

A New Dynamical Bottom-Up Energy Model for Germany

Model Structure and Model Results

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ABSTRACT

The results of calculations made by bottom-up linear optimization models (LP) are to some extent determined by the applied optimization strategy. Existing energy system models most commonly employ an optimization strategy which are known as *perfect-foresight*, i.e. an optimization of the total time period in one system of equations. Perfect foresight means that the model in principle would “know” all the future parameters or boundary conditions and therefore could react on future exogenously given changes in advance of these changes taken place (e.g. prices of energy carriers, climate gas reduction policy etc.)

The new IKARUS-Model described is a time-step or myopic dynamical bottom-up linear optimization model where each time interval is optimized by itself taking into account the heritage due to results from all periods before. So the model does not take into account future changes in each time-step optimization. It is therefore a model with a more realistic character of prognosis and projection. For example with this model aspects like reaction on sudden changes, flexibility of technical scenarios, lost opportunities etc. can be examined. In addition – assuming sufficiently short time-step intervals – 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 without an iterative optimization process.

Recent calculations with this model for Germany up to 2030 show that consistent, reasonable and plausible future energy scenarios can be produced and analyzed. Furthermore some exemplary calculations of lost opportunities and (in)flexibility of technological scenarios to unexpected sudden changes are shown. Future work will include an endogenous integration of non-linear effects and a more detailed vintage capacity calculation, both being components of an integrated dynamical recursive model structure.

KEYWORDS:

Energy model, time-step optimization, IKARUS-Project.

THE IKARUS PROJECT

At the beginning of the nineties the former German Federal Ministry for Education, Science, Research and Technology (BMFT) initiated the IKARUS-Projectⁱ 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. With the aid of the models such scenarios and strategies can be developed and evaluated within the frame of energy technology and energy policy (Fig.1).

The IKARUS instruments consist of 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

are 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) describing the energy system on a national level.
- A very detailed space heat simulation model for different individual buildings 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 detailed specific vehicles.

Fig.1: IKARUS Instruments

Level of Analysis	Data	Method	Results
National Economy	Development of <ul style="list-style-type: none"> • Population • Economy • Energy policy 	Input/Output model with a disaggregated energy sector	<ul style="list-style-type: none"> • Input/Output-table with relational supply • Energy demand
Energy Economy	Development of <ul style="list-style-type: none"> • Energy costs • Energy demand • Technology and potentials 	Optimization model	Total balances of <ul style="list-style-type: none"> • Energy carriers • Emissions • Costs
Sectors	Sector specific information about <ul style="list-style-type: none"> • Policy • Economy • Technology and potentials 	Simulation models for <ul style="list-style-type: none"> • Space heating • Industry • Transport 	Sector balances of <ul style="list-style-type: none"> • Energy carriers • Emissions • Costs
DATABASE			

In addition to these energy models, a macroeconomic model is included. The heart of this model is a demand-driven, dynamic input-output model (IO model) with 24 sectors including nine energy sectors. The model includes sectoral autonomous energy efficiency improving technical progress as well as CES production functions to represent substitution processes. This macroeconomic model can be linked (soft link) to the optimization model. Thereby the technical parameters resulting from the LP-model are first implemented into the economic model. These technical parameters comprise the energy flows like the use of domestic coal, nuclear and others, and the capital structure in the production sectors. The IO model calculates direct investments (for example induced by a CO₂-restriction in the LP model) as well as indirect effects through the investment goods producing sectors. The result of this calculation has to be compared with the basic assumptions and the results of the preceding LP model run. To get a consistent solution, an iterative process may be necessary.

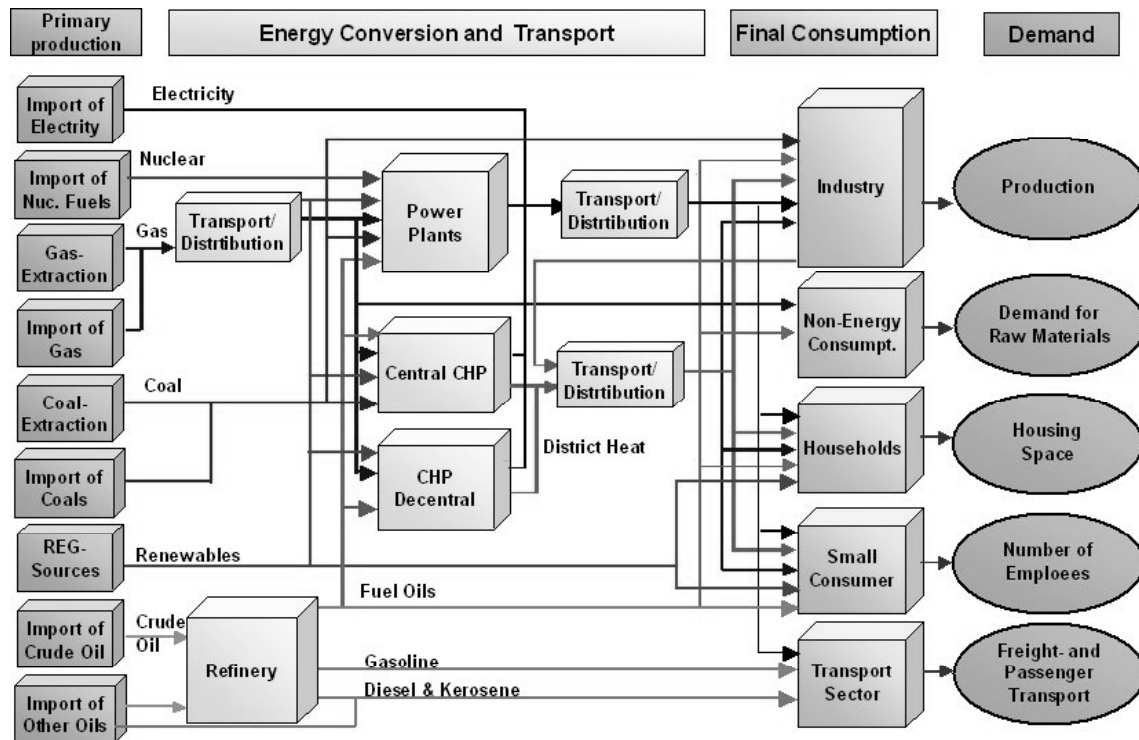
LINEAR OPTIMIZATION MODEL

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 form of cross-linked processes (Fig.2). Such processes are for example the extraction or the import of primary energy, the transformation into secondary energy (for example electric power production) and their distribution as well as the use of final energy carriers in the end use sectors for the demand of energy services (e.g. mobility, space to be heated, industrial production). In the model 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.

