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Model-Based Decision Support in Energy Planning

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1 Decision support features of energy planning

1.1 Objectives in energy planning

Energy planning is a general term that is applied to a variety of issues. It addresses designing energy supply and utilization in new buildings as well as municipal planning of district heat supply and the structure of heating systems. In national energy planning the focus is on political targets like diversification of energy sources or environmental targets like reducing acidification of soil and lakes. International bodies like the World Energy Council (WEC), the International Energy Agency (IEA) or the Intergovernmental Panel on Climate Change (IPCC) investigate the future of our energy system on a multinational or even global level [1, 2, 3]. Many research institutions and scientists focus their research on the long-term future of the global energy system [4, 5, 6, 7, 8].

Depending on the scope of the problem and the decision makers involved the targets of such investigations differ. Industrial bodies and energy utilities strive for strategies with minimum costs. In this case other objectives, like environmental or social aspects, are viewed as constraints. As an example, fuel use in a power plant can be constrained due to site-specific regulatory emission limits. Three types of problems are addressed by industrial or utility decision makers:

- long-term planning (supporting decision makers; planning periods of 15 to 20 years), especially for investment decisions,
- medium-term planning for one or two years, generally addressing resource allocation, contract and plant management and
- short-term operation planning for the day or week, deciding on plant schedules and unit commitment.

National or international bodies, politicians and scientific investigators focus directly on political, social and environmental aspects of the problem. Such investigations generally emphasize the longer term, focusing on 20 to 50 years, while medium-term analyses in this field have a time frame of some 5 to 10 years. Recently, the issue of global warming with the very long time constants involved, has triggered a multitude of energy related studies with a time horizon up to 2100 or even beyond. Such investigations are not directly targeted towards investment or operation decisions, they rather supply a foundation for long term policy decisions, legal acts and international treaties and provide a basis to focus later R&D funds on specific problems.

1.2 Models for energy planning

In energy modeling a wide variety of models have been employed. Three types have found most widespread use:

1. Simulation models that mimic technical features of the modeled system. Their results are directly determined by the input. Such models are useful to evaluate fully defined systems with no degrees of freedom. Open questions have to be investigated by the user prior to model application. They are used for technology-oriented analyses, e.g. to determine the size of the heating system and the degree of insulation for different housing types [9, 10, 11, 12].
2. Econometric models expanding past behavior into the future. Econometric estimates of time series supply the basis for models explaining one variable, e.g. energy use, by some driving forces, like income, prices, etc. Such models are mainly used for demand evaluations and investigating consumer responsiveness to prices. [13, 14, 15, 16].
3. Economy models viewing the energy sector as part of the overall economy. Various types of such models exist, like General Equilibrium models or neoclassical growth models [17, 18, 19, 20, 21]. Their common feature is that the energy system is viewed from outside, with the main focus on the interrelations with the rest of the economy. Their main use is in the evaluation of energy policies with respect to the consequences on the economy or vice versa.
4. Optimization models deriving optimal investment strategies or operation plans for specific utilities or municipalities. Used in national energy planning or international investigations for analyzing the future of an energy system, such models derive the optimal strategies assuming optimal behavior of all acting agents under the given constraints.

Among the optimization models, the most commonly used approach is linear programming (LP [22, 23]). LP models have found widespread application in refinery scheduling, national energy planning[1] and technology-related long-term energy research [25, 26, 27, 28, 29]. There is a growing tendency to base municipal energy plans on formalized modeling tools, mostly also LP models (examples are described in [30, 31, 32, 33]).

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[1] The energy systems model MARKAL [24] is applied by IEA member countries for concerted analyses in special topics. The current focus is on the greenhouse issue.

Modeling the actual system of an electric utility requires greater detail in formulating technical properties and relations; it does not allow full linearization of all relations. Mixed Integer Programming (MIP) offers the possibility to improve the formulations of pure linear (LP) models: it allows to include yes or no (0-1) decisions and nonconvex relations in a model. Unit commitment problems, with decisions on the start-up or shut-down of thermal units, and expansion planning, deciding on which type and size of power plant to build, involve discrete decisions that are most commonly modeled with MIP techniques. Alternative modeling approaches include dynamic programming, which gives fast solutions on 0-1 decision problems with low complexity. Smooth nonlinear optimization problems are often solved using Lagrange relaxation methods. Recently modern techniques like genetic algorithms, simulated annealing [34], etc., are penetrating the decision support market in the energy utility sector. For more complex problems combinations of modeling approaches are applied to solve the problem in a hierarchical or iterative manner [35, 36].

