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ENERGY PLANNING METHODOLOGIES AND TOOLS

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Keywords: Energy policy, models, planning tools, scenarios, optimization, simulation, uncertainty, reserves and resources.

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Summary

As with any tool, it is useful to look ahead before choosing an energy planning tool. Also, there will usually be choice between different tools that all might, at least in principle, serve the energy planning task to be addressed with the tool. To facilitate efficient selection of a tool, it is important to specify not only the overall purpose of using the tool, but also to formulate specific questions. Here it is argued that one criterion for the selection of a tool should be the simplest and gives relevant answers to the questions raised. In many situations of energy planning, uncertainty is an important aspect. Although stochastic models address uncertainty by design, it should be remembered that for this type of models to be really useful, the probability distributions built into the model should be known, at least within reasonable limits. If they are not, the uncertainty is just shifted from the model parameters to the parameters of a class of probability distributions. Care must also be taken when assessing model validity. The so-called "back-casting" (running the model for the past to check whether it correctly produces actually observed values) fails to produce much evidence if it is possible to specify model parameters with the benefit of hindsight. One strategy to stay clear of the pitfalls of modeling would be to attempt to learn from a model in a way that the lessons learned would be explainable without explaining the model.

1. Introduction

Rapid progress made in the field of electronic data processing has led to a boom of computerized tools in the field of energy planning as much as in any other areas of systematic analysis. Not only the quantity but also the quality of energy planning tools has increased markedly in the course of past years. This progress has already come to the point where the capabilities of modern computers have pushed the limits of data handling capacities and computability into domains that challenge the intellectual capacities of the interpreting human mind. Moreover, the ease and speed with which today's hardware and software solve complex problems make it easy for users to forget that the original purpose of modeling was the analysis of simplified abstract images of the real world.

It seems worth remembering then that the thrust of computer modeling ought to point towards simplification, and the model choice ought to be the simplest to serve the given purpose. But which is the given purpose? This is the question that ought to be answered as precisely as possible before any energy planning tool is applied. Ideally, the purpose of modeling should be defined in terms of a set of concrete questions that are to be answered by model results. This normative statement alludes to the common-sense observation that a well-formulated question is already half of its answer, which means that modeling is an art in addition to being a science, at least to the extent that the better the questions the better the expected model results. Trivial as this may sound, the analyses of actual modeling suggest that it seems to have been notoriously difficult for energy analyses to follow such simple advice.

This chapter will therefore take the description of energy planning issues and tasks in *Some Issues in Energy Policy and Planning* of this encyclopedia as a point of departure and attempt to describe tools that appear adequate for their systematic treatment.

2. The Framework

These introductory strategic remarks apply to a wide range of computer models. The models and tools described in this section refer only to energy planning models, however. These models form a subset of all computer models, and it is characterized by very specific features. One of the most important of them is uncertainty surrounding the subject matter, which enters through many doors. Given the premise of *Some Issues in Energy Policy and Planning* – that energy planning is primarily concerned with externalities, most of which belong to the group of environmental impacts – the uncertainty surrounding the size of any given impact can be substantial. As one of the most prominent examples, the size of the impact of climate change is highly uncertain – and is the subject of continued discussion and even controversy. The problem of uncertainty is compounded by the incommensurability of many environmental impacts with other economic variables, most notably costs. Many attempts have been made to quantify the value of human health and an intact environment, but there are no universally accepted values. The problem cannot be ignored, however, because doing so runs the risk of implicitly attaching extreme values to damages in these areas. A zero value would obviously be wrong, but also the other extreme of implicitly attaching an infinite value to such damages is risky because it readily leads to contradictions between normative and actually observed behavior.

