Energy Studies Review Vol. 14, No. 1, 2006 pp.35-57

A Time Step Energy Process Model for Germany - Model Structure and Results

DAG MARTINSEN, VOLKER KREY,
PETER MARKEWITZ and
STEFAN VÖGELE

ABSTRACT

The new IKARUS-Model is a time-step dynamical bottom-up linear optimization model where each time interval is optimized by itself using the heritage from all periods before. Contrary to perfect-foresight models, this model does not take into account future changes in each time-step optimization. It therefore shows a more realistic character of prognosis and projection. Aspects like reaction on sudden changes (e.g. of energy prices), flexibility of technical scenarios, lost opportunities etc. can be examined. Interactions with macroeconomic I/O-models or dependencies on elasticities, technological learning etc. are possible. Recent calculations for Germany up to 2030 show that consistent and plausible future energy scenarios can be produced and analyzed.

The authors work with energy system analysis at the research centre Jülich, Germany. Dr. Dag Martinsen (d.martinsen@fz-juelich.de) and Volker Krey (v.krey@fz-juelich.de) are physicists, Dr. Peter Markewitz is a mechanical engineer (p.markewitz@fz-juelich.de) and Dr. Stefan Vögele is an economist (s.voegele@fz-juelich.de).

THE IKARUS PROJECT

At the beginning of the nineties, the former German Federal Ministry for Education, Science, Research and Technology (BMFT) initiated the IKARUS-Project[1] with the objective to establish a sufficiently homogeneous database as well as models on which basis consistent energy scenarios and greenhouse gas reduction strategies could be formulated and calculated (Martinsen, Markewitz, Müller, Vögele and Hake, 2003). With the aid of the models, such scenarios and strategies can be developed and evaluated within the framework of energy technology and energy policy.

The IKARUS instruments consist of several models and a database developed for the area of the Federal Republic of Germany. The database is available as an information system, where the major section includes detailed technology data and furthermore extensive general data such as inventory, structure and scenario data with respect to energy economy and macro economy. From this database, model data is aggregated and tailored to the requirements of the IKARUS models. Energy models of the IKARUS instruments are:

- A classical bottom-up energy optimization model (LP-model, LP = Linear Programming) describing the energy system on a national level.
- A very detailed space heat simulation model for different individual building types as well as for a partial or an entire building stock.
- A transport simulation model for passenger and freight transport where energy consumption, costs and emissions are broken down to travel purposes and specific vehicles.
- A macroeconomic model including a demand-driven, dynamic input-output model (IO model) with 24 sectors including nine energy sectors. The model includes sectoral autonomous energy efficiency improvement (AEEI) factors to describe technical progress as well as CES (Constant Elasticity Substitution) production functions to represent substitution processes.

A review of the IKARUS models as compared with similar models world wide can be found in (Drake, Herzog, Kendall and Levin, 1997).

---

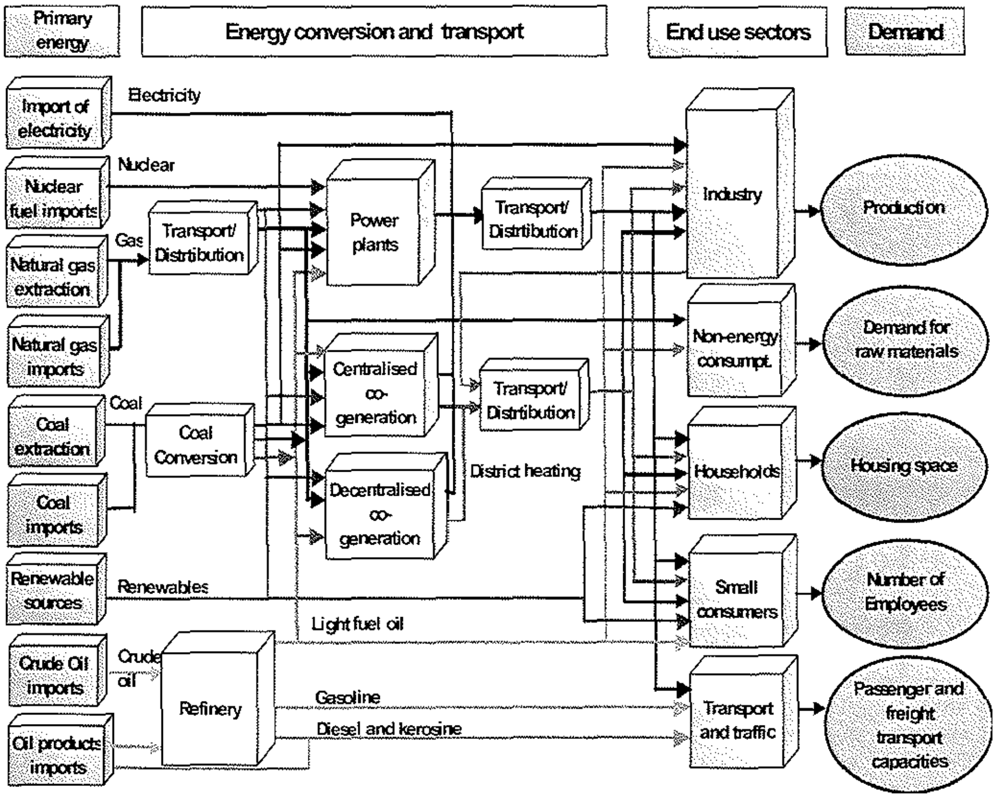
[1] Instrumente für Klimagasreduktionsstrategien (Instruments for climate gas mitigation strategies)

LINEAR OPTIMIZATION MODEL

The linear optimization model is a central part of the IKARUS-instruments. In the following, model structure and some model results will be presented.

The model is mapping the energy system of the Federal Republic of Germany in the form of cross-linked processes (Figure 1). A large number of technological options are included with their corresponding specific emissions and costs as well as possible networks of the energy fluxes. In addition, general political set-ups are considered (for example the agreement of the phase-out of nuclear power in Germany). The energy system is formed within the model in such a way that the demand for energy services is fulfilled. (Partial equilibrium model)

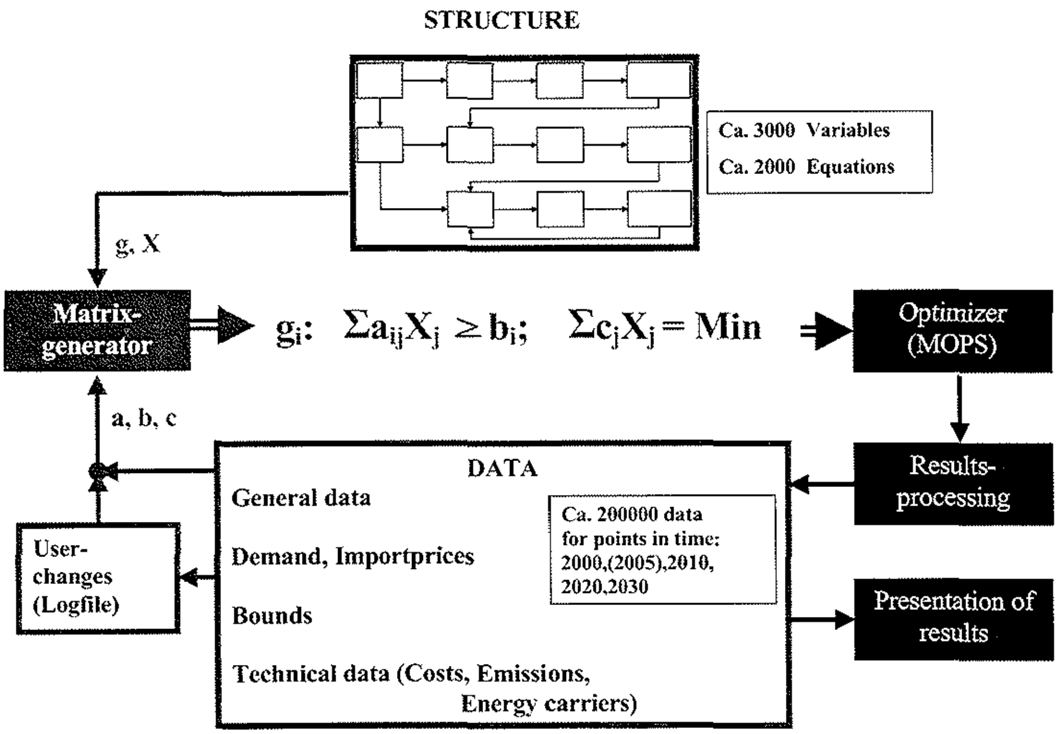
Figure 1: Structure of the IKARUS Energy system