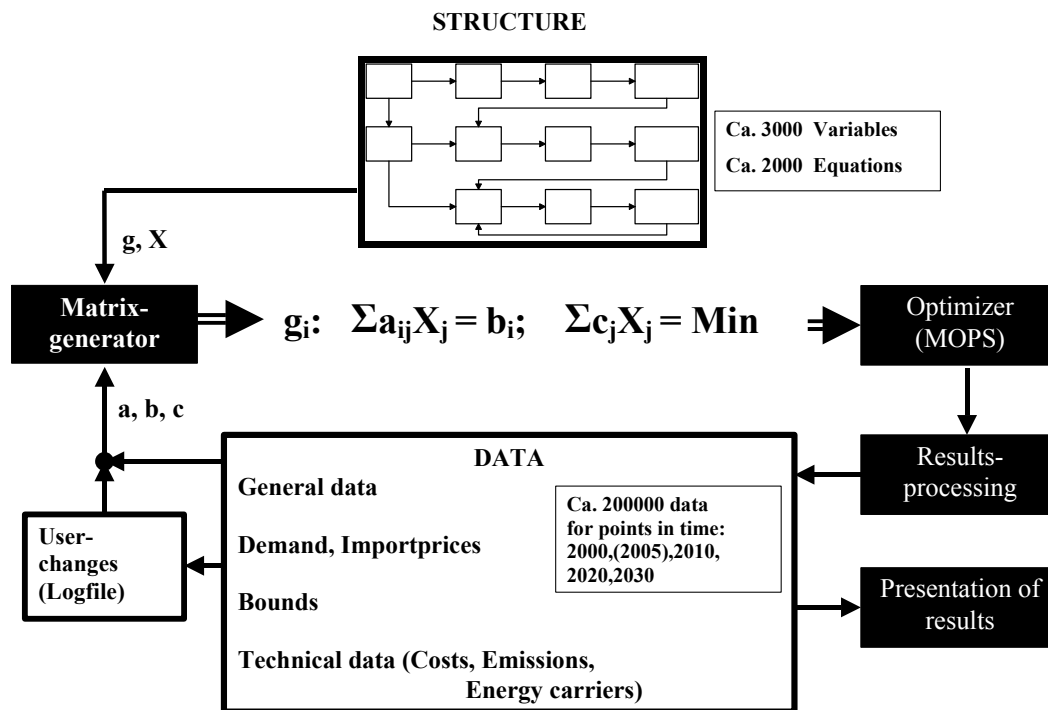
Fig.2: Structure of the IKARUS Energy system



The structure of the model is broken down into ten major sectors. 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 and new buildings. Each subsector is described by a number of representative technologies characterized by specific energy carrier inputs, costs and emissions. The model contains so called “placeholders” for the representative technologies or technical measures. This “placeholder concept” with initially empty “technology boxes” ensures that the user can have his own occupancy options (choosing different specific techniques of the same technology from a model database) and thus an extensive flexibility in selecting the representative technology. These occupancy options are particularly important when non linear effects have to be considered during calculation.

Both structural data - related to placeholders and network - 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 Fig.3. The structural data contains about 3000 variables (placeholders for 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. Numeric data exist at the moment for the following chronological checkpoints or footholds: The years 2000, 2010, 2020, 2030 and partly for 2005 . Altogether the model database contains a total of ca. 200000 numerical entrees for these basic years. Calculations for years in between are made possible through interpolation of the basic input data.

