takes into account the differences in excess of and below the *mean* , where the CVY takes into account *proportional* differences, and measures deviations from the *median* .

The log-transformation of the data ensures that proportional differences are taken into account, which is preferable as a consequence of the multiplicative (as opposed to additive) features of the simulation outcomes. The median (of the difference between simulated and historical data) is used so that 50% of the data lie above it and 50% below it, thereby preventing possible huge discrepancies in certain years from distorting the overall picture, which would happen if the mean was used (Slob 1986).

In order to get a clear picture of the proportional value of the CVY relative to the average value of the variable under calibration, it can be decided to divide the CVY by this average and express the result as a percentage. This was not done for each calibration exercise, as the main purpose was to look for the combination of parameters that provide the lowest value for the CVY, which is independent of either an absolute or a relative CVY. However, for the sake of consistency throughout the entire model calibration, it is advisable to keep to one standard expression, in this case the relative CVY, as it can also offer a means of comparing the accuracy of simulation results of different variables to one another. The definitive expression for the CVY would then become:

$$CVY(\text{relative}) = \frac{CVY}{\bar{u}} * 100\%$$

3. Based on the CVY, some of the model parameters are changed in such a way as to minimize the CVY-value. For the results presented in this report, this has not been done systematically. In connection with such parameter changes, sensitivity analyses have been performed to get a better understanding of the changes and their interaction. As an additional check, those real-world variables which are themselves estimates from more limited data sets or inference structures and which are available from published literature, have been used for comparison.

APPENDIX F: LIST OF SUBMODEL VARIABLES

ED-model : List of variables

Name	Variable	Unit	Default[a]
ε	energy-intensity	GJ/$	
A	activity	$/yr	
AEEI	Autonomous Energy Efficieny Increase factor	(-)	
ε^*_{limit}	lower limit on AEEI-factor	(-)	0.15-0.4
c	annual decrease rate of AEEI-factor		
PIEEI	Price Induced Energy Efficiency Increase factor	(-)	
B_{max}	upper bound on PIEEI-factor	(-)	0.4-0.9
UECost	Useful Energy Cost	$/GJ	
PBT	desired/required PayBack Time	yr	1-3.5
d	annual decrease rate of PIEEI-curve	%/yr	0
α	steepness parameter PIEEI-curve		10-50

Name	Parameter / Index	Unit	Default[a]
β_i	structural change parameter (i=1,2,3)		
avg	index for average		
limit	index for lower bound		

a) see Table 3.1

LF-model : List of variables

Name	Variable	Unit	Default[a]
AD	Anticipated Demand for liquid fuel	GJth/yr	
BLF	BioLiquidFuel	(-)	
α	autonomous discovery rate parameter	(-)	0.1-1
ß	price ratio between LLF and HLF	(-)	2
C	LiquidFuel producing Capital stock	$	2.58e9
c	cost	$/GJth	
γ_i	capital-output ratio	$/GJth/yr	3(CO) 5(BLF)
CLR	Capital Labour Ratio for BLF	$/person/yr	
D	Demand for LiquidFuel	GJth/yr	0.86e9
∂	fraction of LLF in total LF-demand	(fraction)	0.06-0.5
DGM	Desired Gross Margin	(fraction)	1.2
EL	Economic Lifetime	yr	8
EPIP	Expected Profits from Inv in Prod multiplier	(-)	
F	Loss fraction in transport and refining	(fraction)	0.1
f	functional for depletion effect	(-)	
FP	FuelPrice	$/GJth	
IEXPL	Investments in CO-exploration	$/yr	

IMS	Indicated Market/Share of BLF	(fraction)	
IPROD	Investments in CO-production	$/yr	
L	Labour input	person-yr	
μ	actual market share	(fraction)	
P	Production of CO	GJth/yr	0.86e9
p	price	$/GJth	
R	identified Reserve of CO	GJth	12.6e9
r	interest rate	(-)	0.1
RPR	Reserve-Production Ratio	yr	15
S	Supply of BLF	GJth/yr	
SDM	Supply-Demand Multiplier	(-)	
TL	Technical Lifetime	yr	11
X	undiscovered Resource of CO	GJth	36000e9
Y	cumulated production of CO	GJth	9.3e9

Name	Parameter / Index	Unit	Default[a]
a	annuity factor	(-)	
avg	index for average		
BLF	index for BioLiquidFuel		
CO	index for Crude Oil c.q. Conventional Oil		
d	index for desired		
expl	index for exploration		
HLF	index for HeavyLiquidFuel		
k	multinomial logit parameter	(-)	0.3
L	index for Labour		
LF	index for Liquid Fuel		
LLF	index for LightLiquidFuel		
m	max fraction of reserve producible per year		0.1
OLLF	index for Oil-based LightLiquidFuel		
p	index for political[ly desired]		
prod	index for production		
req	index for required		
tL	time at which depletion/learning starts	(yr)	1900(CO) 1970(BLF)
TH	time horizon for anticipation	(yr)	
tr&ref	index for transport and refining		
π	learning curve constant	(-)	0.8(CO) 0.9(BLF)

a) if taken constant. For state variables X, R, Y and C and for production and demand, values are for the starting year 1900. For the RPR it indicates the desired value. For time-dependent variables, values are for 1900 and 1990.