The model is structured into ten major sectors (primary energy, electricity, district heat, refinery, gas, coal conversion, industry, transportation, small consumer, household), where each sector is subdivided into subsectors. Thus, for example, the household sector is subdivided into single and multiple family houses and a further differentiation is made between old (<1995) and new (>1995) buildings.

Both structural as well as numerical data, related to technologies, economy, energy policy and scenario data, are stored in a model database (MS Access). The system of equations to be solved is generated by bringing these two categories of data together as shown in Figure 2. In these equations g_i is the name of restriction i, X_j the name of the variable j, a_{ij} the coefficient for variable X_j, b_i the lower limit of the right hand side, c_j the cost-coefficient of variable X_j in the objective function. The structural data contains about 3000 variables (energy converters, technical measures, imports of energy carriers etc.) and about 2000 equations (balances of energy-carriers, emissions, costs or load curves etc.). The numeric data are made up of general data, data for components of demand vectors, prices of imported energy carriers, upper and lower limits (bounds) of different categories and of course all technical data like specific costs, emissions, input and output of energy carriers.

Figure 2. Calculation scheme for the IKARUS LP-model



Before numeric and structural data are combined in a matrix generator, the model users can define their own scenario (e.g. energy prices, technological or political bounds etc.) and if desirable, make their own selection of technologies as well as changing any specific technical and economic attribute (for example efficiency, specific costs etc.). In addition to these changes, the user can add their own equations to the matrix or alter any existent user equation. Normally total system costs are chosen as the objective function (least costs).

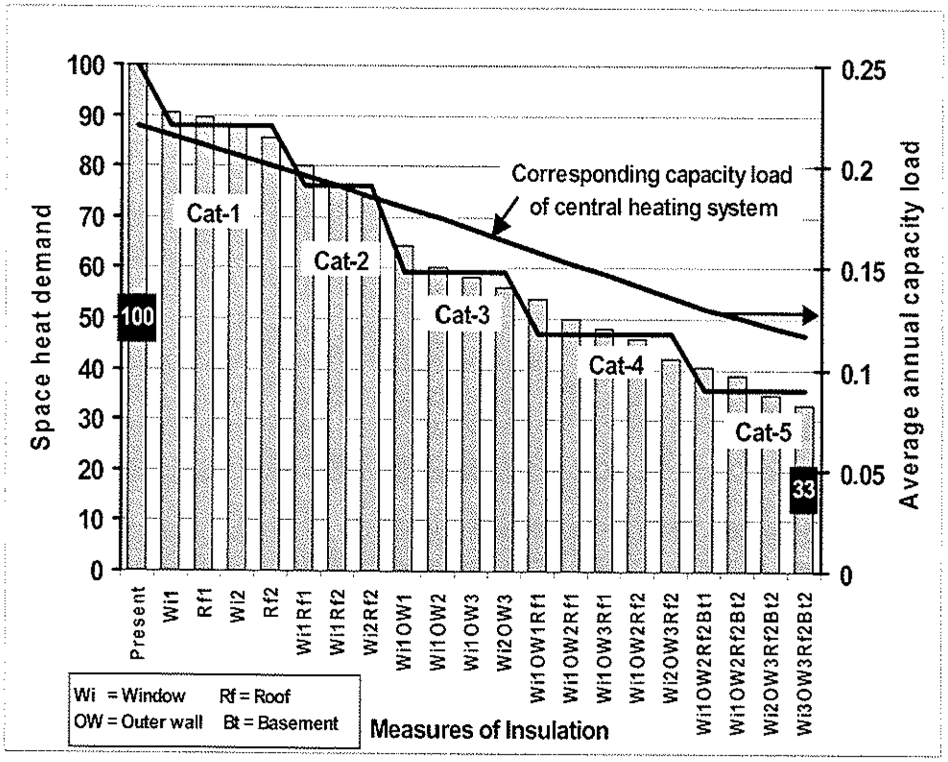
The matrix generator will build up the linear equation system in the format of a standard MPS-file that is the input to a commercially available mathematical optimizer (MOPS = Mathematical Optimization System) (Suhl, 1994). The result processing program will immediately calculate typical table values for energy, emission and cost balances and store these values in the model database. The presentation of user selected results in a tabulated or graphical form is made from a separate program where also multiple varying cases or scenarios can be compared to different levels of detail.

The new IKARUS LP-Model is a time-step dynamical linear optimization model. The time horizon is divided into intervals (with 5 or 10 years time steps). Each time interval is optimized by itself taking into account the heritage due to results from all periods before in a separate dynamic program module. The model therefore does not follow a perfect foresight approach, i.e. an optimization of the total time period in one system of equations. Perfect foresight means that the model in principle "knows" all the future parameters or boundary conditions and therefore, can react on future exogenously given changes in advance of these changes taking place (e.g. prices of energy carriers, climate gas reduction policy). Well-known energy systems models that employ the perfect-foresight optimization approach are MARKAL (Fishbone, Giesen, Goldstein, Hymmen, Stocks, Vos, Wilde, Zöcher, Balzer and Abilock, 1983), (Loulou, Goldstein and Noble, 2004) and MESSAGE (Messner and Strubegger, 1995). The time-step model, however, is myopic and does not take into account future changes in each optimization step. It is therefore a model with a more realistic character of prognosis and projection. For example with this model aspects like reactions on sudden changes (like a sudden jump of oil and gas prices), flexibility of technical scenarios (like the use of long lived and high investment technologies by varying energy policy), lost opportunities (like not taking measures for insulation in old buildings in good time i.e. inside of building renovation cycle) can be examined. The approach is more common in top-down models like GREEN (Burniaux, Martin, Nicoletti and Martins, 1992) or DART (Springer 1998) where it is referred to as recursive-dynamic or static expectations approach, but it is also used in bottom-up (i.e. technical) models like SAGE (EIA, 2003). A backcasting experiment comparing both the time-step and the perfect-foresight approaches with the help of a computable general equilibrium model can be found in a publication of Manne and Richels (Manne and Richels, 1992). A broader overview over different energy-economic modelling approaches can be found in the IPCC Third Assessment Report on Mitigation (Markandya, Halsnaes, Lanza, Matsuoka, Maya, Pan, Shogren, de Motta, Zhang and Taylor, 2001).