An important stratagem devised to deal with uncertain risks is the so-called precautionary principle, according to which decision making should not rely on an "infinitely forgiving mother nature", but rather proceed cautiously, trying to keep the environmental impact of policy measures within limits so as to cater for some outcomes to turn out on the unfavorable side. Elegant and reasonable as this principle may sound, the problem with it is that it is not readily quantifiable, and we are back to the basic requirements of energy planning tools, i. e., that they must account for uncertainty. And if it is not the tools themselves, then the way of their application must come to rescue. The common way to address uncertainty with deterministic models is via the use of scenarios. A scenario is a possible development of the system modeled. The main feature of a scenario is that it is a complete and consistent description of a given system. In a scenario, a subsystem cannot be changed in isolation without proper regard of the repercussions of such a change in the entire system.

Important functions of scenarios are that they are suited to study the consequences of given decisions in a predefined and reproducible way. A collection of different scenarios allows for the analysis of the robustness of decisions. If scenarios reflect different "states of the world", i. e., different uncontrollable developments, a decision is robust if its consequences are acceptable under a wide range of assumed developments, i. e., in a large fraction, if not all, of the scenarios considered.

In cases where scenario projections take the place of forecasts (in most cases of applying energy planning models, the term "forecast" has been eliminated as being potentially misleading by implying a truth value that is not actually warranted), scenarios are often required to be plausible.

Such scenarios are also referred to as descriptive. This term is intended to distinguish them from normative – or prescriptive – scenarios. There are several possible reasons for wanting to construct normative scenarios that are not necessarily plausible. One example is to describe limiting cases of developments to define a range of possible outcomes. A given policy would then attempt to address all eventualities of this range including the extremes. Another possible purpose of a normative scenario is to describe an example of a sufficient condition for the achievement of a given goal, for example a stabilized global climate or sustainable development.

To the extent that scenarios address uncertainties, the question arises whether stochastic models, i. e., models that work with parameters and variables that are distributed according to probability functions, can serve the same purpose more efficiently. One answer to this complex question is that stochastic modeling is particularly useful in those cases where the probability distributions are known well enough. If they are not, a full analysis of a stochastic model would have to include a sensitivity analysis testing the consequences of using different probability density functions for one and the same model variable. In the face of the infinitely dimensional space of such functions, this seems like a rather arduous – not to say infeasible – task.

3. Classification of Energy Planning Tools

Energy planning tools can be classified according to many criteria, one of which – descriptive vs. prescriptive we have just presented in Section 2. In particular in the area of models setting out to calculate the costs of climate mitigation strategies, the distinction between "bottom-up" and "top-down" models has become a subject of intense debate of the question whether there is such a thing as an emission reduction potential at zero costs. Before summarizing this discussion, let us briefly characterize these two model types.

Bottom-up models, sometimes also referred to as "engineering-type" models, typically include the description of given energy-related tasks (rather than energy demands), which are to be accomplished at minimum costs by a given menu of technologies. In contrast, typical top-down models do not consider energy-related tasks but energy demand in the form of functions that typically depend, among others, on total or sectoral economic product and on energy prices.

The question about the costs of climate mitigation arises because bottom-up models very often find a portion of emission reduction that can be achieved at negative "costs" (the so-called "free lunch" situation). This kind of result arises whenever it can be shown that a better (i. e., less emitting) way than the one actually chosen for performing a given energy-consuming task existed. In contrast to such bottom-up models, the results of typical top-down models suggest that even the slightest amount of mitigation costs something ("There ain't no free lunch."). To make the discrepancy even more pronounced, top-down models usually project demand to increase in response to innovative energy supply options that make energy conversion cheaper. Although this discrepancy between model results of these different kinds puzzled many, it can be largely resolved by two observations.

The first observation concerns the definition of a "free lunch". In top-down models, any emission reduction that comes at negative "costs" is not an emission reduction because it is simply included in the "base line". By the same definition, genuine emission reduction is a measure that incurs extra costs. The second observation has roots in the introductory remarks made on energy planning tools, in particular those that concern the issue of a question to be answered by energy models. In our illustrative example, top-down models ask: *By how much does a given energy price movement change energy demand or energy-related carbon emissions?* In contrast, bottom-up models ask: *How can a given emission reduction task be accomplished at minimum costs?* There seems to be nothing in these questions that justifies the expectation of identical outcomes of the two approaches.