GF-model : List of variables

This model is almost identical to the LF-model : G[aseous] instead of L[iquid].

SF-model : List of variables

Name	Variable	Unit	Default[a]
AD	Anticipated Demand for liquid fuel	GJth/yr	
ADD	Average Deposit Depth	m	50
α	factor price-elasticity in UC production fct	(-)	0.47
ß	overhead factor (transport & processing)	(-)	1.4
c	cost	\$/GJth	
CDR	Coal Discovery Rate	GJth/yr	
γ	capital-output ratio	\$/GJth/yr	0.7(SF)
D	Demand for SolidFuel	GJth/yr	3e9
DGM	Desired Gross Margin	(fraction)	1.2
EL	Economic Lifetime	yr	8
FR	Fraction Re-invested	(-)	
f	functional for UC depletion effect	(-)	
g	functional for SC depletion effect	(-)	
IMSI	Indicated MarketShare in Investments	(fraction)	
IUC	Investments in UC	\$/yr	
L	Labour input	person-yr	
λ	Technical Lifetime	yr	11
μ	actual market share	(fraction)	
p	price	\$/GJth	
P	Production of coal/SF	GJth/yr	
PC	Production Capacity of coal/SF	GJth/yr	
R	identified Reserve of coal	GJth	100e9
r	interest rate	(-)	0.1
ROI	Return On Investment	(-)	
RPR	Reserve-Production Ratio	yr	15
SDM	Supply-Demand Multiplier	(-)	
SC	Surface Coal producing Capital stock	\$	0.1e9
UC	Underground Coal producing Capital stock	\$	10e9
X	undiscovered Resource of coal	GJth	230000e9
Y	cumulated production of coal	GJth	9.3e9

Name	Parameter / Index	Unit	Default[a]
a	annuity factor	(-)	
avg	index for average		
expl	index for exploration		
ex	index for exogenous		
k	multinomial logit parameter	(-)	0.3
L	index for Labour		
SF	index for Solid Fuel		
UC	index for Underground Coal		
SC	index for Surface [mined] Coal		
prod	index for production		
tL	time at which depletion/learning starts	(yr)	1900(SF)
π	learning curve constant	(-)	0.8

a) if taken constant. For state variables X, R, Y and C and for production and demand, values are for the starting year 1900. For the RPR it indicates the desired value. For time-dependent variables, values are for 1900 and 1990.

EPG-model : List of variables

Name	Variable	Unit	Default[a]
AEND	Anticipated Electricity Net Demand	GJe/yr	
AFP	Average Fuel Price	\$/GJth	
BF	Baseload Fraction elec demand	(fraction)	0.9
BLF	Base Load Factor	(-)	0.55 (T) 0.43 (H) 0.67(NT)
E	Electric power capacity	MWe	
EGD	Electricity Gross Demand	GJe/yr	
EL	Economic Lifetime	(yr)	15 40(T&D)
END	Electricity Net Demand	GJe/yr	
EP	Electricity Production	GJe/yr	
ε	conversion efficiency TE-capacity	(-)	0.095
FP	Fuel Price	\$/GJth	
I	specific Investment cost	\$/MWe/yr	550000(T)
IE	total Investments in Electricity sector		
IMS	Indicated Market/Share		
LF	Load Factor	(fraction)	
μ	actual market share	(fraction)	
p	price of fuel for electricity generation		
PLF	Peak Load Factor	(-)	
r	interest rate	(-)	0.1
RF	Reserve Factor	(fraction)	0.2
SLF	System Load Factor	(-)	0.4
TDL	Transport and Distribution Losses	(fraction)	0.1
TH	Time Horizon for anticipation	(yr)	
TL	Technical Lifetime	(yr)	30(NT) 15(T) 100(H) 50(T&D)

Name	Parameter / Index	Unit	
a	annuity factor	(-)	
b	index for baseload		
d	index for desired		
exc	index for excess		
h	index for hydro		
k	multinomial logit parameter	(-)	0.3
NTE	index for non-thermal		
p	index for political[ly desired]		
TE	index for thermal		
TD	index for Transmission and Distribution		
β	conversion factor from MWe to GJe/yr	(GJe/MWe/yr)	
γ	ratio end-use price and generating cost	(-)	
π	learning curve constant	(-)	0.8
λ	pricing factor		

a) if taken constant. For capacity and demand/production, the figures are for 1900. For time-dependent variables, values are for 1900 and 1990.

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