Energy Models: Methods and Trends

1 Introduction

Energy environmental and economical systems do not allow for experimentation since this would be dangerous, too expensive or even impossible. Instead, mathematical models are applied for energy planning. Experimenting is replaced by varying the structure and some parameters of 'energy models', computing the values of dependent parameters, comparing variations, and interpreting their outcomings.

Energy models are as old as computers. In this article the major new developments in energy modeling will be pointed out. We distinguish between 3 reasons of new developments: progress in computer technology, methodological progress and novel tasks of energy system analysis and planning.

2 Classes of Energy Models

Even though a taxonomy of energy models can be by no means complete, the description of some of the most frequently applied types of models will be given: Process Engineering (PE) Models, Computable General Equilibrium (CGE) Models, Macroeconomic Growth (MG) Models and Aggregate Optimization (AO) Models which are coupled PE and MG models.

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Process Engineering Models

MARKAL [3], EFOM [17] MESSAGE [11] and LEAP were the most frequently used process engineering models for energy policy analysis of the eighties and beginning nineties. The following description of MESSAGE by Messner and Strubegger [11] can serve as a general description of the basic characteristics of process engineering models:

In first approximation MESSAGE could be labeled a physical flow model. Given a vector of demands for specified goods or services, it assures sufficient supply, utilizing the technologies and resources considered. In its usual application the model is used to evaluate energy systems, but any other problem dealing with commodity flows, where specified demands are to be met by a given set of supply options could be modeled.

The backbone of MESSAGE is the technical description of the modeled system. This includes the definition of the categories of energy forms (commodities) considered and actually used, as well as the definition of the energy services to be provided. The technologies are defined by their inputs and outputs, the efficiency and the degree of variability among complementary inputs or outputs.

By all these definitions of energy carriers and technologies a so-called energy chain is structured, where the energy flows from supply to the demand side. The supplying energy carriers have to be specified in light of the actual problem. Limits on the amounts available inside the region/area and import possibilities have to be considered. Together with the demand, that is exogenous to the model, the technical system provides the basic set of constraints: The demand has to be met by the energy flowing from domestic resources and imports through the modeled energy chain.

Process engineering models are mainly used for policy evaluation or strategic issues from a governmental perspective. Examples are the evaluation of cost efficient emission reduction strategies on a regional or national level but also for power plant and refinery operation planning and for long term capacity planning. They are either simulation or optimization models.

Process engineering models are dynamic, i.e. they calculate several periods which are connected by storage of resources, intermediate commodities and production capacities. Models applied for capacity planning or emission reduction do not only account for commodity flows but also for existing capacities and minimize the total system cost including construction of additional units and operations. Process engineering models are also denoted as “bottom-up” models.
Computable General Equilibrium (CGE) Models

The theory of general equilibrium assumes that there is a multitude of suppliers and demanders for energy, non-energy commodities and primary factors of production which act individually on markets. It assumes that the market shares of all actors are small enough so that nobody can influence the market prices. Commodity prices result only of the optimizational behavior of the actors and of their technological and social restrictions. The following description of CGE models is given by Kydes et al.[6]:

General equilibrium models use underlying behavioral relationships derived from utility maximization by households and cost minimization by firms to explicitly incorporate links between the energy sector and the rest of the economy. These links arise because energy demand is derived from the demand for other goods and services and energy supply in turn requires inputs of capital, labor, and intermediate goods. Explicitly incorporating them provides information about how relative product and factor prices, and the intertemporal allocation of resources, are influenced by policy measures or technological change.

Typical CGE market participants include producers and other commercial firms, households, the government, and a rest-of-the-world sector. Production is divided into distinct commodity groups, a subset of which includes various primary and secondary energy sources. Such disaggregation by commodity type permits price-induced substitution away from energy-intensive products in response to policy changes. Total demand for each sector's output consists of intermediate demands by other firms and final demands by households, government, and foreign importers. Firms choose their inputs of primary factors (labor and capital), demand for intermediate goods, and level of investment by minimizing costs due to their technological options. This minimizing of input requirements is accompanied by a maximizing of the outputs of the producing sectors. Same is true for the household sector where the consumer behavior is directed by a maximization of the quality of services and the relative prices of goods and services. This profit and stability maximization determines the time-path of consumption spending, savings, and labor supply. The government collects taxes, distributes transfers, and purchases goods and services.