In addition, interaction with macroeconomic input-output models or dependencies on elasticities, technological learning, economy of scale etc. as well as other non-linear (dynamical) effects can be taken into account. A major part of these effects can probably be considered without an iterative optimization process if sufficiently short time-step intervals are chosen. At the moment, some of these non-linear aspects are handled in a semi-manual way. A real dynamic recursive model concept will be prepared in the time to come. In order to compare results from the time-step approach with results from a perfect foresight model, we also operate a multiple period MARKAL (Fishbone, Giesen, Goldstein, Hymmen, Stocks, Vos, Wilde, Zöcher, Balzer and Abilock, 1983) based optimization model having a comparable structure and using the same IKARUS data. The MARKAL model is a stand-alone application and not a member of the IKARUS instruments itself (Kraft 1997). It is an often used model for German energy scenarios.

From the large set of technical input data for the model, we will only pick out one example. Figure 3 shows the dependence of specific space heat demand (normalized to 100 for the present heat demand) of an average old (built before 1995) single family house on different measures for thermal insulation. The horizontal axis contains measures for thermal insulation for windows (Wi), roof (Rf), outer walls (OW) and basement (Bt) where the numbers 1 to 3 describe an increasing thickness and efficiency of insulation layer. For each measure, the bars show the corresponding relative space heat demand (left ordinate) and the straight line the corresponding load of the central heating system (right ordinate). The measures are divided into five categories (Cat-1 – Cat-5). Correlated to these measures the average capacity load of existing central heating systems is also shown in figure 3 as an example of non-linear effects.

Figure 3: Space-heat demand for different measures of thermal insulation and corresponding annual capacity load of the central heating system in old single-family-houses.



SCENARIOS

The scenarios presented here serve as examples of energy projections for Germany achieved by the model. They are typical, but of course do not cover all plausible future developments. Before showing some typical results from the IKARUS LP-model runs for Germany up to 2030, we will describe some of the most important assumptions that are to be considered when evaluating the results.

The demographic evolution is assumed according to the 2nd variant of the population development of the German Statistical Federal Office (Statistisches Bundesamt, 2000). Correspondingly the population decreases from 82 to approx. 78 million over the coming 25 years.

Table 1: Demographic and overall economic data.

	Unit	Relevant numbers				Annual changes in %/a		
		2000	2010	2020	2030	2000/10	2010/20	2020/30
Population	Mio.	81.99	81.50	80.34	77.98	-0.06	-0.14	-0.30
Number of households	Mio.	37.5	38.5	38.80	38.10	0.26	0.08	-0.18
Persons per Household	#	2.19	2.12	2.07	2.05	-0.32	-0.22	-0.12
Apartments	Mio.	36.82	39.64	41.60	43.08	0.74	0.48	0.35
Apartments per 1000 Households	#	982	1030	1072	1131	0.48	0.41	0.53
Total floor space	Mio. m^2	3116.5	3408.6	3637.1	3838.6	0.90	0.65	0.54
Floor space per Capita	m^2	38.0	41.8	45.3	49.2	0.96	0.80	0.84
Size of single-family house	m^2	105.95	108.31	110.62	113.43	0.22	0.21	0.25
Size of multi-family house	m^2	65.94	66.45	66.88	67.35	0.08	0.06	0.07
Number of employed	Mio.	37.54	37.34	37	34.92	-0.05	-0.09	-0.58
Gross domestic product	10^9 € (95)	1963.8	2366.7	2797.5	3189.6	1.88	1.69	1.32
GDP per Capita	€	23951	29039	34821	40903	1.94	1.83	1.62
Value added industry	10^9 €	362.65	440.65	507.68	585.21	1.97	1.43	1.43

Due to the smaller number of children per family, a growing life expectancy as well as a trend towards single person households, the number of the private households will increase up to 2010. In the last decade, however, this number will decrease again due to a declining total population. The number of apartments and houses climbs by far more strongly than the number of the households. The reason is the increasing number of second homes for working commuters as well as of pensioner households. Because of this, the number of apartments increases from 36.8 million today to about 43 million in the year 2030.

It is assumed, that the average apartment size in new single-family houses will rise from 106 m^2 today to 113 m^2 in the year 2030. The size of an average apartment in multiple family houses changes only slightly from 66 to 68 m^2 during the model's time horizon. The total floor space increases by 23% up to the year 2030. As a result, the floor space per capita rises from today 38 m^2 to 49 m^2 in 2030.

The assumptions for the economy were generated on the basis of the IKARUS IO-model. Accordingly the real gross domestic product increases from 1964 billion € in the year 2000 to nearly 2367 billion € in 2010, i.e. an average annual increase of almost 1.9 %. In the period of 2010 to 2020 the annual growth decreases slightly to be 1.7%. Thereafter, up to 2030, a further attenuation to 1.3%/a is assumed. The corresponding value added for industry is increasing with about 60% in the period 2000 to 2030. However, the annual rate differs strongly between industrial sectors. Whereas the value added for chemistry is growing with about 1.6% per year, the growth rate of other energy intensive sectors like iron industry, cellulose and paper is by far lower.

The number of employees in the small consumer sector increases slightly up to 2020. Thereafter, it drops noticeably giving in this sector about one million employees less in 2030 (30.4 millions) compared to 2000 (31.4 millions). At the same time, the private and public services gain importance while in particular the number of employees in agriculture and forestry shows a further decrease.

The transportation sector is divided into passenger transport and freight transport, as well as into long-distance and short-distance traffic. The demand for passenger transport is growing from 926 billion pkm (passenger kilometers) in the year 2000 to 1190 billion pkm in 2030 (Table 2). The increase of freight traffic, however, is much stronger. It climbs from 489 billion tkm (ton kilometers) to 889 billion tkm, i.e. an increase of more than 80% in the coming 30 years.

Table 2: Demand of passenger and freight traffic.

Area	Unit	Relevant numbers				Annual changes in %/a		
		2000	2010	2020	2030	2000/10	2010/20	2020/30
Passenger traffic1)	Billion pkm	926	1025	1116	1190	1.01	0.85	0.65
Freight traffic	Billion tkm	489	613	750	889	2.29	2.04	1.71

1) Without pedestrians and cyclists. Air traffic: Domestic concept

The prices for the most important imported energy carriers are assumed to have only a moderate increase over the coming 25 years (Horn, 2002).

Table 3 presents, beside limitations on quantities of imported energy carriers like coal and gas, other national restrictions based on domestic potentials and political framework set by the Federal Government. As decided by the government, the minimum extraction of domestic hard coal is limited to 300 PJ in 2010 (approx. 10 million tons). For the period after that, the subsidies are assumed to be running out and domestic hard coal will have to compete with imported coal. Based on the actual known plans of the lignite enterprises as well as on the age distribution and future plans of lignite power plants, a minimum output of 800 PJ and a maximum output of 1600 to 1400 PJ was estimated for German lignite. The production of domestic natural gas is assumed to be declining in the future.

Table 3: Some important bounds concerning energy policy and quantity potentials.