Fig.3: Calculation scheme for the IKARUS LP-model



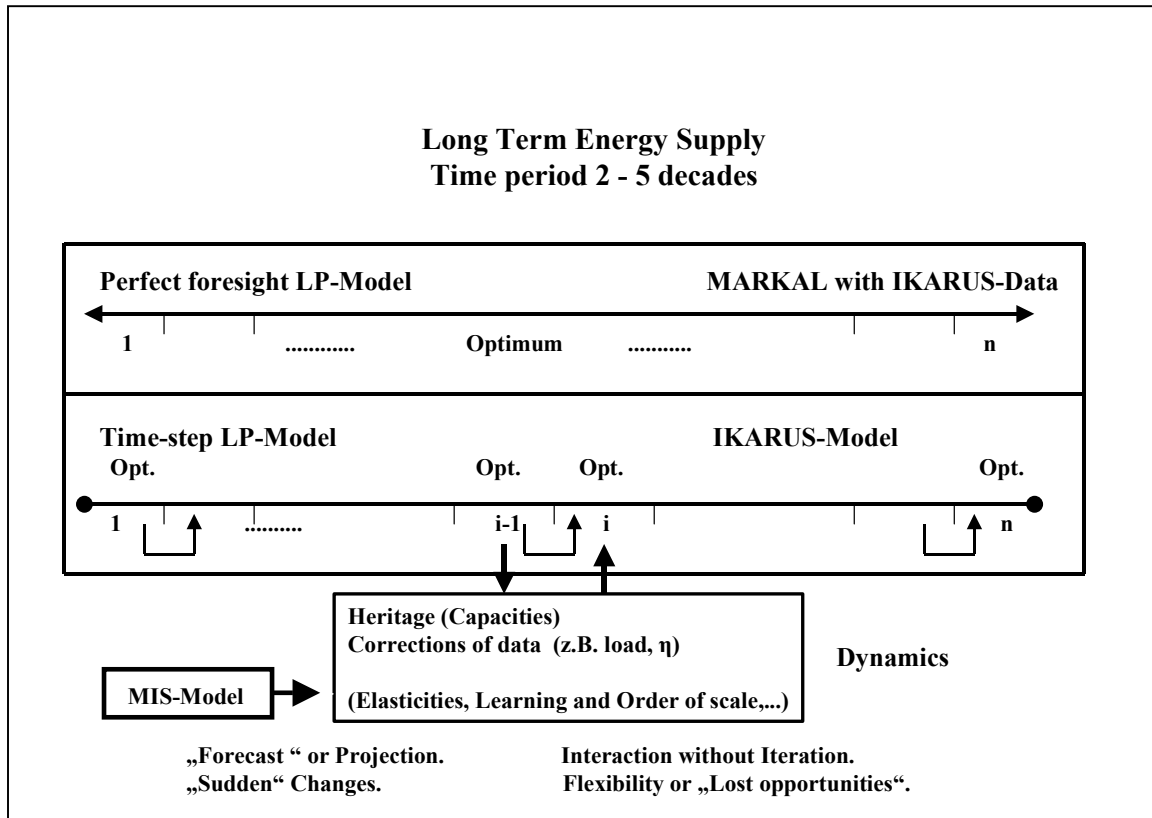
Before numeric and structural data are combined in a matrix generator, the user of the model will define his own scenario (like energy prices, technological or political bounds etc.) and - if desirable - make his own selection of technologies as well as changing any specific technical and economic attribute (for example efficiency, specific costs etc.). In addition to these changes the user can add his own equations to the matrix or alter any existent user equation. He can also choose among different objective functions (like costs, emissions, energy-efficiency and also a fuzzy approach to maximize contentment). Normally total system costs are chosen as the objective function (least costs). All the modifications and extensions made by the user are recorded in a log file.

The matrix generator will calculate all coefficients and build up the linear equation system in the format of a standard MPS-file. This file is the input to a commercially available mathematical optimizer (Mathematical Optimization System: MOPS) which contains several Fortran dynamic links libraries that are embedded in our personal result processing program. In addition to the standardized (LPS) output file, which only shows the mathematical solution, the result processing program will immediately calculate typical table values for energy-, emission- and cost balances and store these values in the model database. This is done while all mathematical results from MOPS are still stored in the computers main memory making the runtime of this result preparation program very short. 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 (Fig.4). The time horizon is divided into intervals (at the moment four or eight) and 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 would "know" all the future parameters or boundary conditions and therefore could react on future exogenously given changes in advance of these changes taking place (e.g. prices of energy carriers, climate gas reduction policy etc.). 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 reaction on sudden changes (like a sudden jump of prices of oil and gas), 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.

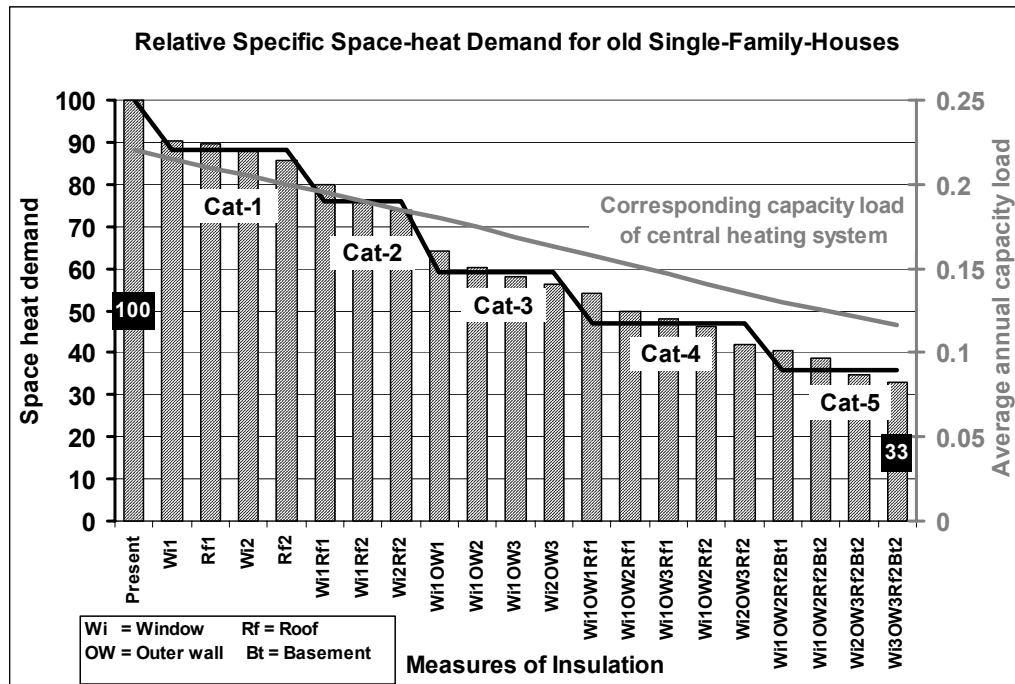
Fig.4: Dynamics of the IKARUS LP-model



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. Probably a major part of these effects can 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 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. It is an often used model for German energy scenarios.

From the huge set of technical input data for the model we will here only pick out one example. Figure 5 shows the dependence of specific space heat demand of an average single family house, old building (built before 1995), on different measures for thermal insulation. The index 1 to 3 describes an increasing thickness and efficiency of insulation layer. The measures are divided into five categories. Correlated to these measures the average capacity load of existing central heating systems is also shown in figure 5 as an example of non-linear effects.