The complex real world does not follow either of these two paradigms literally, however, and both approaches tell some important part of the full story, and the discrepancies between the model types have led those interested in a resolution of seeming contradictions to learn from the logic and from the lessons taught by the two approaches.

Another methodological classification distinguishes between optimization and simulation models. This is not quite the same as the distinction between normative and descriptive models – the normative being similar to the optimization and the descriptive being similar to the simulation models – but it comes close. An important ingredient of optimization models is the *objective function*, i. e., a mathematical formula describing, the minimand or maximand depending on the definition..

One class of optimization models that has been very popular since its invention in the 1940s is the class of Linear Programming models. Besides their obvious limitation relative to the fact that the world is not always linear, this type of models has other specific problems, particularly with the stability of the optimal solution. Ways around these problems have been introduced over the years, but the most important progress has been made in the wake of drastically increasing computer power, which is responsible for the enormous development of the state of the art of modeling methods. Models of ever increasing size can now be solved within reasonable time with the help of more flexible tools such as non-linear and discrete-optimization methods.

A similar caveat as the one described above for stochastic models applies to optimization models. Optimization is most effective in cases where the functioning of a system and its objective function are known with sufficient precision. The notion of being able to have all energy planning tools calculate optimal decisions (and thereby rendering human decision makers redundant) is – largely as a consequence of the uncertainties involved – false.

4. Energy Planning Techniques

Following the rather general methodological classification of energy planning tools as above, this section describes energy planning techniques at increasing levels of comprehensiveness. These techniques may or may not fall completely into one of the above classes. Since in many cases the membership of a technique in one of the model classes from above depends on the specific kind of application, no cross-classification is attempted in the sequel.

The following gives an introductory overview. Readers interested in further information are referred to the literature in the field.

4.1. Basic Techniques

A basic technique of energy planning is to portray the state of a given energy system in a specific year. The common tool for this task is an *energy balance*. An energy balance follows the concept of a reference energy system (RES) as presented in Section 2 of *Some Issues in Energy Policy and Planning* by distinguishing different energy carriers and different stages of conversion between the energy levels, but does not go into the detail of singling out energy conversion technologies.

Cost-benefit analysis assesses the costs and benefits of a given option. Conceptually, this technique is rather straightforward. In the real world, its application is made difficult by the fact that costs and benefits can occur at different points in time, to different individuals, and that the units in which they can be measured are incomparable. On top of these, uncertainty can further complicate the analysis.

Cost-effectiveness analysis is a comparative assessment of the costs of different options to achieve a given task or goal. This tool is therefore useful in cases where benefits cannot be measured in the same units as the costs. A typical application of cost-effectiveness is the assessment of alternative options to save human lives. With the help of cost-effectiveness analysis, the candidate life-saving options can be ranked according to their monetary costs per life saved without having to attach a money value to individual lives.

4.2. Energy Demand Projections

The simplest form of demand projection is to express energy demand as a function of economic activity. The next level of sophistication is to additionally postulate a dependence of energy demand on energy price. The most common form of both dependencies is log-linear, that is, a change of the independent variable (GDP, price) of x percent leads to a change of energy demand (the dependent variable) by $k \times x$ percent. The factor k is called *elasticity*. For example, an income (=GDP) elasticity of 0.8 therefore expresses the assumption that every time GDP grows by one percent, energy demand grows by 0.8 percent. This does not yet account for the price effect, which is usually described by a negative price elasticity, expressing the fact that increasing prices lead to decreasing demand – assuming constant GDP. In very general terms, a third important factor determining energy demand is technological progress. In its simplest form, technological progress assumes the form of a factor that reduces energy intensity (energy demand per unit of economic output) over time.

One important point in the area of energy demand projections is the choice of sector for which energy demand is to be projected. Since different economic sectors have – in general – different energy intensities, an aggregated demand estimate (one that depends on total instead of sectoral GDP) could be misleading if the economic structure, i. e., the relative sizes of the economic sectors, change over time. In fact, the ever-increasing share of the service sector in post-industrial economies is one factor that has contributed to a decrease of overall energy intensity of total GDP in high-income countries.