There is a single stock of capital that is allocated among all sectors, and the supply of capital available in each period is the result of past investments as represented by an accumulation equation. Output and factor prices vary so that activity levels satisfy equilibrium conditions governing the model's behavioral relationships:

(a) prices adjust so that the demand for each industry output equals its supply;

(b) wages adjust so that the demand for labor by producing sector equals the labor supply of households;
(c) interest rates adjust so that total demand for capital by firms equals the supply of capital;

(d) government final demands are determined by the income-expenditure identity for the public sector;

The mapping of the energy supply system in CGE models is less detailed.

CGE models permit the simulation of price-induced substitution away from or towards energy-intensive products in response to policy changes. Starting with a benchmark, the effects of exogenous actions, e.g. the implementation of carbon taxes can be examined. Such actions cause variations of the benchmark price relations and induce adaptation processes to achieve a new equilibrium. According to Böhringer [1], the main questions being examined by applying CGE models are:

- What are the main properties of cost efficient and fair greenhouse gas reduction strategies?
- What is the impact of environmental taxes on the whole economy?
- How is the competitiveness of a national economy affected by national energy and environmental taxes?
- What are the national and international consequences of electricity market deregulation measures?

**Macroeconomic Growth Models**

Manne’s MACRO [7], which shall serve as an example for MG models, has been designed for energy policy analysis. The following description of MACRO is by Kydes et al. [6]:

<MACRO represents aggregate output> of the non-energy sectors <by a nested, nonlinear production function that employs the primary factors capital and labor together with electricity and non-electricity energy as inputs. The allocation of output between final consumption, investment, and energy expenditures is determined by maximizing the discounted utility of consumption, with optional constraints on regional or global CO2 emissions. This optimization problem is dynamic due to resource depletion and the accumulation of capital stock. So a lower rate of current investment reduces the amount of output available for future consumption. The aggregate production function in the MACRO-model calculates the demand for electric and non-electric energy as a function of annual GDP growth, exogenous own- and cross-price elasticities, and relative factor price changes. Given this demand for energy products, a conventional linear programming analysis equating factor shadow prices to long-run costs is applied to determine detailed least-cost supply patterns.>
In energy system analysis and planning, MG models are rarely applied solitary. Mostly they are linked to PE models of the energy supply sectors. Such combined models are denoted Aggregate Optimization Models.

**Aggregate Optimization Models**

MARKAL-MACRO by Manne and Wene[9] is an example of an Aggregate Optimization (AO) Model. Demands for electric and non-electric energy are endogenously determined by the activity of the non-energy sectors and by price induced and autonomous conservation in the energy supply sectors. The MG model of the non-energy sectors and the PE model of the energy sectors are linked by flows of electric and non-electric energy from MARKAL into MACRO and energy cost payments from MACRO into MARKAL. Energy supply costs enter into MACRO through the period-by-period constraints governing the allocation of aggregate output between consumption, investment, and energy cost payments. While the objective of a stand-alone MARKAL model is to minimize the overall energy supply costs, MARKAL-MACRO maximizes the discounted utility of energy consumption over time.

In the seventies and eighties, AO models have been applied to examine the interrelations between the energy supply system and the other sectors [7]. Recently they have been used to estimate the consequences of international mandates to limit CO2 emissions and to calculate the carbon tax required to reach specified reduction targets [8].

**3 Progress in Computer Technology**

The tremendous progress in computer hardware technology and recent software developments open up a new dimension of energy planning.

While in the past energy models were designed on a stand-alone basis, where for each program a specific data-input format was required, modern energy models have direct access to database systems. Standardized formats allow access of databases from different models and for different purposes. The relational database system, the most widespread one in the energy field, is capable and suitable of taking over a large part of the functionality which was formerly provided by the models. The energy models on the other hand can concentrate on sophisticated mathematical algorithms. New model-design tools assist the analyst to develop the topology of his system model in a user-friendly environment. The GAMS-system is an example of such a development. Recently GAMS-versions of the EFOM and Markal models were developed. The handling of energy models, which some years ago required in-depth knowledge of the operating system is being replaced by comfortable graphically oriented user guides.

The development of PC-networks and possibilities of international data and model exchange provoked the development of energy information systems. In the German
IKARUS project for example, data, models and results can be communicated all over Germany. Another example is the Environmental Manual, a World Bank/GTZ/Öko-Institute development, is freely available on the Internet. Teams of energy modelers, which are working jointly on one task may exchange their formulation of text elements in the final report through the Internet (as has been the case in writing this paper).

Data intensive programs which use sophisticated optimization algorithms were not subject to numerical solving a decade ago. Modern computer technology makes it possible to concentrate on the issue to be solved rather than being idle with waiting for the optimization results. Parallel and distributed computing might even allow an almost dimensionless modeling detail, although these developments are still in the infants stage today.