	Unit	2000	2010	2020	2030
Domestic hard coal	PJ	1005	> 300	(-)	(-)
Import of hard coal	PJ	910	< 1800	< 2400	< 3000
Extraction of lignite	PJ	1521	> 800 < 1600	> 800 <1500	> 800 < 1400
Domestic natural gas	PJ	633	< 700	< 600	< 500
Imported natural gas A	PJ	2683	< 4000	< 4000	< 4000
Imported natural gas B	PJ		< 4000	< 4000	< 4000
Wind power	GW	5.9	> 12	> 12	> 12
Nuclear power plants	GW_{netto}	22.2	18.3	7.8	0

With regard to the future role of nuclear energy, the remaining residual capacities for the nuclear power plants were estimated based on the agreement between the Federal Government and the utilities concerning the nuclear phase-out. For wind power we assumed a future minimum capacity of 12 GW corresponding to the installed capacity at the end of 2002.

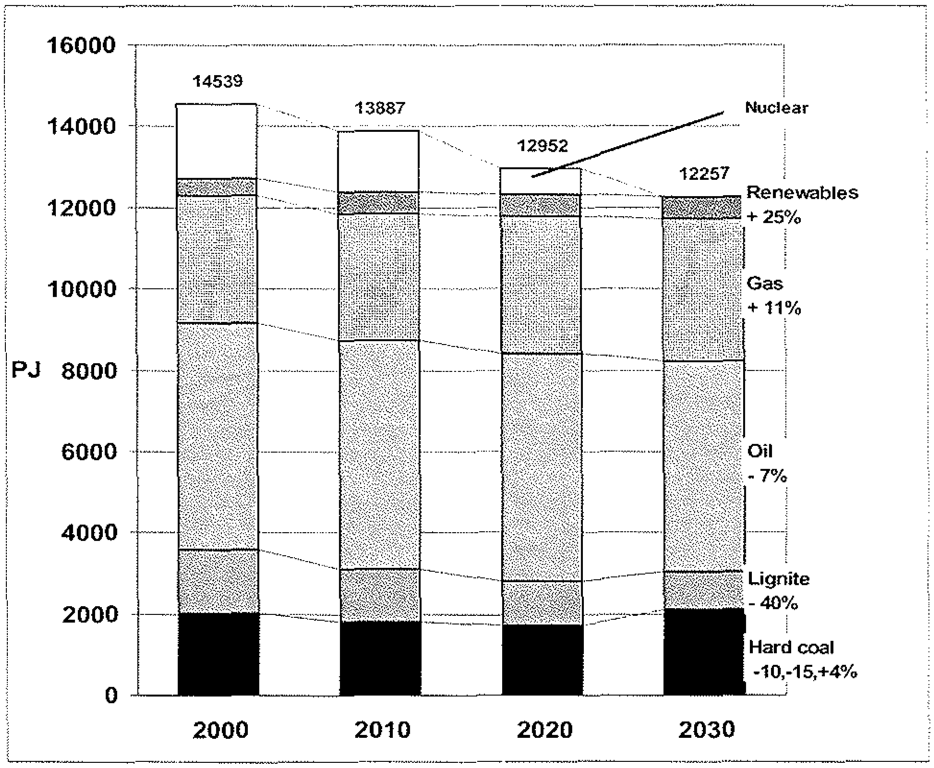
SCENARIO RESULTS

These assumptions lead to primary energy consumption as shown in Figure 4.

Even in this reference scenario, the primary energy consumption is declining. In the year 2030, it is about 15 % lower than in 2000. Beside final energy savings, this is mainly due to changes in the conversion sector. However, it is also partly caused by the energy balance sheet values of non-fossils. For example, the primary energy value of nuclear electricity is based on an efficiency of 0.33. The nuclear reactors are substituted (nuclear phase-out) by fossil power stations having a much higher efficiency. This leads to a calculated drop of primary energy. Up to 2030, the shares of coal+lignite and oil are decreasing, and the contribution of natural gas and renewables are increasing.

In Germany there has been a continuous discussion in the last 10 – 15 years about ways of energy saving and reducing green house gases, particularly the CO_2 emissions. In the following examples of typical results from the IKARUS model, we shall therefore concentrate on a CO_2 scenario ("Reduction scenario") and an energy saving scenario ("Innovation+Saving") as compared to a business-as-usual scenario ("Reference scenario"). They might also represent two different types of philosophy in energy policy:

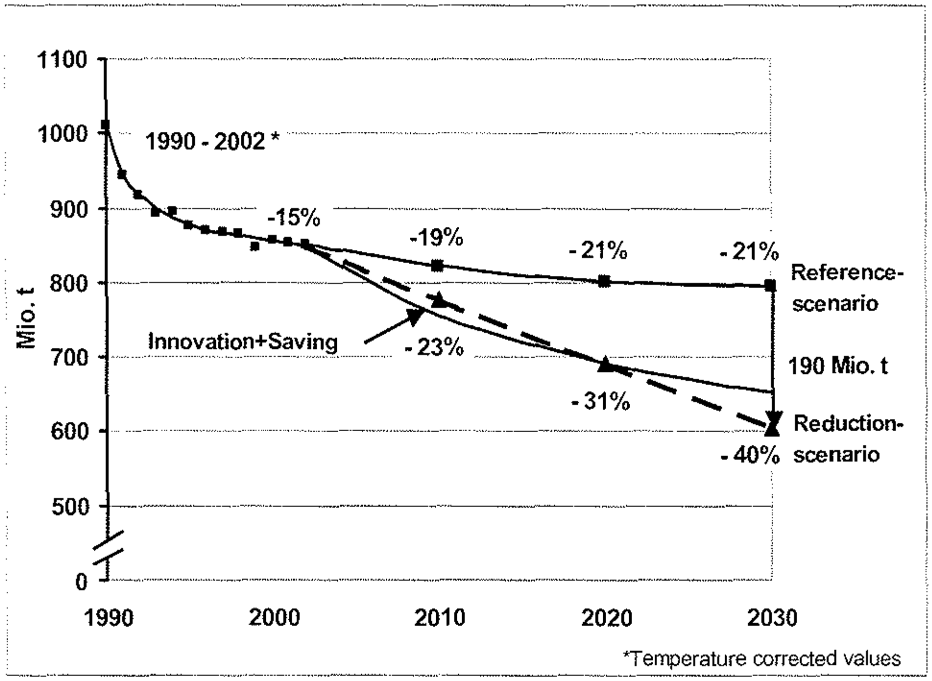
Figure 4: Projection of primary energy in the reference case.



Innovation+Saving:	Imposing various technical and economic guidelines in order to advance innovation and energy saving for example by law or subsidies.
Reduction scenario:	Giving boundary conditions only and leaving it to the energy system to decide which options should be chosen to fulfill these conditions.

The energy related amount of CO_2 emissions in Germany caused by energy conversion in 2003 was about 837 million tons. This is a reduction of about 15% compared to the emission level of 1990. Figure 5 shows the CO_2-emissions (temperature corrected values) in the reference case as well as for the reduction and innovation+saving scenarios. The high reduction rates in the first half of the nineties were in particular due to measures of restructuring in East Germany that among other things led to a drastic reduction of the use of lignite.

Figure 5: CO_2-emissions in Germany.