The accuracy of depicting the system, the choice of modeling technique and decision variables all depend on the type of system, the time horizon and the questions asked.

1.3 General requirements of decision support

Energy-related decision support systems generally fall under two categories:

- Systems applied by specialists (in industrial, institutional or scientific environments), where the evaluated results are presented to the decision maker. This type of decision support is generally applied if high-ranking persons are involved or if the decisions have far-reaching consequences.
- Systems continuously used for short to medium-term planning. Such systems are mostly applied by the decision makers themselves. As an example, scheduling and resource planning for the production of an electric utility is decided by the load dispatcher, who is also using the decision support software.

Clearly the two types of users and the two types of decision makers call for different types of decision support systems. The most important requirement to decision support systems for high-ranking decision makers is flexibility in order to answer any upcoming question. Strategic investigations often call for changes in existing models. The requirements on the man-machine-interface (MMI) are moderate, because the system is applied by specialists with specific interest in the issue. The decision makers, who are usually not applying the DSS themselves, require relevant strategic information of the what-is-when type. They need to understand the implications of certain decisions and the interrelations of the components in the system investigated. Generally, decisions with far-reaching consequences are not taken according to the solutions proposed by a model. They are evaluated on the basis of model results, but incorporating the specific experience, skills and judgement of the persons involved.

Decision support systems of the second type, like scheduling the operation of power plants and energy exchange contracts for a utility, which are applied by the load dispatcher with some special training, have quite different requirements: They must be linked to the data base of the utility in order to always reflect the current situation; they have to be of high quality (error-free) and give defined results under all circumstances; and the man-machine-interface (MMI) must be easy to operate and understand and cover all possible manipulations including transfer of the results to any consecutive process. In operation planning, the decision maker (load dispatcher) analyses the proposed solution in view of his experiences and objectives and either accepts it or disagrees with one or more of the decisions involved. As a consequence, the DSS has to have the flexibility to start from the last solution proposed and incorporate additional constraints or other settings given by the load dispatcher. Most DSS of that sort also offer the option to just simulate a solution defined completely by the operator of the power system.

A major problem faced by load dispatchers of energy utilities are uncertainties in basic parameters influencing the decision process. Uncertainties in short-term decision problems usually concern the demand given by the load curve over the day or the week and the uncertainties in the supplies from some energy sources (e.g. inflow into a water reservoir, water freight of rivers). In countries like Austria this concerns hydro-power generation, which is highly dependent on rainfalls in the water catchment areas. Various types of forecasting systems can expand the range of fairly exact results to a period of up to 8 hours. Forecasts exceeding this time frame tend to be of more speculative nature. Consequently, another requirement of on-line decision support systems is the ability to start a new model run at any point in time from the current situation, revising the plans in operation according to any changes in forecast data. Also forced-outages of power-plants can lead to new emergency plans.

In any case, maintaining the consistency of the data base and the model are of utmost importance in continuous model application. Changes in exogenous conditions, internal structure or objectives of the system should be continuously monitored.

2 Examples

The following examples describe some applications that have been developed to support decisions in the area of energy planning. All of them are based on LP or MIP optimization models. They cover different applications, different decision makers addressed and different time frames.

2.1 Short- and Medium-Term Planning for Utilities

Planning the operation of a utility's power system (fuel storage, hydro-reservoirs, contracts) involves a hierarchical set of time frames. Fuel stockage and use, annual hydro-storage utilization and contractual arrangements are managed in annual resource allocation plans. Actual scheduling is done on a weekly or daily basis, while sudden changes in the system's parameters have to be covered by emergency plans established within a few minutes.

Optimization tools to provide support for these decisions and plans have been based on various types of methods, like Dynamic Programming, Lagrangian optimization, and Mixed Integer Programming [34, 37, 38, 39, 40]. For complex systems and easy parametrization for various kinds of applications (i.e. to be applied in a standardized software tool) Mixed Integer models have proven to be most reliable.

Presently systems that integrate the planning horizons from short-term plan revisions for the next few hours up to planning for the next fiscal year begin to penetrate the market. These time horizons are linked conceptually by using results from the longer time horizon to generate constraints for the shorter one or by integrating models with different time horizons. Model characteristics for annual resource allocation problems and the weekly/daily operation model differ in terms of technical detail, but the basic underlying model is the same.