Generally spoken the progress in computer hardware and software make the energy planners life easier, allows him to concentrate on the planning task and gives way to answer to new demanding and more sophisticated questions.

4 Methodological Progress

Recently, some ideas, methods and algorithms developed in other areas of science and research were successfully adopted by energy planning: Stochastic Programming and Fuzzy Linear Programming are applied to incorporate uncertainties into energy models and neural networks are used for the estimation of short-term electricity demand. Another issue worth mentioning is the synthesis of CGE and PE models in order to overcome the disadvantages of both modeling approaches [1].

Incorporation of Uncertainties into Energy Models

Uncertainty is the basic problem of every planning. Canz [2] distincts 3 kinds of uncertainties:

1. Parameter uncertainties adress the fact that the values of some exogenously defined parameters cannot be specified exactly. An example from energy system planning is an assumed future price of a fuel type.

2. Data uncertainties are introduced by aggregating information, by incorrect statistics etc.. Some examples from energy system planning are the aggregation of individual power plants to generic types and all related data such as efficiency or specific costs.

3. Decision uncertainties reflect the fact that the decision-making process cannot be captured in mathematical models. For example, it does not make sense, that the acceptance of a solution changes from being entirely feasible to being completely infeasible within very small ranges.
A special effect which is caused by parameter and data uncertainties in linear programming PE models is called \( \text{\texttt{\textregistered}} \)-penny-switching', i.e., the sensitivity of computation results to the coefficients of the objective function. LP models tend to favor extreme solutions instead of mixing various strategies.

Applying a scenario approach to overcome the problem of uncertainty is rather labor intensive and requires vast modeling experience. Moreover, it can result in a large number of model runs or in model outcomes that are not robust with respect to small changes in the model parameters.

A major drawback of conventional PE models is the use of point estimates for uncertain input parameters. Stochastic Linear Programming PE models [4] overcome this kind of problem by explicitly introducing distribution functions for technology parameters and for the expert's opinions of future costs. While this approach only allows for addressing data and parameter uncertainties, fuzzy linear programming offers the opportunity to explicitly incorporate all three types of uncertainty in a mathematical model [2].

**Estimation of Short-Term Electricity Demand with Neural Networks**

Neural networks are applied to generate short term prognoses of electricity demand [19]. Using meteorological information together with type-of-day characteristics as inputs and electricity demand as an output, the network is adapted to typical situations of the past in a learning phase. Thereafter, it is able to calculate a demand value according to the present meteorological situation and other input data.

**Synthesis of CGE and PE Modeling**

Despite its strengths in consistent energy policy evaluation the 'top-down' CGE approach is often criticized because of its lack of detailed technological information regarding the energy system.

Within CGE models the production of different energy sectors is typically described at an aggregated level by means of neoclassical production functions which capture transformation possibilities through elasticities. Reliable estimates for these parameters are crucial for the empirical evaluation of the quantitative effects induced by alternative energy policy strategies. Unfortunately, empirical estimates on elasticities are rare and differ quite a lot with respect to the underlying assumptions. Moreover, most CGE models employ simple functional forms such as separable nested CES functions which restrict the numerical scope to which empirical estimates of elasticities can be incorporated. The rudimentary representation of the energy system is the reason for the skepticism of many energy system analysts who rather sacrifice the overall economic perspective for the richness of technological detail. They favor \( \text{\texttt{\textregistered}} \)-bottom-up' process engineering models which provide a precise technological description of the energy system while neglecting the interactions with the rest of the economy. In the PE framework a large number of technologies capture the impacts...
of exogenous energy policy constraints on the energy system such as substitution of energy carriers, process substitution, process improvements (gross efficiency improvement, emission reduction) or energy savings. Yet, if economy-wide feedback is important, the PE approach is obviously inappropriate.

It is often overlooked that the differences between both approaches are less of a theoretical nature but simply relate to the level of aggregation and the scope of ceteris paribus assumptions. As pointed out in previous methodological papers ([10], [18]) general economic theory provides a unifying concept for both approaches. CGE modeling can incorporate both - PE and top-down neoclassical production functions - within a uniform mathematical format: It can be shown that the approach of formulating and solving a general equilibrium problem as a complementary problem (CP) accommodates the hybrid description of production possibilities in energy policy modeling: To enhance the credibility of the analysis, those energy sectors whose technological options are of major importance for the policy issue can be represented through PE. To restrict data requirements as well as the dimensionality of a complex-world model, the technological options of the remaining production sectors can be described by means of continuous neoclassical production functions. Given the recent availability of commercial software for model formulation and solution in the complementarity format [15] the computer-based implementation of the PE/CGE synthesis is straightforward.