In the projection of the reference scenario, the CO_2 emissions drop by about 5% from 2000 to 2010, decrease a further 2 percent until 2020 and remain constant thereafter. This is close to the climate gas reduction obligation made for Germany within the framework of the EU-Burden sharing process, i.e. -21 % in 2010 when compared to 1990 including all climate gases (Commission of the European Communities, 2004), (Council of the European Union, 2002). More far-reaching reduction goals like a decline of 40 % up to the year 2020 or 2030, as currently discussed in energy policy, are clearly missed in the reference scenario. Therefore, a reduction path with a linear CO_2 decrease is imposed to the model demanding a 40% reduction of CO_2 emissions in 2030 as compared to 1990:

- 2010: - 23% as compared to 1990
- 2020: - 31% as compared to 1990
- 2030: - 40% as compared to 1990

Figure 5 also shows the resulting CO_2-emissions from the innovation+saving scenario where, in contrast to the reduction scenario, specific technological innovations and measures of energy savings are imposed to the model instead of a CO_2-constraint. This scenario is therefore more close to a simulation where the most important assumptions divergent from the reference scenario are:

- Power stations: Improvement of efficiency by 2-3 percent points.
- Industry: Measures of energy saving for production and utilization of process heat and electricity.
- Small consumer: Insulation of buildings within cycles of renovation. Measures for saving of process heat and use of electricity.
- Household: Insulation of old buildings within cycles of renovation. Improved space heat standard. More efficient use of electricity in new appliances.
- Transport: Vehicles with a clear reduction of fuel consumption. Share of public transport to modal split at the upper limit.

The corresponding CO_2-emissions show a more hyperbolic curve compared to the linear reduction scenario showing a –25% reduction in 2010 and ending up with a reduction of about –35% in 2030. The cumulated emissions for the period 2000 – 2030 are about the same in both scenarios.

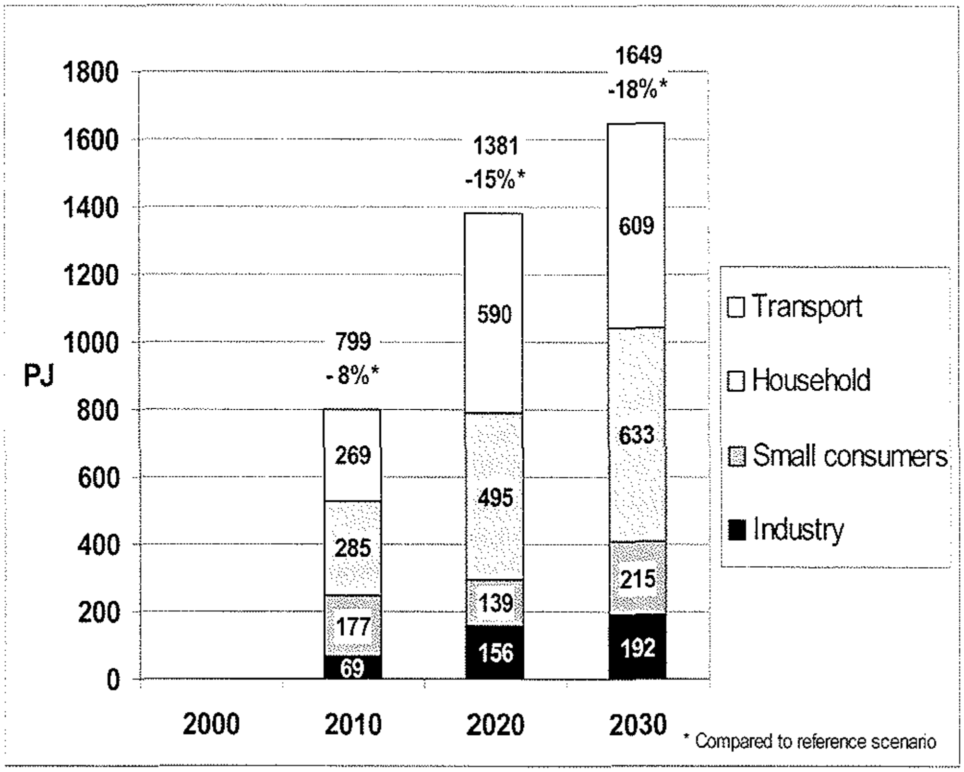
In the following, we will limit ourselves to mainly describe deviations of the innovation+saving and the reduction scenario from the reference scenario. A detailed description of the reference scenario can be found in (Martinsen, Markewitz, Müller, Vögele and Hake, 2003).

Figure 6 shows the share of sectors to the saving of final energy in the innovation+saving scenario as compared to the reference scenario. The main contributors to this saving are the household and transport sector. The relative saving in 2030 is 9% in the industry sector[2], about 16% in the sector of small consumers and reaches nearly 25% in both sectors household and transport. In total, the added innovations in technology and measures of energy saving result in a reduction of 18% of the final energy demand as compared to the reference case in 2030. In the reduction scenario (not shown in figure 6), the saving of final energy is considerably smaller with a total of –8% in 2030.

---

[2] A considerable reduction of final energy in the industry (- 11%) has taken place between 2000 and 2030 in the reference scenario already mainly due to structural changes.

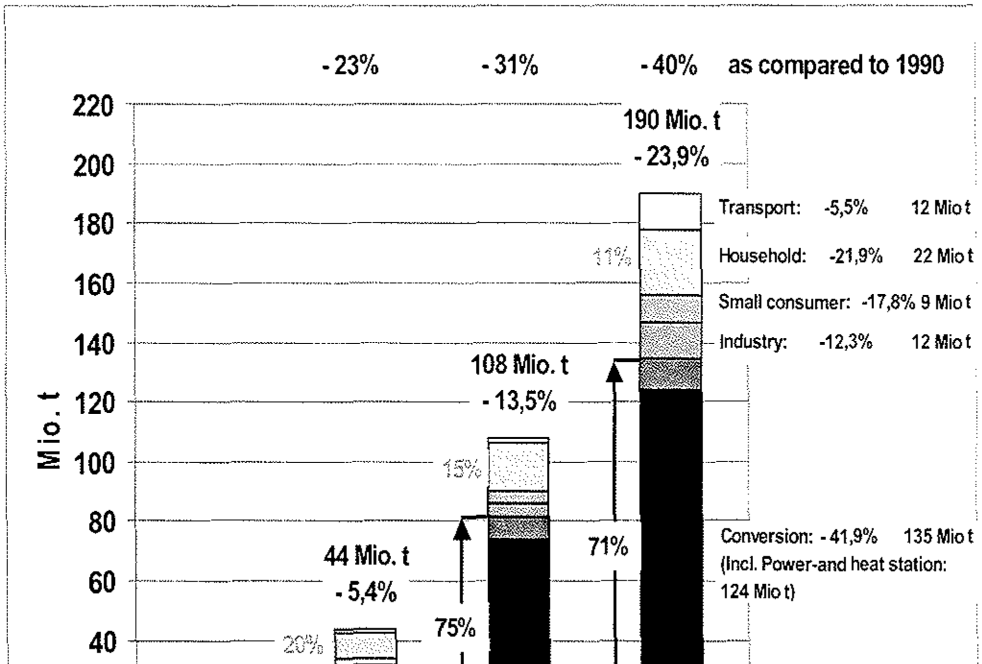
Figure 6: Share of sectors to the saving of final energy in the innovation+saving scenario.



The share of sectors is dominated by the household sector although far weaker (and less costly) measures of thermal insulation are taken as compared to innovation+saving. In the transportation sector, additional (non-autonomous) saving occurs only at the end of the time considered. In order to meet the CO_2 constraint, additional measures are taken in the conversion sector like very efficient natural gas combined cycle power plants substituting coal plants. Measures in the conversion sector are mostly cheaper than in the end use sectors.