Fig.5: Space-heat demand for different measures of thermal insulation and corresponding annual capacity load of the central heating system.



ASSUMPTIONS FOR MODEL RUN

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 in the next 30 years. The annual rate of decline varies from 0.06%/a until 2010 up to 0.30%/a in the period 2020 – 2030. (Table 1).

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	Number	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	Number	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 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 square m today to 113 square m in the year 2030. The size of an average apartment in multiple family houses changes only slightly from 66 to 68 m² in the time horizon 2000 – 2030. The floor space increases by 23% up to the year 2030. As a result the floor space per capita rises from today 38 m² to 49 m² in 2030.

The assumptions for the economy were generated on the basis of the 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 or on the average 1.6% per year. However, the annual rate differs strongly between industrial sectors. Whereas the value added for chemistry is growing with about 1.6% per year, the growing rate of other energy intensive sectors like iron industry, cellulose and paper is by far lower.

Table 2 shows the evolution of some important energy intensive products on a quantity basis. Accordingly a downward trend of many of these products is to be expected in the future. The production of aluminum in Germany is supposed to be stopped until 2030.

Table 2: Development of some industrial products in terms of quantity.

Product	Products (Mill. ton)				Annual changes in %/a		
	2000	2010	2020	2030	2000/10	2010/20	2020/30
Cement	36.05	35.05	34.55	33.53	-0.28	-0.14	-0.30
Lime	7.26	6.90	6.50	6.00	-0.51	-0.60	-0.80
Brick	17.00	16.90	16.00	15.60	-0.06	-0.55	-0.25
Glass	6.61	6.78	6.90	6.95	0.26	0.18	0.07
Sugar	4.30	4.50	4.58	4.45	0.45	0.18	-0.30
Rolled steel	38.97	36.10	35.90	34.80	-0.76	-0.06	-0.31
Crude steel	30.85	26.23	23.25	20.46	-1.61	-1.20	-1.27
Electric steel	13.32	14.69	17.03	18.60	0.98	1.49	0.88
Aluminium	0.64	0.65	0.20	0.00	0.09	-11.12	-100.00

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 today 926 billion Pkm to 1190 billion Pkm in 2030 (Table 3). The increase of freight traffic, however, is much stronger. It climbs from 489 billion tkm to 889 billion tkm, i.e. an increase of more than 80% in the coming 30 years.

Table 3: 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 traffic ¹⁾	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

Table 4 shows the prices for the most important imported energy carriers. We assumed only a moderate increase for the coming 30 years. These prices are based on a study made for the IKARUS project (Horn, M., 2002). The import of natural gas is divided into two price-quantity categories A and B where the amount of the cheapest category (A) is limited (Table 4).

Table 4: Assumptions for future prices of imported energy carriers.

Energy carrier	Prices in €/GJ (2000)				Annual changes in %/a		
	2000	2010	2020	2030	2000/10	2010/20	2020/30
Hard coal	1.32	1.76	1.80	1.87	2.90	0.22	0.42
Crude oil							
Gazoline	7.06	6.28	6.51	6.79	-1.15	0.36	0.42
Diesel	6.95	5.45	5.61	5.85	-2.41	0.30	0.42
Domestic fuel oil	6.95	5.45	5.61	5.85	-2.41	0.30	0.42
Residual fuel oil	5.06	3.51	3.60	3.75	-3.58	0.23	0.42
Natural gas A	3.27	3.65	3.82	3.98	1.09	0.46	0.42
Natural gas B	4.11	4.56	4.77	4.97	1.04	0.46	0.42
In comparison with lignite	1.44	1.51	1.64	1.68	0.48	0.83	0.25

Table 5 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 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.

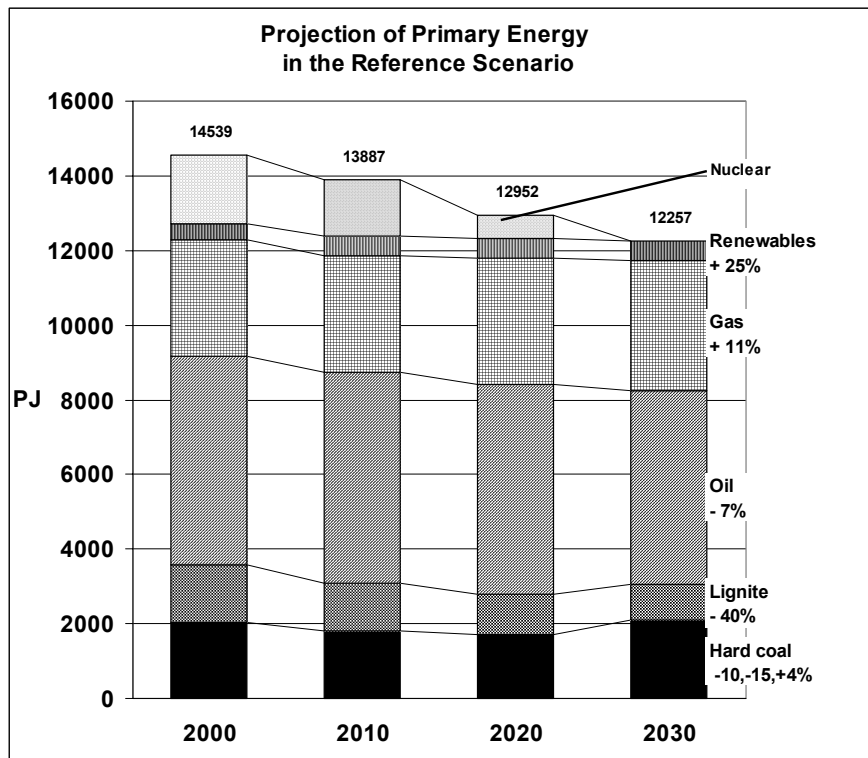
Table 5: Some important bounds concerning energy policy and quantity potentials.