5 Novel Tasks

Impressive advances in computing capability coupled with new modeling methodologies allow the (numerical) solving of complex problems in all fields of research, not only in energy modeling. Over time new fields of research have been developed which, even when assuming the availability of necessary computing power and methods, would not have been considered relevant only a few years ago. An almost 'classical' example for a novel task is the issue of climate change which is 'on the agenda' for only a relatively short time. In this section some of the novel tasks in energy modeling are mentioned which in future are likely to constitute major challenges for energy modeling.

Task I: Model Integration

Integration of models can be seen from all three perspectives considered in this paper (advances in computing power and methodology as well as integration as result of new tasks to be solved). In principle, models can be integrated by several dimensions:
Figure 1: Model Integration

1. History shows that there is a need for greater integration of individual sectoral 'stand-alone' models in a more general modeling framework. In a first step, this type of integration primarily facilitates the technical aspects of model running, e.g. automatic data exchange between the models involved and, more elegantly, the definition of a common data base (format) which can be accessed by all individual models. This kind of integration assures a consistent definition of variables used. As a result of this type of integration, issues considered can be modeled on a more general level by looking at a problem from a wider perspective. This kind of integration would be the combination of individual energy sub-sector models which, previously, were used independently. For example, in the transformation system of an energy system, power generation models and refinery models could be integrated to model the transformation system of an energy system more comprehensively. This type of model integration could be defined as horizontal integration.

2. Also there is need for better integration of sectoral and general economic models in an energy/environment modeling context. This kind of approach is, in principle, already covered by conventional CGE models. A problem with this approach is the treatment of exogenous technical progress which needs improvement. A feature of this model type is their top-down perspective since they are dealing with highly aggregated variables even though the economy is disaggregated into subsectors. For this model type, more vertical integration needs to be achieved.

3. A third dimension of model integration is that of process engineering approaches and (macro) economic models (Wene, 1996). A sloppy description for this kind of
integration would be the integration of top-down-approaches and bottom-up-approaches. In energy modeling, bridging of the trade-off between macroeconomic energy-economy interactions and the energy sector detail of bottom-up-models continues to be a principal challenge for long term energy/environment modeling. A first step in this direction is the so-called 'soft linking' of models. In this case results from one model are fed into another model. Optima can be calculated by iterative running of both models. This type of integration could be called cross-integration.

Task II: Long Term Modeling

To a larger extent energy models will be asked to respond to hypothetical questions covering longer time periods involving technologies known but not yet adopted. Long term modeling has become relevant with the issue of meeting global environmental problems.

- Environmental Policy

In order to analyze ways of reducing global warming, energy modeling will have to play a more prominent role in future. 'Old' definitions of short, medium and long term perspectives must be seen in context: in environment modeling, a planning/projection horizon of, let's say, twenty years is absolutely short term while for other energy models, (for example power plant dispatching,) it is definitely too long a perspective. In general it is technically easy to extend the projection horizon of a model. The problem that arises is that, for example in the case of an econometric model, the model results become statistically very weak because they are based on only relatively few observations compared with the length of the projection period.

Given the change of relative prices, for example upon introduction of environmental taxes, there is a need for models analyzing the possibilities of new, less polluting (i.e. energy saving) technologies. Endogenisation of technological change in both, production and consumption, will have to play an increasing role in future environmental modeling. [12]

- Solving Environmental Problems 1: Joint Implementation (JI)

Environmental issues and energy related problems are many and of diverse nature. They can be local, such as oil spills, or regional and transboundary, such as the impact of SO2 emissions. Environmental issues can also be of global nature, such as greenhouse gas (GHG) emissions which are suspected to contribute to long term climatic changes. Therefore, the control of gases with global warming potential should be implemented globally and in a cost-effective way. Benefits of JI can be financial, technological, social and political. Modeling these effects of JI on industrialised and developing countries constitutes a major challenge for the future.
Assessment of technologies must not only be made at their point of use' but their energetic (and environmental) impacts have to be seen from a holistic' perspective. A generalisation of the classical life cycle analysis in the sense of full life cycle analysis, i.e. incorporation of the full length of energy chain of technologies/processes remains a challenge. In an environmental context, life cycle analysis also can be applied to greenhouse gases: the global warming potential of all gases with climate change potential has to be taken into account over their full cycle length in order to be able to formulate effective mitigation policies.