The share of sectors to the CO_2 reduction in the reduction scenario as compared to the reference scenario is shown in figure 7. The overwhelming contribution to this reduction is given by the conversion sector whose share is between 2/3 and 3/4 in the period 2010 – 2030. In 2030, the reduction of CO_2 in this sector reaches nearly 42% or 135 million ton as compared to the reference scenario, most of it being achieved in power stations and CHP (Combined Heat and Power) plants. The main contributing end user is the household sector with a 22% decrease of CO_2 emissions in 2030 compared to the reference scenario. However, the relative share of households to total reduction is dropping from 20% in 2010 to 11% in 2030. A significant share of other end-use sectors (small consumer, industry, transport) does not show up until the last time period.

Figure 7: Share of sectors to CO_2 reduction in the reduction scenario.

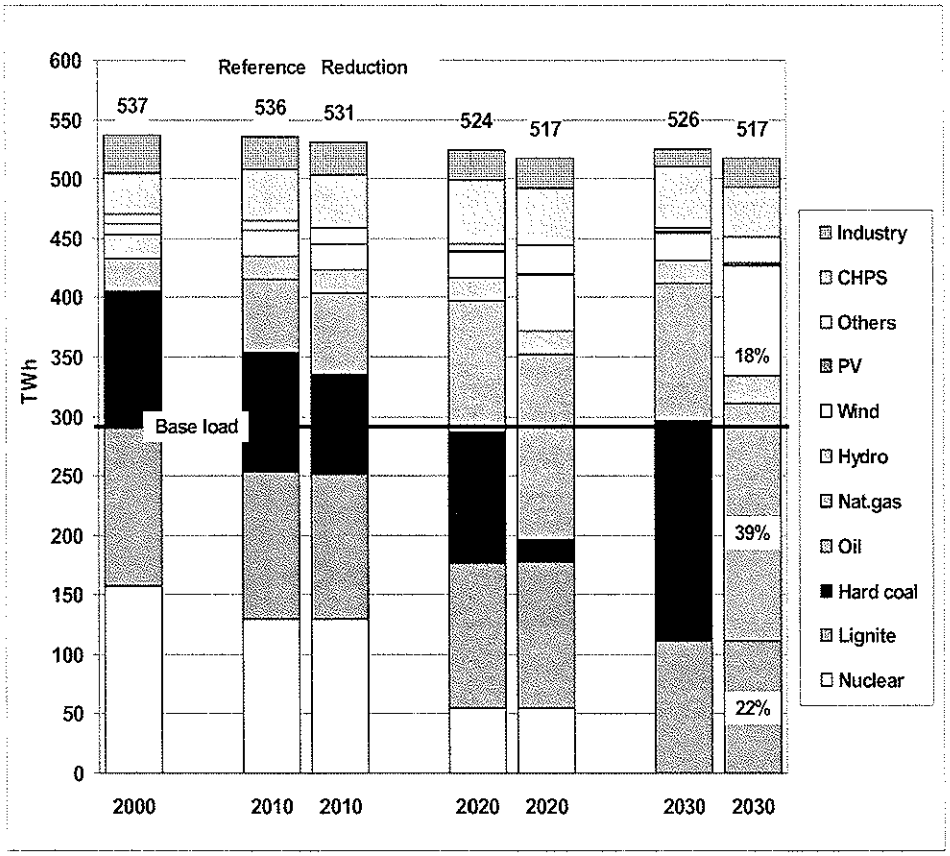


* Compared to reference scenario

Because of the dominant part of the electricity sector to meet the CO_2 constraint, we exemplarily show the structure and changes of the electricity production in the model results in figure 8 with the reference scenario (grey) to the left and the reduction scenario (black) to the right.

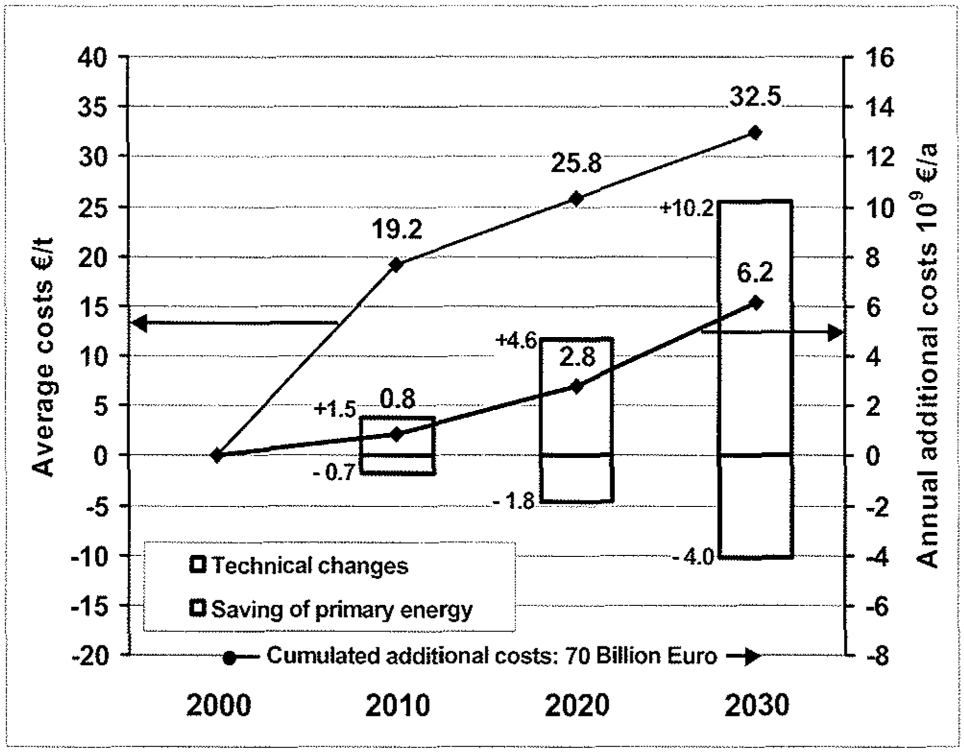
Whereas in the reference scenario, the compensation of the phase-out of nuclear base load power plants is made up by additional hard coal and new lignite power plants, the substitution in the reduction scenario is mainly done through the construction of new highly efficient natural gas combined cycle power plants which have a share of nearly 40% to total electricity production in 2030. Another significant difference between the reduction and the reference scenario is the strong increase of wind power reaching a capacity of 35 GW (onshore and offshore) in 2030 and corresponding to a share of 18% to the electricity production. Also the share of CHP based on biomass is increasing. In addition an overall modernization and increase of efficiency take place. Altogether, the CO_2 reduction is about 120 million tons in 2030 compared to the reference scenario.

Figure 8: Structure of electricity production in the reference and reduction scenario.



Meeting the CO_2 constraints lead to additional system costs in the model (Fig. 9). The annual additional costs increase from 0.8 billion €/a in 2010 to 6.2 billion €/a in 2030. These are differences of system costs between reduction and reference scenario. In the period 2000 to 2030 the costs cumulate to about 70 billion euro. The corresponding average specific CO_2 reduction costs are ca. 19 €/ton in 2010 and ca. 32 €/ton in 2030.

Figure 9: Annual and specific costs of CO_2 reduction in the reduction scenario.