	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 minimum capacity of 12 GW corresponding to the installed capacity at the end of 2002.

These assumptions lead to a primary energy consumption as shown in figure 6.

Fig.6: Projection of primary energy in the reference case.



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.

SCENARIO RESULTS

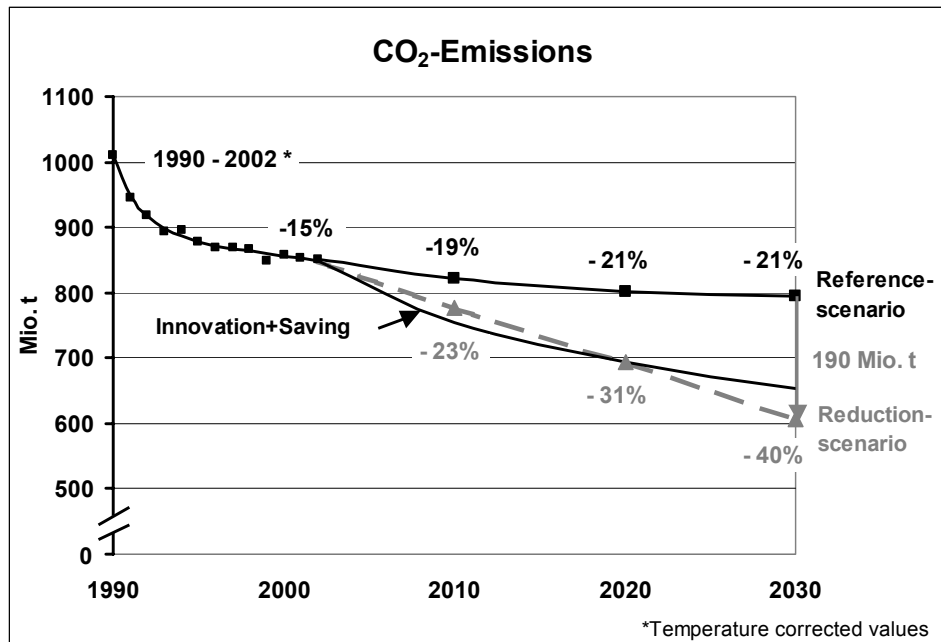
In Germany there has been a continuous discussion in the last 10 – 15 years about ways of energy saving and reducing green house gases, particularly the CO₂ emissions. In the following examples of typical results from the IKARUS model we shall therefore concentrate on a CO₂ scenario (“Reduction scenario”) 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:

1. Imposing various technical and economic guidelines in order to advance innovation and energy saving for example by law or subsidies.

2. Giving boundary conditions only and leaving it to the energy system to decide which options should be chosen to fulfill these conditions.

The amount of CO₂ emissions in Germany caused by energy conversion was in the last year (2003) about 837 million tons. This is a reduction of about 15% compared to the emission level of 1990. Figure 7 shows the CO₂-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 was in particular due to measures of restructuring in East Germany that among other things led to a drastic reduction of the use of lignite.

Fig.7: CO₂-emissions in Germany.



In the projection of the reference scenario the CO₂ emissions drop about 5% from 2000 to 2010, decrease with 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 (-21 % in 2010 when compared to 1990 including all climate gases). More far-reaching reduction goals like for example 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 CO₂ decrease is imposed to the model demanding a 40% reduction of CO₂ 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 7 also shows the resulting CO₂-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 CO₂-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 CO₂-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 description of the reference scenario can be found in (Martinsen, D. et al, 2003).

Fig.8: Share of sectors to the saving of final energy in the innovation+saving scenario.