The model for annual resource allocation problems is applied in the energy planing division of utilities and used to determine how contracts should be negotiated, the quantities of fuel to order and how to utilize seasonal hydro-storage reservoirs. It can also be used for strategic planning problems and what-if questions, e.g. to investigate the impacts of building a new power plant or failures in system components. The model is applied by one or more utility-based specialists that operate the model when analyses are required.

In its use for weekly and daily operation planning the model is applied by the load dispatcher. It runs at least once a day to generate the plan for the next day and more often in case of major changes in the parameters of the power system. Main requirements to the DSS system are (a) on-line data exchange with other programs and use of process information from the power plants, (b) computational speed, (c) easy management and (d) the possibility to override the results and incorporate the load scheduler's decisions into the actual plans.

An example of such a system is described in [41, 42]. This system has a very high degree of flexibility from the mathematical kernel. It is currently used by 4 utilities for short-term scheduling or annual resource allocation (see, e.g., [43] or [44]). It has a modular structure with the major elements (a) thermal power plant, (b) hydro power plant, (c) contract and (d) balance of supply and customer demand. Additional modules allow very complex formulations like logical relations between different units, reserve conditions, non-convex efficiency curves and various types of constraints based on legal, contractual or technical conditions. It allows to set up a new application by parametrizing the energy system in terms of input data. This modeling effort requires in-depth knowledge of the utility's energy system and experience in model setup. The objective of this process is to generate a model that is accurate enough to satisfy all operational requirements of the utility and produce results that meet the required standards in terms of quality and accuracy. On the other hand, adequate model formulation has to enable fast computation [45].

Presently, model sizes range from 5000 to 20000 variables, with CPU-times between 3 and 30 minutes for scheduling and resource allocation models, respectively.

Figure 1 gives an overview of the interfaces of the product, as they are documented in [46]. The optimization package has six external interfaces: The interface to the user (MMI), to the power-plant processes (to get information about the operational state of the power-plants and give information on planned changes), an interface to an additional optimization package for cascaded hydro-power system with a highly nonlinear model [47] as a subsystem with iterative linkage via quantities and shadow prices, the link to the load and hydraulic forecast modules, to external computational equipment like printer, plotter, and to the central archive of the utility via databank routines.

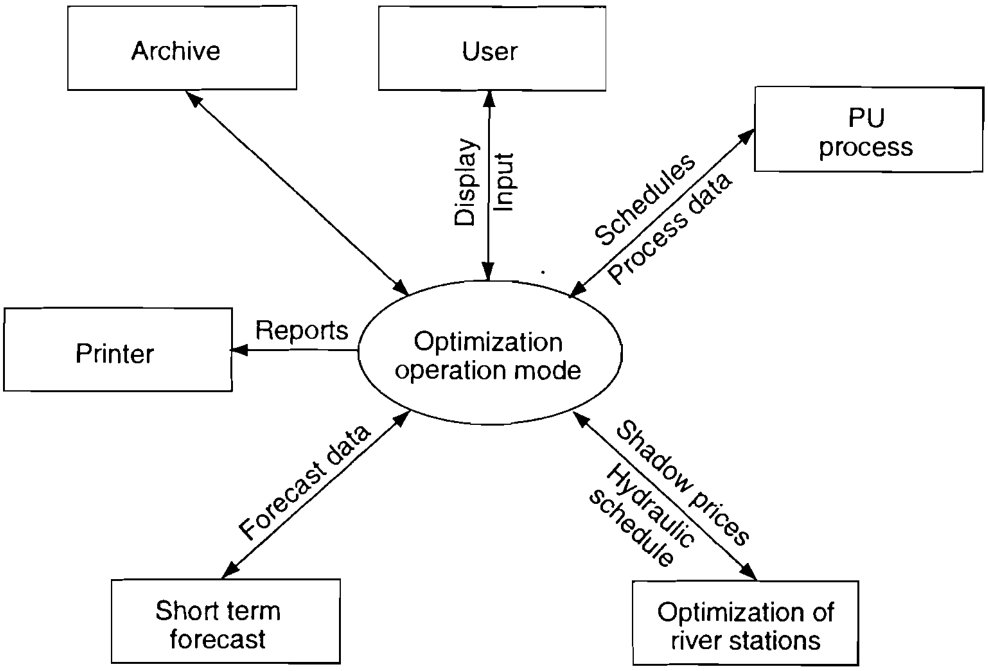

Figure 1: Environment of annual energy planning package XOPT

During the initial learning phase of model configuration and application, the planner and the load dispatcher sometimes encounter situations where model outcomes suggest schedules that are not commonly applied. These schedules, which are innovative in the sense of applying existing machines in a different way to reduce expenditures, deepen the understanding of the power generation system. In the wider sense, this innovation process could be grouped into the new innovation procedures as suggested by Cowan and Foray [48], which are triggered by good simulation models.