The marginal costs are of course higher, being about 95 €/ton in 2030. These costs have an exemplary character only. They depend on assumptions made and bounds set (tables 1 – 3) as well as on time dependency and magnitude of the CO_2 constraint. For example changing the restriction for CO_2 emissions in 2030 from –40% to –31% (= 2020 value) respective –50%, the average specific mitigation costs (annual additional costs) will drop to 10.3 €/ton (1.1 billion €/a) respective climb to 129 €/ton (37.5 billion €/a). The high specific costs of 129 €/ton, however, could be brought down to about 50 €/ton if the (costly) lower limit on the use of German lignite (800 PJ, table 5) was dropped.

ADDITIONAL POSSSIBILITIES OF TIME-STEP OPTIMIZATION

The results shown above do not differ very much from similar perfect foresight optimizations. The reason is the relatively smooth time dependency of assumptions and restrictions made for these calculations. However, in the perfect foresight calculations generally measures will be chosen earlier than in the time-step calculations to avoid a more costly action at a later time period.

A further use of the time step model will be the investigation of lost opportunities and the flexibility of technological scenarios to unexpected sudden changes as this will in general lead to additional information compared to the perfect foresight approach.

Figure 10: Demand and lost potential of space heat savings for old buildings in household 2030.

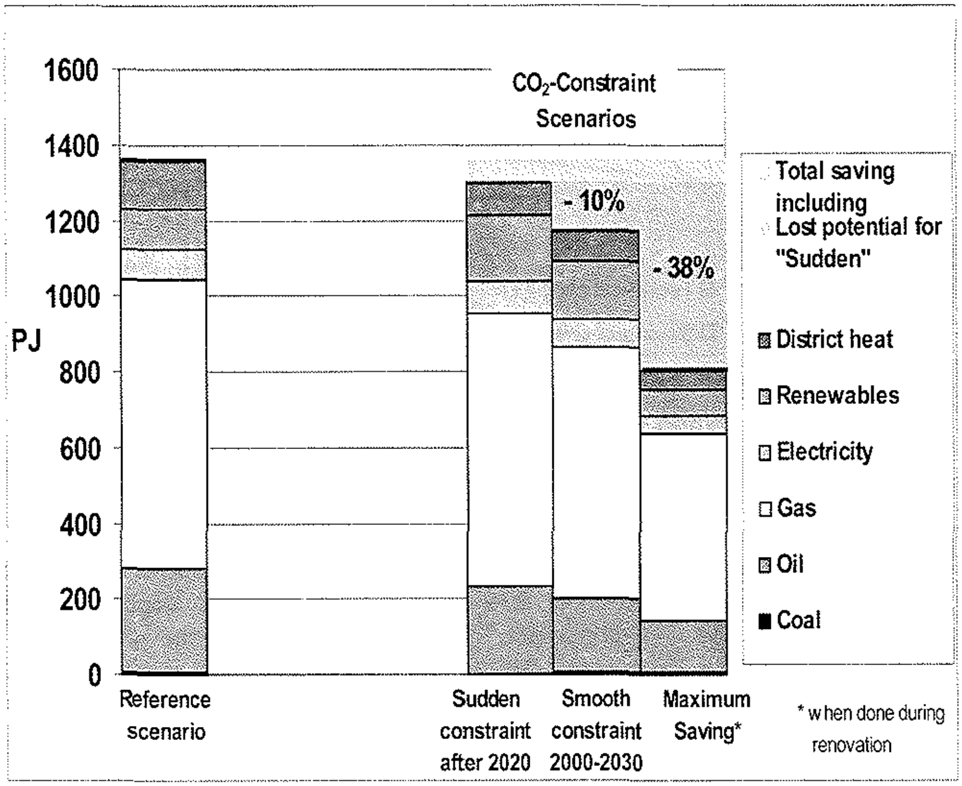


Figure 10 shows an example of a lost potential for energy saving by insulation of old buildings in the residential sector. The insulation is supposed to be done during renovation of the buildings where the fraction of old buildings to be renovated in one time period is limited. The figure illustrates the demand of space heat in 2030 for three CO_2-scenarios, all constrained to a 40% reduction of CO_2 in 2030 as compared to 1990.

- **"Sudden"** constraint after 2020. In this scenario, there is no CO_2 constraint before 2020. Thereafter, however, a sharp decrease of CO_2 is imposed. The model, not knowing the future, will apply additional (to reference scenario) insulation measures only after 2020, not before. The potential of space heat savings due to insulation of buildings having their renovation in the period 2000 – 2020 is therefore lost. (As far as the CO_2 constraint is concerned, this is partly compensated by the increased use of renewables).
- **"Smooth"** constraint 2000 – 2030. This scenario is identical to the reduction scenario as described above with a linear increase of the CO_2 restriction. The result of this scenario is close to a perfect foresight optimization and the model will choose insulation measures during renovation in all periods.
- **"Maximum"** saving. This case model will make use of the maximum potential of insulation measures with a high degree of space heat savings (category 5 in figure 3) within renovation at all time periods.
- The potential of saving lost in the "Sudden" scenario as compared to the "Smooth" scenario is about 10% and therefore, comparatively small. However, in the "Sudden" scenario more expensive measures are taken in a short time compared to the "Smooth" scenario where several low to medium cost measures are chosen distributed over a longer time period.
- In comparison to the "Maximum" scenario, where a saving of space heat of about 41% is achieved when compared to the reference scenario, the lost potential is considerable: 38% for the "Sudden" and 31% for the "Smooth" scenario.

The dynamics of prices for energy carriers is another important aspect in a model without perfect foresight. An example of the result of a sudden change of prices for imported oil, oil-products and natural gas after 2020 as compared to a scenario with a steady increase of these prices from 2000 to 2030 is presented in figure 11 for the electricity sector.

The two scenarios shown are identical to the reference scenario with the only exception that prices for oil and gas are much higher, i.e. reaching values twice as high as in the reference scenario in 2030.

Figure 11: Installed capacity and load of lignite, hard coal and gas power plants for two price scenarios.

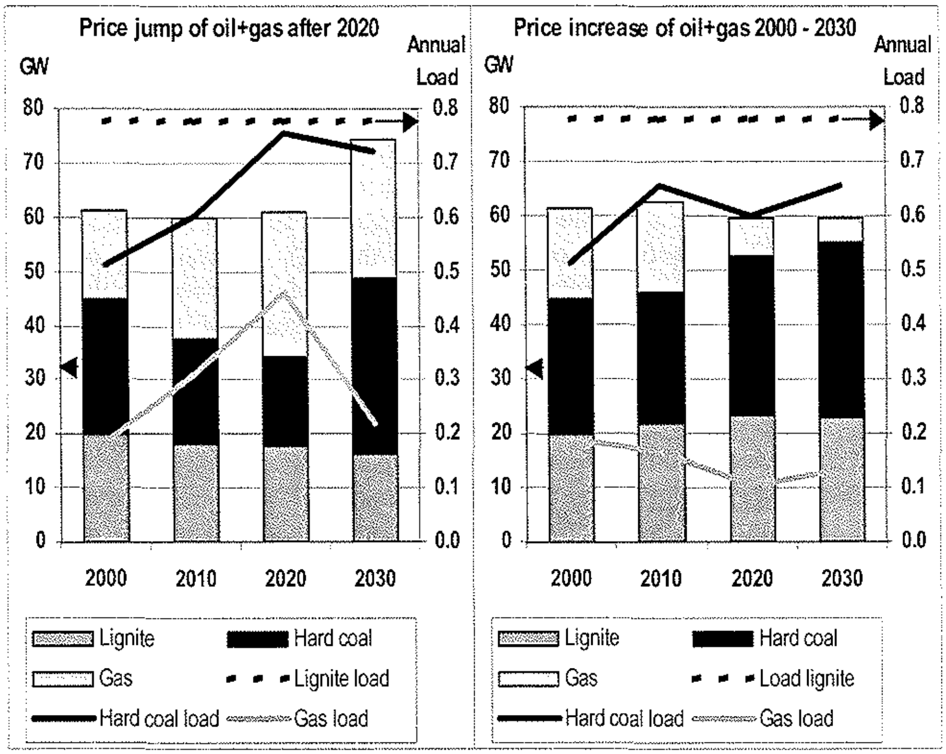


Figure 11 illustrates installed capacity and annual load of lignite, hard coal and gas power plants (the capacity of other power plants are not shown).