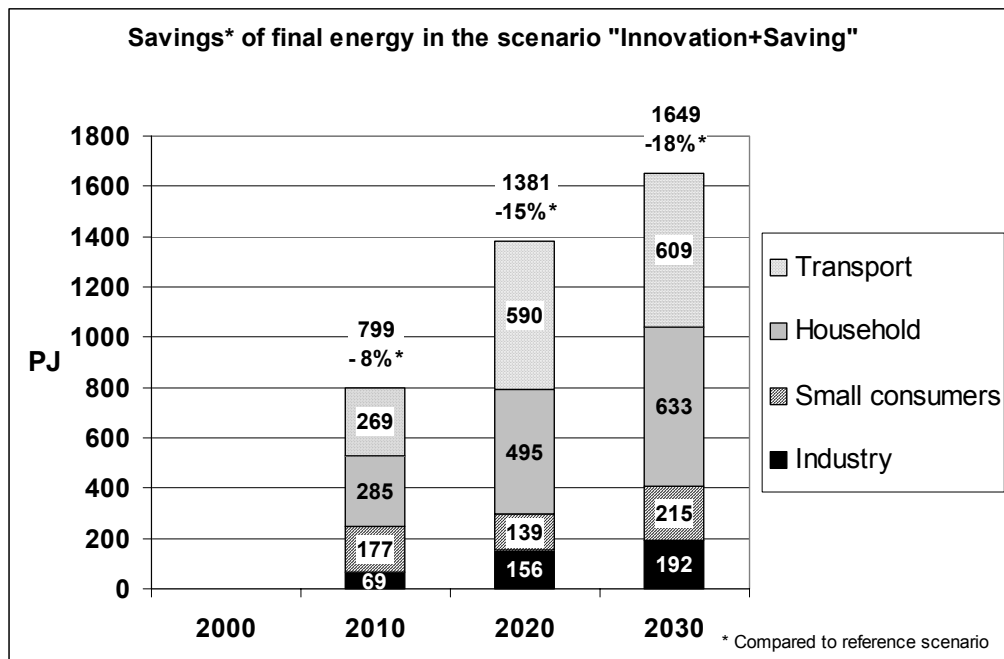
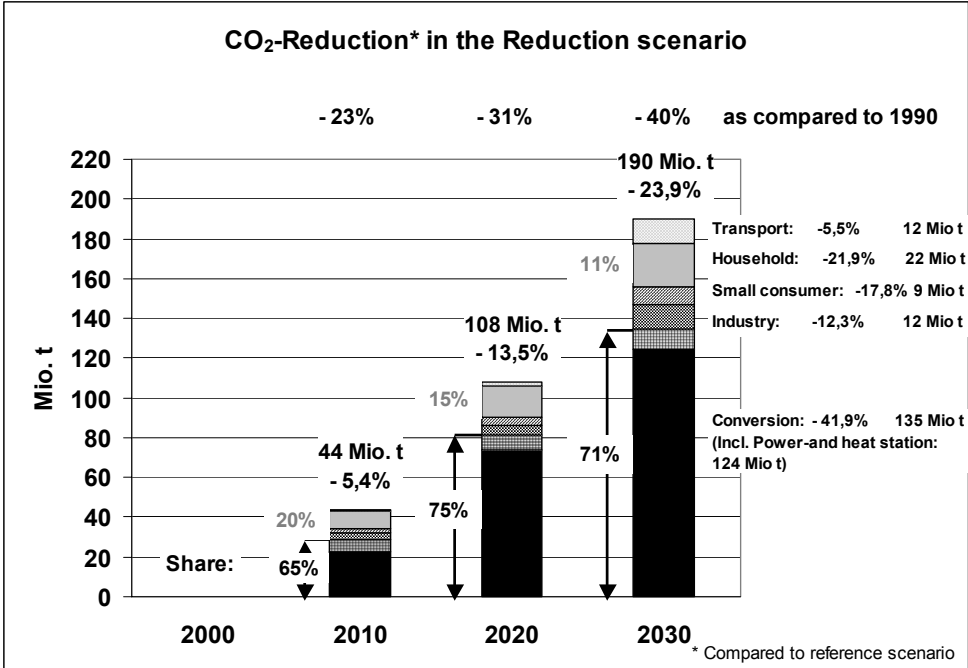


Fig. 8 shows the share of sectors to the saving of final energy in the innovation+saving scenario as compared to the reference scenario. The main contributors to this saving are the household and transport sector. The relative saving in 2030 is 9% in the industry sectorⁱⁱ, about 16% in the sector of 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 8) the saving of final energy is considerably smaller with a total of –8% in 2030. The share of sectors is dominated by the household 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 CO₂ 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 user sectors.

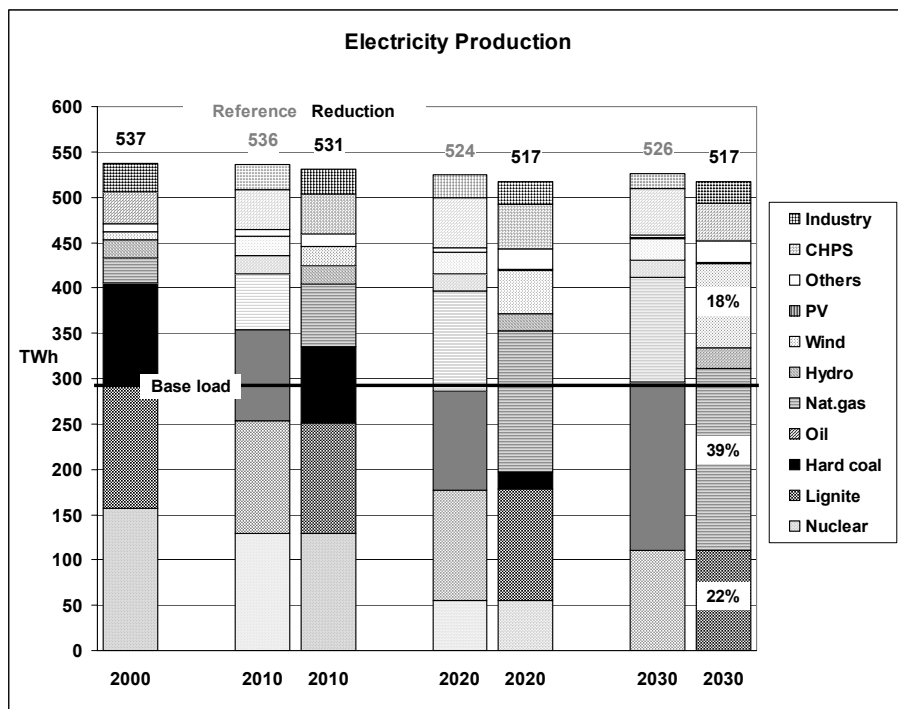
The share of sectors to the CO₂ reduction in the reduction scenario as compared to the reference scenario is shown in figure 9. The overwhelming contribution to this reduction is given by the conversion sector which share is between 2/3 and 3/4 in the period 2010 – 2030. In 2030 the reduction of CO₂ 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 in CHP plants. The main contributing end user is the household sector with a –22% decrease of CO₂ in 2030. 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-user sectors (small consumer, industry, transport) do not show up until the last time period.

Fig.9: Share of sectors to CO₂ reduction in the reduction scenario.