2.2 Planning a metropolitan energy system

The public utility of Vienna used the dynamic linear programming model MESSAGE [50] for its most recent energy plan [49] to evaluate the future development of the municipal energy system, especially with respect to the coordinated expansion of the gas and district heat grids. From the organizational structure, electricity, district heat and natural gas are handled by three players in the energy market of Vienna. For establishing the 1991 energy plan, they delivered the input for formulating an energy model for Vienna and monitored the development of this model. The resulting model subdivides Vienna into 5 regions with clear priorities for the future expansion of the gas and district heat grids. [32] gives a short overview of this effort.

The model for Vienna is set up as multi-objective optimization model observing three objectives: system costs, energy imports and pollutant emissions (using an index for different pollutants that is generally applied in Vienna) are minimized.

The approach used to formalize the minimization of multiple objectives is based on the reference point optimization method (see [51] and [52]). This method allows the user to formalize each objective in its natural units. In an application, each objective is formulated as target trajectory over time. The modeling system will then try to equally reach each of the target trajectories. Internally these target trajectories are evaluated in relation to so-called "utopia" and "nadir" trajectories. The single points for the utopia trajectories are derived by optimizing each single time step for each objective. The utopia trajectories are established by putting together all these single optimal points; they are really utopic in the sense that, although each single point can be reached, there is no feasible solution that achieves all of them. The nadir points are computed by just putting together the worst solution for each single time step and objective. Figure 2 shows the nadir and utopia points for an example with two objectives. It also shows how an optimal solution is reached from two given examples of reference points by driving the solution towards the pareto-optimal surface of the solution space. If the reference point lies inside the feasible region an improvement with respect to both objectives is reached, while in the case of too high expectations, when the reference point is outside the feasible region, the optimum is worse than the reference point for both objectives.

In addition to supporting multi-objective solution of complex systems the approach helps to investigate the shape of the pareto-optimal border of the solution space (the thick line in Figure 2). This border comprises all solutions that cannot be improved with respect to one objective without decreasing the performance with respect to another objective.

Figure 3 shows the optimal energy mix for Vienna in the year 2015 for each of the single objectives, as well as the compromise solution reached with the reference point method. Cost minimization yields a considerable share of oil, while both, energy minimization (due to the higher efficiency) and emission minimization (due to the lower emissions), result in higher shares of natural gas. In the case of energy minimization, investments in insulation reduce heating demands. The compromise solution also gives considerable demand reductions, and a fuel mix similar to energy minimization, but with a slightly higher share of natural gas.

As an example the NO_x emissions related to the four results are shown in figure 4. These emissions are highest for the cost minimization scenario with 85% of the 1990 level, while energy and emission minimization both result in a reduction to 60% by 2015. The compromise reduces NO_x emissions by 30% and lies in between these two ranges.