Task III: Externalities / Optimal taxation of energy use and environmental damage

Energy pricing often constitutes an important barrier to change. Externalities of energy use (typically negative ones) are rarely taken into account. Charging the full costs of different technologies should include not only economic but also social and environmental components: land use, noise, pollution, climate impact, risks and effects of large accidents, visual impacts, degree of supply security and safety.

Today, in many studies the environmental consequences of changes in economic activity are the principal focus of analysis. However, many forms of environmental regulation also affect other sectors. Consequently, there is a tendency to under-estimate total environmental benefits since these positive externalities are typically not accounted for. Introduction of a CO₂ tax, for example, will in general result in a reduction of CO₂ emissions. This reduction is likely also to reduce other environmental problems (e.g. the production of waste). Future perspectives for economic energy and environmental modeling will therefore require the use of cost-benefit-techniques in order to identify more comprehensively social benefits and costs associated with economic activity and/or policy. By internalising these social costs and benefits into prices, and therefore models, social optima can be calculated.

One way of incorporating externalities is to tax the economic activities causing them. The design of an optimal taxation policy is of great importance also because of its welfare implications. The conventional reaction of increased taxation on energy use is substitution away from energy to other factors of production. Modeling impacts of energy taxes has become a field of research in the early nineties. The OECD GREEN [13] model can be considered the model that induced substantial research on the question of how energy taxes could contribute to a reduction of GHG emission, particularly CO₂ emissions from burning of fossil fuels.

In the case of CO₂ emissions reduction, there are three principal paths available: apart from measures to increase (technical) efficiency of energy use and demand side approaches to restrain energy use, a transition to renewable energies is the third chief instrument to achieve a CO₂ emissions reduction. An energy taxation policy therefore has to assess all three routes that could result in the goals to be achieved.
**Task IV: Optimal tariffs and prices**

Though delivering the bases for setting of optimal tariffs is an old task of energy planning, more and more frame conditions have to be considered. Not only the cost truth is required of setting tariffs in relation to the actual cost of supply, but also social and macro economic concerns have to be considered. Energy pricing is also a major instrument for boosting the economy, raising the competitiveness of the industry and for inducing energy savings. This leads to an unpredecessing complexity of the task to set optimal tariffs and energy prices.

**Task V: Communal Energy Planning**

A further step would be to examine the consequences of a more normative use of economic policy instruments developed to reduce not only energy consumption but also materials use and thereby to reduce environmental pollution and the use of natural resources in a more general sense. In order to achieve this goal, attempts will have to be made to relate economic and taxation policies to technology change and through technological change to changes in factor inputs.

Modeling a policy integration will be needed. The next step of integration solve issues of modelling cogeneration and district heating; renewable energies; education and training; transport; water. Special emphais have to be laid on:

- changing lifestyles
- advances in telecommunication and
- urban structure (urban density, decentralisation of employment and commercial activities) [14]

**Task VI: Integrated Resource Planning (IRP)**

Integrated resource planning started from so-called Demand Side Management (DSM) which in the United States has become a veritable industry after the 'energy crisis':

- Isolated optimization of demand side: DSM
- Isolated optimization of supply side: SSM
- Joint optimization of DS and SS: LCP/IRP  (DSM+SSM=LCP/IRP)
Figure 2: The Energy System in Integrated Resource Planning

So far, IRP is applied only to electricity applications. As a next degree of generalisation, the idea of IRP could be applied to all energy services. This would result in an optimization of not only the 'electricity-type' of energy services but lead to an optimization of all energy services which are, principally, fuel-independent. This fuel-independence could be called Energy Service Management (ESM) - in analogy to DSM/SSM. Under such a regime, utilities' role would change from the energy producer to the energy service provider. More comprehensive analytical tools, i.e. models, will be highly necessary in future.

Task VII: Optimisation of power plant operation on a daily, weekly and yearly basis and optimisation of power expansion planning

Here the main task is the harmonisation of the different models optimised for modelling the different aspects of power supply planning each. The output of one model serves as input for next model. 'Cascading' of models as one form of model integration.

The critical question is how best to model dynamics. Implicit in this question is how to best model expectations and how to reflect the effect of different vintages of capital given the limitations of existing capital measures.
6 Conclusions

- Computer technology is improving, but the knowledge and experience of the expert is still most important in rational energy planning.
- The methodological progress is not yet operational, but the implementation is necessary to solve tomorrow's problems.
- Novel tasks require system analytical approaches on an international and interdisciplinary level.

7 References