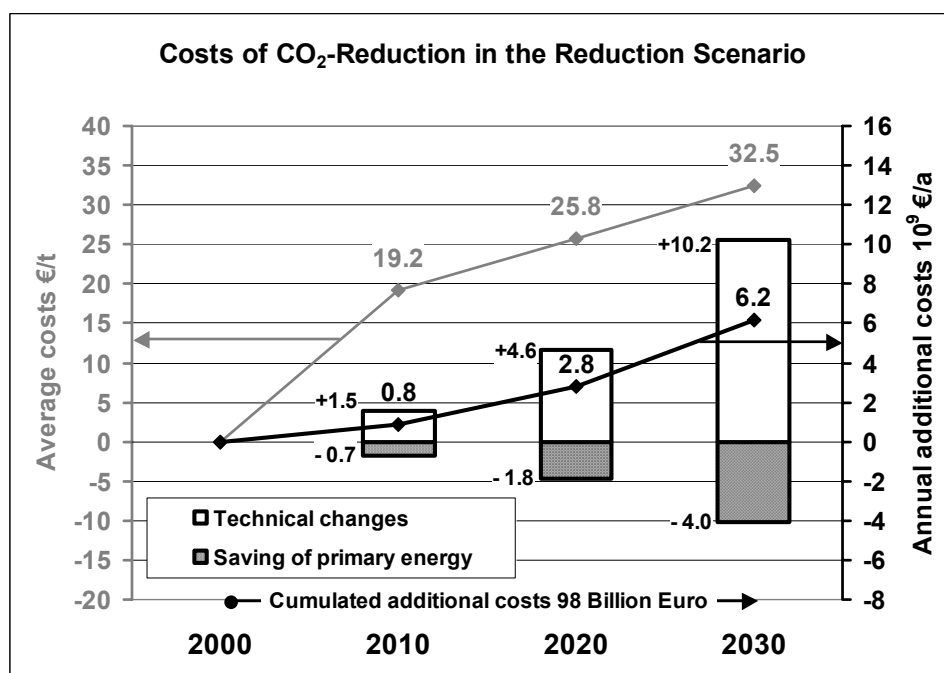
Because of the dominant part of the electricity sector to meet the CO₂ constraint we exemplarily show the structure and changes of the electricity production in the model results in figure 10 with the reference scenario (grey) to the left and the reduction scenario (black) to the right. Whereas in the reference scenario the compensation of the phase-out of nuclear base load power plants is made up by additional hard coal power plants (and new lignite 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 CO₂ reduction is about 120 million tons in 2030.

Fig.10: Structure of electricity production in the reference and reduction scenario.



Meeting the CO₂ constrains lead to additional system costs in the model (Fig. 11). 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 100 billion euro. The corresponding average specific CO₂ reduction costs are ca. 19 €/ton in 2010 and ca. 32 €/ton in 2030.

Fig.11: Annual and specific costs of CO₂ reduction.



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 – 5) as well as on time dependency and magnitude of the CO₂ constrain. For example changing the restriction for CO₂ emissions in 2030 from –40% to –31% (= 2020 value) respective –50%, the average specific 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.

OUTLOOK

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. 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 the end of the 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.

Fig. 12: Lost potential of space heat savings for old buildings in household.

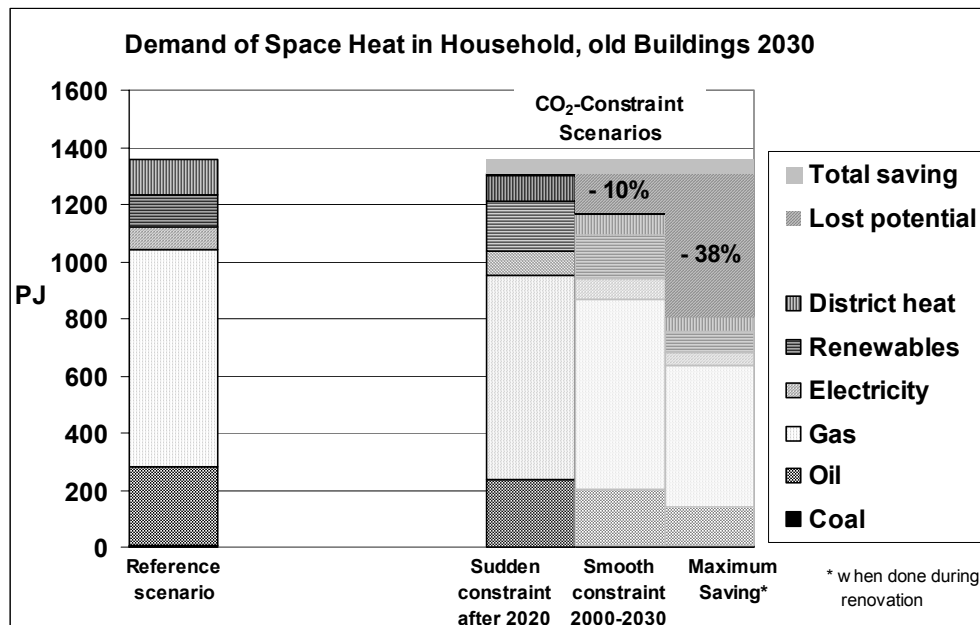


Figure 12 shows an example of a lost potential for energy saving by insulation of old buildings in the residential sector. The insulation is supposed to be done during renovation of the buildings where the fraction of old buildings to be renovated in one time period is limited. The figure illustrates the demand of space heat in 2030 for three CO₂-scenarios, all constrained to a 40% reduction of CO₂ in 2030 as compared to 1990.

- **“Sudden”** constraint after 2020. In this scenario there is no CO₂ constraint before 2020. Thereafter, however, a sharp decrease of CO₂ 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 CO₂ 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 CO₂ restriction. The result of this scenario is comparable to a perfect foresight scenario and the model will chose insulation measures during renovation in all periods.
- **“Maximum”** saving. In this case the model will make use of the maximum potential of insulation measures with a high degree of space heat savings (category 5 in figure 5) 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 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 13 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

Fig. 13: Installed capacity of lignite, hard coal and gas power plants for two price scenarios.