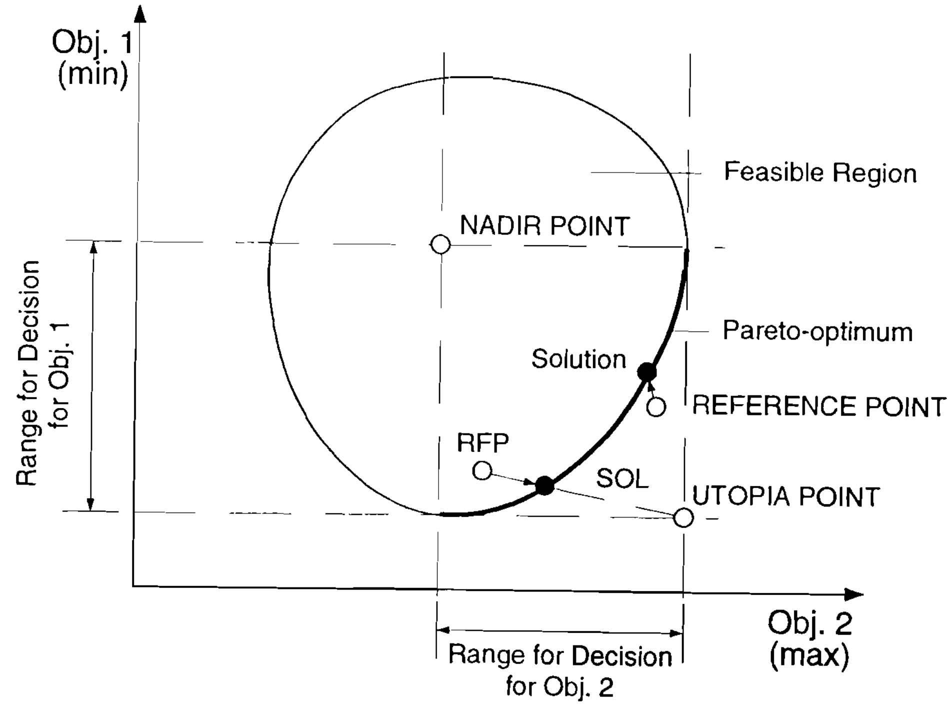

Figure 2: Two-dimensional solution space for reference point method

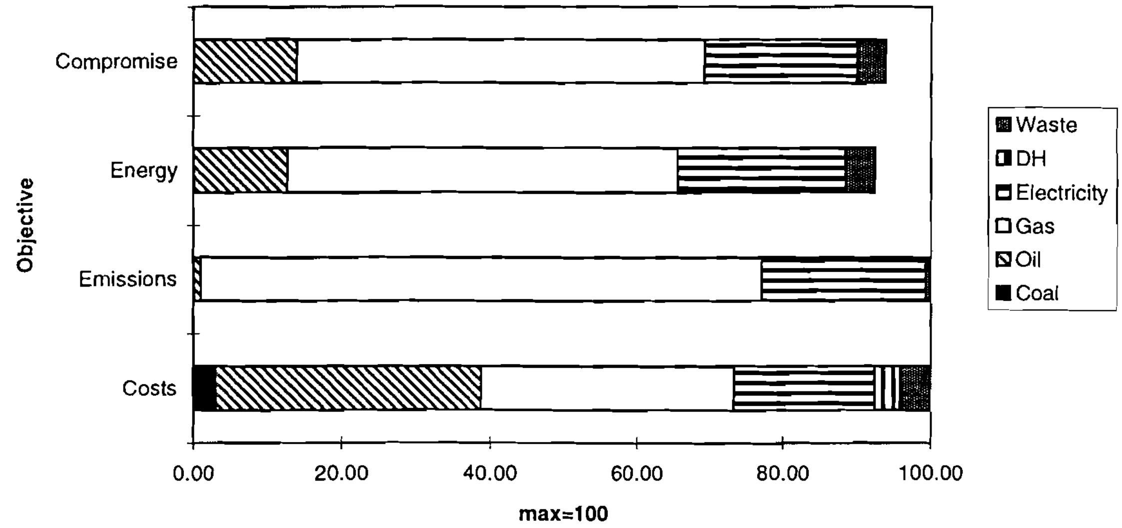

Figure 3: Vienna: Final energy consumption per energy carrier in 2015

The model was optimized on the IBM mainframe of the Vienna municipal utility, with MINOS [53], CPU-times were in the range of 2 to 3 hours.