The left part of the figure shows the case of a sudden price "**Jump**" after 2020 and the right part shows the case of a "**Steady**" price increase from 2000 to 2030. In the "Steady" scenario, in contrast to the reference case, there is a continuous increase of the capacity of power plants based on hard coal and lignite and a reduction of gas power plants. In the "Jump" scenario, the development of capacities will follow the reference scenario up to 2020 (the price jump after 2020 being "unknown" to the model before 2020), i.e. the model will first invest in new gas power plants substituting medium load coal power plants by pushing some of those into base load to replace nuclear power plants being shut down. Thereafter, due to the increase of prices for oil and gas, the optimal strategy will be to build new coal power plants and drastically reduce the load of the existent gas power plants. This gives rise to a total (including also all other types of power plants not shown in figure 11) net surplus of about 9 GW of installed electric capacity by 2030.

The example above shows that also least cost scenarios that are based on a special course of energy prices can lead to an irreversible build-up of costly surplus capacities when unforeseeable price changes occur.

SUMMARY AND OUTLOOK

In the paper, a new version of the IKARUS energy systems optimization model for Germany was described. In contrast to former versions and also other models of the same type, it employs a myopic time-step optimization approach. Apart from the new methodology, the model structure along with the most important energy-economic assumptions have been outlined. Two scenarios for Germany until 2030 have been developed with the help of the model and the results of these calculations have been presented. Several model runs of the time step IKARUS model show that with this model consistent, reasonable and plausible future energy scenarios can be produced and analyzed. In addition, the time-step optimization approach enables the modeler to investigate the impact of sudden changes on the energy system. An abrupt introduction of CO_2 mitigation obligations and a sudden rise of oil and natural gas prices served as examples for the application of the new methodology.

Another aspect of future work will be the endogenous integration of non-linear effects like for example learning curves. These, together with a more detailed vintage capacity calculation, will be components of an integrated dynamical recursive model structure.

The increasing entanglement of national economies and the liberalization of energy markets in the EU have a strong impact on the development of the member countries' energy systems. In particular the exchange of grid-bound energy carriers such as electricity and natural gas and the construction of the required infrastructure is even a primary target of the European Commission.

Therefore in addition to the national model for Germany, a bottom-up multiple sector EU-model is under development. This model includes the perfect foresight as well as the time step options. The model's system of equations for each period is identical for both optimization strategies; the difference is the coupling of the individual model periods.

REFERENCES

Burniaux, J.-M., J.P. Martin, G. Nicoletti, J.O. Martins, (1992) 'GREEN: A Multi-Sector, Multi-Region General Equilibrium Model for Quantifying the Costs of Curbing CO2 Emissions,' Working Paper 116, OECD, Paris.

Commission of the European Communities (2004) 'Catching Up with the Community's Kyoto Target,' COM(2004) 818, Brussels, 20.12.2004.

Council of the European Union (2002) 'Council Decision of 25 April 2002 concerning the approval, on behalf of the European Community, of the Kyoto Protocol to the United Nations Framework Convention on Climate Change and the joint fulfilment of commitments thereunder,' (2002/358/CE), *Official Journal L* (Legislation) 45:130:1-20.

Drake, E.M., H.J. Herzog, M. Kendall, J. Levin (1997) 'Energy Technology Availibilty: Review of Longer Term Scenarios for Development and Deployment of Climate-Friendly Technologies,' Prepared for The International Energy Agency, Paris.

EIA Office of Integrated Analysis and Forecasting (2003) 'Model Documentation Report: System for the Analysis of Global Energy Markets (SAGE),' DOE/EIA-M072(2003)/1, Energy Information Administration, U.S. Department of Energy, Washington DC.

Fishbone, L.G., G. Giesen, G. Goldstein, H.A. Hymmen, K.J. Stocks, H. Vos, D. Wilde, R. Zöcher, C. Balzer, H. Abilock (1983) 'User's Guide for MARKAL,' Brookhaven National Laboratory and KFA Jülich.

Horn, M. (2002) 'Entwicklung der Importpreise für fossile Energieträger bis zum Jahr 2030 [Development of Fossil Fuel Import Prices until 2030],' In IKARUS-Bericht Nr. 3-10, Forschungszentrum Jülich.

Kraft, A. (1997) 'Einsatz der linearen Programmierung zur Analyse des energiewirtschaftliche Potentials von Brennstoffzellen [Application of Linear Programming for the Analysis of the energy-economic Potential for Fuel Cells],' Diploma thesis, Technical University of Aachen, Aachen.

Loulou, R., G. Goldstein, K. Noble (2004) 'Documentation for the MARKAL Family of Models,' IEA Energy Technology Systems Analysis Programme, http://www.etsap.org/documentation.asp .

Manne, A.S. and R.G. Richels (1992) 'Buying Greenhouse Insurance: The Economic Costs of Carbon Dioxide Emission Limits,' The MIT Press, Cambridge, USA.

Martinsen, D., P. Markewitz, D. Müller, S. Vögele and J.-Fr. Hake (2003) 'IKARUS – Energieszenarien bis 2030 [IKARUS – Energy Scenarios until 2030],' In Das IKARUS-Projekt: Energietechnische Perspektiven für Deutschland, Schriften des Forschungszentrums Jülich, Reihe Umwelt/Environment, Band/Volume 39.

Messner, S., M. Strubegger (1995) 'User's Guide for MESSAGE III,' IIASA Working Paper WP-95-69, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Markandya, A., K. Halsnaes, A. Lanza, Y. Matsuoka, S. Maya, J. Pan, J. Shogren, R.S. de Motta, T. Zhang, T. Taylor (2001) 'Costing Methodologies' in Metz, B., O. Davidson, R. Swart, J. Pan (eds.) *Climate Change 2001: Mitigation. Third Assessment Report of the IPCC*, Cambridge University Press, Cambridge, http://www.grida.no/climate/ipcc_tar/wg3/ , pp. 455-498.

Springer, K. (1998) 'The DART General Equilibrium Model: A Technical Description,' Working Paper 883, Institut für Weltwirtschaft, Kiel.

Statistisches Bundesamt (2000) 'Bevölkerungsentwicklung Deutschlands bis zum Jahr 2050. Ergebnisse der 9. koordinierten Bevölkerungsvorausberechnung [Population Development in Germany until 2050. Results of the 9th Coordinated Projection],' Wiesbaden.

Suhl, U. (1994) 'MOPS – Mathematical optimization system,' *European Journal of Operational Research* 72:2:312-322.