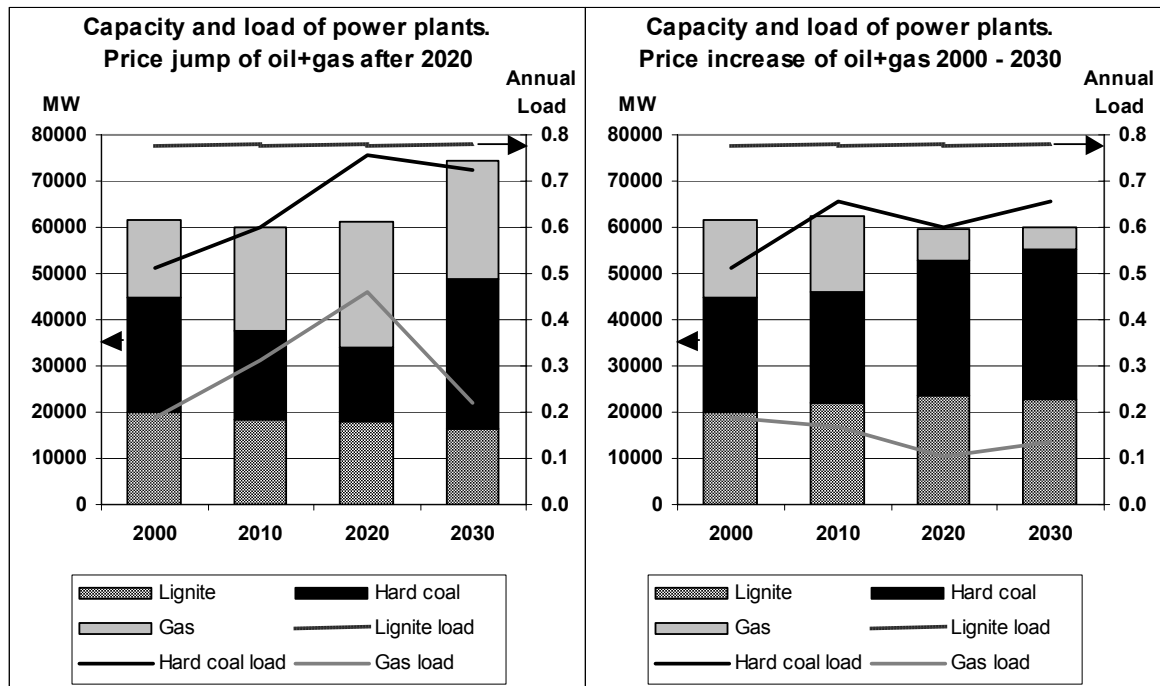


Figure 13 illustrates installed capacity and annual load of lignite-, hard coal- and gas power plants (the capacity of other power plants are not shown). The left part of the figure shows the case of a sudden price “Jump” after 2020 and the right part shows the case of a “Steady” price increase from 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 drastic reduce the load of the existent gas power plants. This gives rise to a total (included also all other types of power plants not shown in figure 13) net surplus of about 9 GW of installed electric capacity.

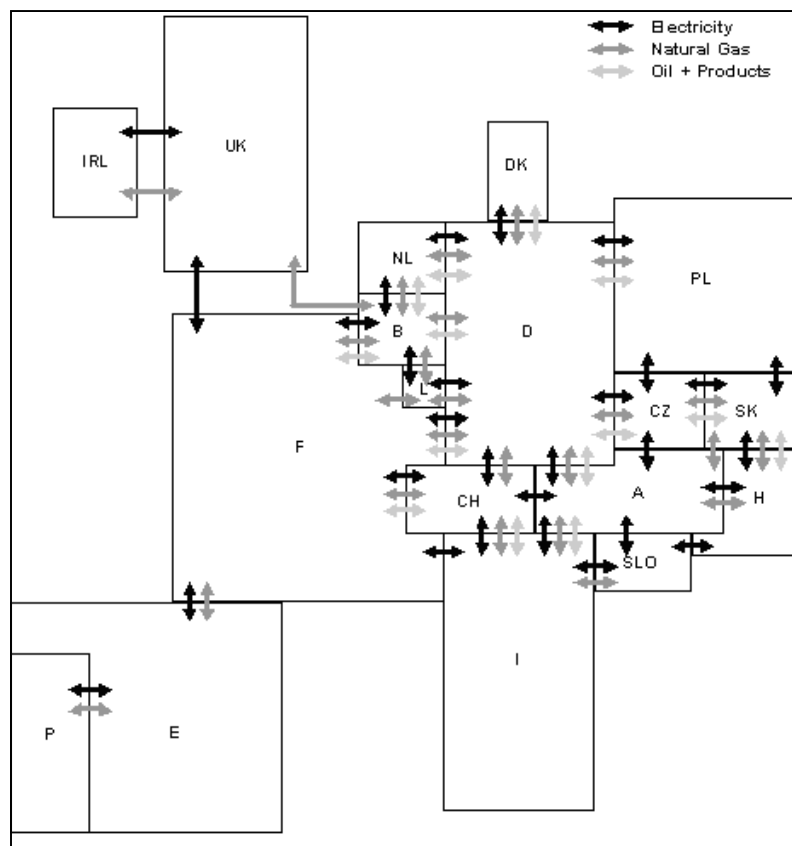
The example above shows that also least cost scenarios that are based on a special course of energy prices can lead to an irreversible build-up of costly surplus capacities when unforeseeable price changes occur.

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.

Fig. 14: Energy-related infrastructure in Western and Central Europe



One focus of the model application is energy-related infrastructure (transmission lines, pipelines, etc.), also serving as the interconnection of the national energy systems (Figure 14). Due to high investment

costs and long payback times, the effect of different optimization strategies on infrastructure is expected to give varying results.

LITERATURE

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ⁱ Instrumente für **Klimagasreduktionsstrategien** (Instruments for climate gas mitigation strategies)

ⁱⁱ 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.