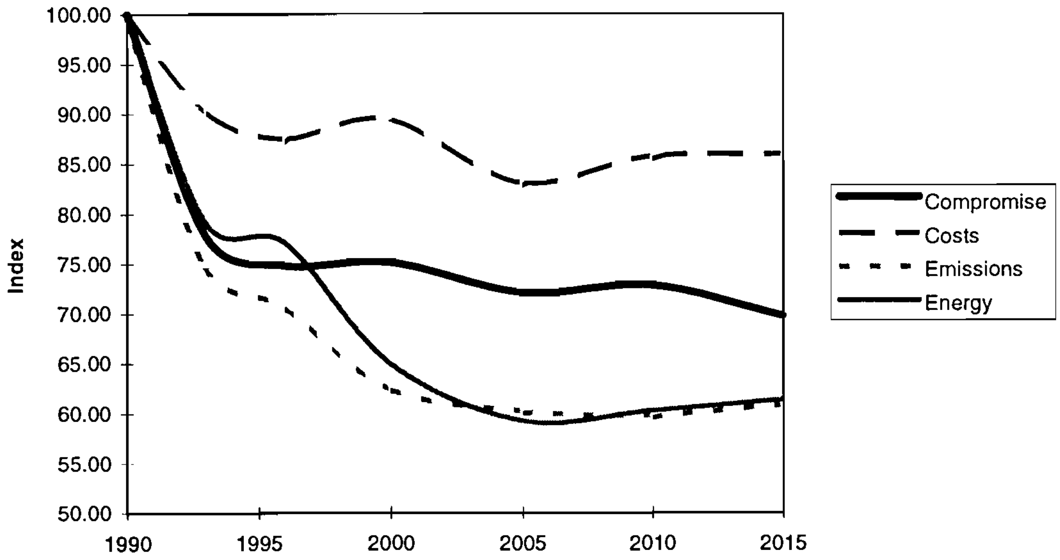

Figure 4: Vienna: NO_x emissions, 1990 to 2015

2.3 Expansion planning for district heat supply

Historically, the Austrian federal state of Lower Austria did not have its own capital. All relevant infrastructure, legislative and executive bodies were located in Vienna, which is situated within Lower Austria, but is a federal state itself. In a referendum in 1992 the population of Lower Austria decided to select St. Pölten, a city with 40,000 inhabitants, as capital of the state. St. Pölten will get a new government quarter by 1998. Clearly the utility of St. Pölten now has the task to supply this quarter with energy in a cost-effective and environmentally benign manner. Since St. Pölten already has a district heat system with two production sites, the prime choice is to expand this system to also supply the new government buildings. Several alternative options are available for the future supply of district heat, and construction can take place at each of the two existing sites (commonly labeled North and South) and at a potential new site called East, which would be in the vicinity of the new buildings.

A MIP model was built to depict all these investment options as integer variables (71 technological options are represented with integer variables for the investment decisions for 11 time steps).[2] Additionally district heat trunk-lines connecting the subareas and the distribution system are modeled. Reserve in the supply system is guaranteed by a constraint requiring adequate generation capacity for each period. Electricity from co-generation can be delivered to the utility of Lower Austria at a contractually fixed price, while district heat is delivered to the customers at the set price.

The mixed integer model generated for this problem consists of 6500 constraints, 6300 variables with 300 integer variables. The solution of the full MIP problem requires several

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[2] For this analysis MESSAGE [50] was used applying the capability to model investment variables as integer decision variables.

CPU hours on an IBM workstation (RS/6000 model 375) using the IBM Optimization Subroutine Library (OSL, [54]).

The technical director of the utility had planned to use the integrated model of all supply options in the system to check the various alternatives of investment measures that had been evaluated so far. The model was used to simulate these decisions, i.e. with fixed 0-1 variables for the major decisions. Using the model in a "free" mode, letting all decision variables open, showed that the optimization could give a better solution than derived without a formalized model. Additional sensitivity analyses were then performed on some technical issues:

A free optimum solution,
B simple hot water boilers are not allowed to enter the solution,
C existing steam turbines fall out of operation earlier and
D no gas-turbines in the southern site.

Table 1 shows the expenditures and incomes related to these variants. All figures are based on the total discounted costs (scrap values were not subtracted) and expressed as % of overall expenditure (investments, fuel cost, operating and maintenance cost, personnel cost, excluding the income from electricity and district heat sales). The last column shows the discounted income generated over the optimization horizon of 17 years as a percentage of overall cost.

Table 1: St. Pölten: Expenditure and income as % of total

	Inv.	Fuel	O&M	Pers.	Elec.	DH	Income
	Discounted expenditures (income) as % of total						
A	21.74	37.71	25.79	14.76	-22.47	-80.50	(2.98)
B	24.68	37.43	24.03	13.86	-26.88	-75.58	(2.46)
C	25.47	37.27	23.75	13.52	-26.76	-73.74	(0.49)
D	20.18	37.49	26.93	15.40	-18.35	-83.96	(2.32)

In Figure 5 the discounted income is compared to the overall discounted system cost, both in relation to the highest value. The highest discounted income can clearly be generated with variant A, which has the least constraints. Variant D, with no gas turbines allowed in the south, has the lowest overall expenditures of these variants. In case the existing turbines go out of operation earlier than planned (variant C), expenditures are highest and the lowest income is generated (less than 20% of the income in variant A). In this case some investments would have to be done earlier, with considerable negative effect on profitability.

2.4 Long-term policy issues

The Environmentally Compatible Energy Strategies Project (ECS) at IIASA has, together with the World Energy Council (WEC), developed a set of long-term scenarios to

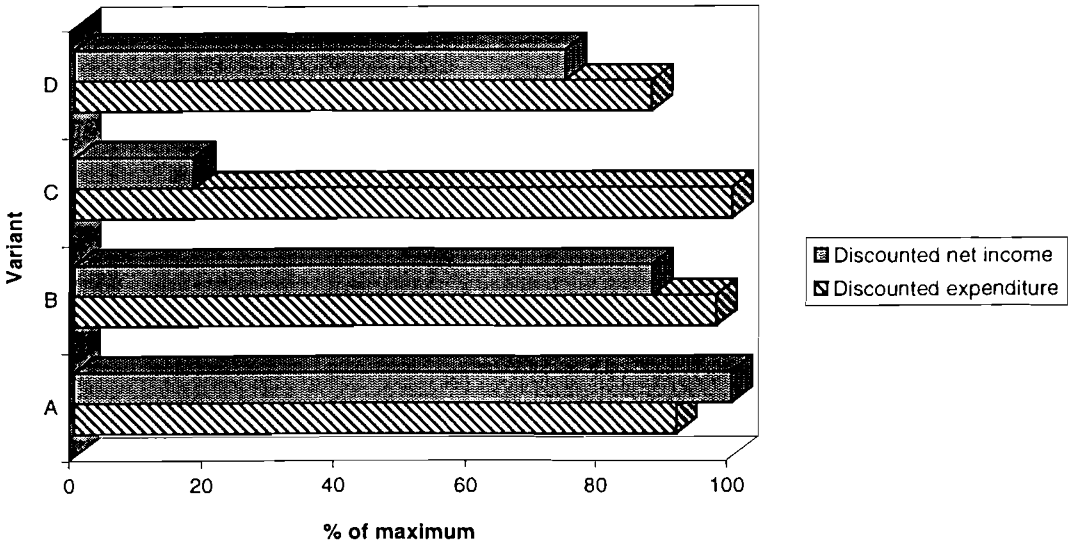

Figure 5: St. Pölten: Cost and income relative to maximum

investigate the energy implications of global economic development and its environmental impacts, including the issue of global warming [55]. In comparison with the previous examples, this effort is a more scientific one, with no direct interaction with potential decision makers in the modeling process. Rather, the results of the study and the model outcomes are targeted to give decision makers from various fields, like industry, policy and R&D, background information on long-term energy and environmental issues.

The modeling approach used is similar to long-term planning of utilities. The dynamic optimization model MESSAGE III [50] is applied to eleven exhaustive world regions. The regional models are interlinked by international energy trade of all major energy commodities. Overall model size is in the order of 35,000 variables and 50,000 constraints, optimization is performed with HOPDM [56] in approximately 1 hour CPU-time on a SUN Sparcstation 1000 with 2 CPUs. Background research required for the model analyses included the energy resource base available, the future technological options and the dynamics of technological parameters over time.

Three conceptually different types of scenarios were developed, covering (A) high-growth, (B) middle-course and (C) ecologically-driven types of expectations concerning the future economy and energy system.

For this comprehensive effort, additional modeling tools were required. The two major additional components of the model set applied are the Scenario Generator (SG [57]), a framework to evaluate the future development of the economy and energy requirements on the basis of historical time series. It applies an approach of path-dependence, where economic development can be achieved on different development paths (e.g., American versus Japanese type of development model). The third model applied is the macroeconomic model 11R [58], which is based on the well-known Global 2100 model [8]. It is used to investigate the economy-wide consequences of the energy development scenarios.

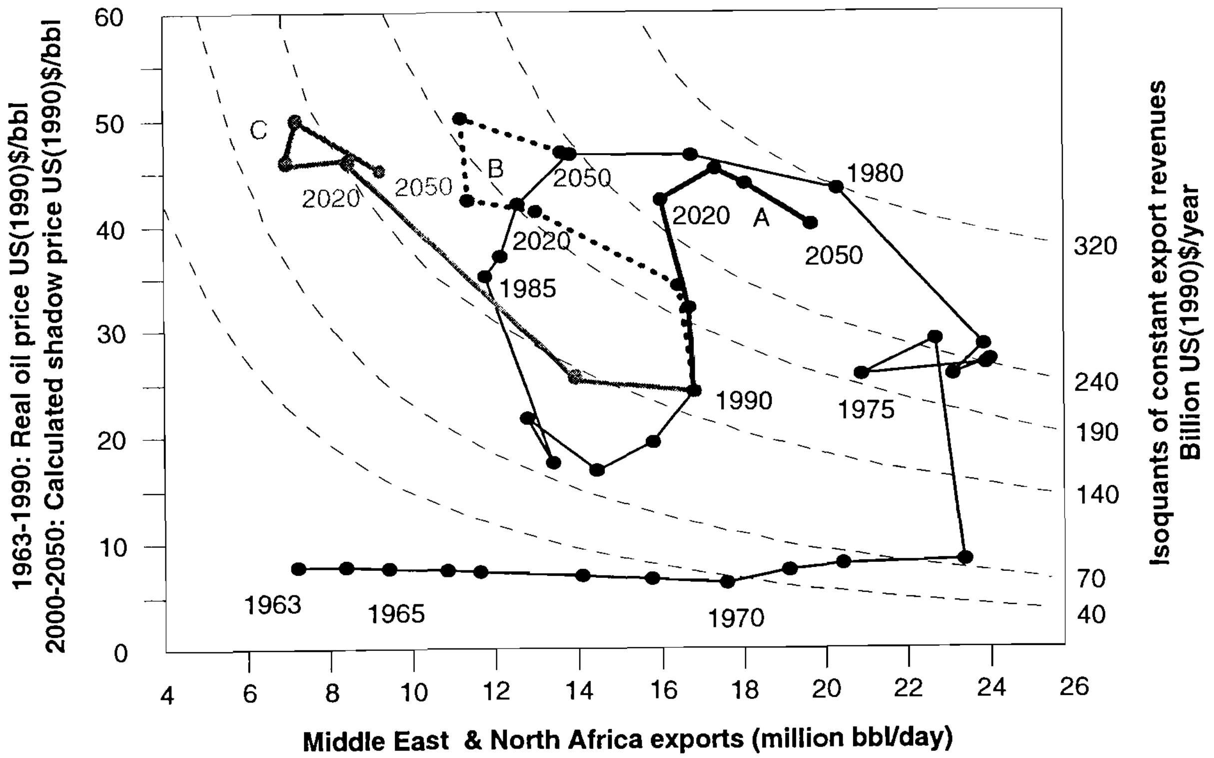

Figure 6: Oil export quantities and revenues of Middle East & North Africa, 1963 to 1990 and scenarios to 2050

For the longer-term focus of the study, which is up to 2100, the issue of global warming is of importance. Here, the model provides information on annual and cumulative CO_2 emissions for all scenarios. Using the carbon cycle and climate model developed by Wigley et al. [59], these carbon emissions are translated into the corresponding atmospheric concentrations of CO_2 and potential temperature changes.

The information provided by the IIASA-WEC analysis is focussed on the needs of decision makers: it gives an overview of features of the future energy system common to all scenarios and demonstrates how differences in short-term economic and technology policies translate into long-term divergences of energy systems structure; it investigates the investment requirements over the coming 25 years, especially in the developing world; and it analyses the resource requirements in terms of fossil and non-fossil sources of energy. Specific industry issues are addressed in special sections of the full report.

Figure 6 gives a sample study result: an overview of the oil export quantities and related income for Middle East and North African countries in the scenarios, including historical data starting in 1963. The figure clearly shows, that export quantities of 240 Billion US$(90) per annum as reached in the early seventies are not achieved easily again. Since also prices are not considerably higher than the US$(90) 44 per barrel achieved in 1980, annual revenues through 2050 will remain below the 1980 level of US$(90) 320 billion. On the other hand, the 1990 income level of US$(90) 140 billion seems to be a lower bound for potential future revenues from oil exports of the region.

The study outcomes were presented at the 16th congress of the World Energy Council in Tokyo in October 1995, a conference with a very large audience, mainly from industry and policy. Results are also published in a number of supporting papers [55, 60, 61].

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