Price elasticities of energy demand are the keys to assessing the likely impact of the policy instruments that affect energy prices, i. e., taxes and subsidies.

4.3. Energy Supply Modeling

The energy supply part of energy planning models concerns the availability of primary energy and of fuels. The more aggregated the geographical level of an energy-planning model, the more important is the resource part of supply. In particular in models of small open economies imports can easily substitute for indigenous resources.

In particular for long-term models, the distinction between energy reserves and resources is crucial. According to the conventional definition as depicted in the so-called McKelvey diagram, reserves are only those fractions of existing occurrences of primary-energy forms that are situated in known locations and that can be produced economically. For further classification, resources are ranked according two dimensions, likelihood of existence and extraction costs. Both dimensions usually change over time. Exclusively considering known reserves – and thus failing to include primary energy resources that will eventually be converted into reserves – in long-term energy planning models can quickly lead to projections of catastrophic situations of energy supply shortages.

4.4. Technological Forecasting

The bridge between energy demand projections and energy supply is provided by energy conversion technologies. In particular for longer-term analyses, technological progress therefore plays a decisive role in energy planning tools. In the analysis of technological progress, the experience-curve (also: learning-curve) concept is gaining increasing attention. The experience-curve concept describes technological progress as a regular function of cumulative experience. In the most common form of this concept, technological progress is expressed in terms of specific technology costs and cumulative experience is measured as total (cumulative) installed capacity of that technology. In this case, an experience curve describes a situation in which specific technology costs decrease by a fixed amount after each doubling of cumulative capacity of this technology. From an overall and long-term perspective it can therefore be advantageous to invest in energy technologies that are more expensive than the cheapest competitor because doing so will make the new "learning" technology economically advantageous and thus lead to overall cost savings in the longer run. For obvious reasons, this concept is particularly attractive to describe the potential of new and promising technologies such as fuel cells, solar photovoltaic electricity generation, and wind energy.

Described thus far, the experience-curve concept is completely deterministic. Recent energy planning studies therefore have aimed at expanding this concept to include the influence that support of research and development (R&D) or other policies can exert on accelerating technological progress over and above the mechanistic accumulation of experience and how this process can be modeled.

4.5. Energy-Economy-Environmental Models

Historically and conceptually, there is a logical path leading from "pure" energy models to models that embed the energy system in the overall economic system and, eventually connect the combined system with the natural environment. Accordingly, today's standard of energy modeling includes the so-called E3 (energy-economy-environmental) models.

In E3 models, the connection between the energy-economy system and the natural environment is conceptually obvious, but one general technique that describes the relation between the energy system and the overall economic production shall be described specifically. This technique is the *production function*, more precisely a family of functions by which (economic) output is explained by a mathematical formula that combines a number of independent variables – the production factors – in a way that gives an output quantity (i. e., the dependent variable) for each set of values of the production factors. The idea behind production functions is that the same quantity of output can be generated by more than one combination of input quantities. Dependent on the costs of each factor there is often a single optimal (cheapest) mix of production factors generating a given level of output. A change of factor costs then leads to a change of this optimal mix, and the more expensive one production factor becomes, the more it will be substituted by other.

In macroeconomic production functions built into E3 models, energy is usually one of the production factors (also, more than one energy form can be formulated as more than one production factor). The effect of increasing energy demand as a consequence of increasing efficiency of energy use – described above for top-down models – is a direct result of the responsiveness of production functions to changing costs.

4.6. Integrated-Assessment Modeling

The aspect of modeling to provide for a complete framework for the system under consideration is stressed in *Integrated Assessment Modeling (IAM)*. Recently, this model type has been featuring in particular,in modeling climate change, where IAM refers to the integration of earlier modeling of mitigation costs with newer efforts to also quantify the benefit side of the issue and to balance the two in the style of a cost-benefit analysis. These models not only aim at shedding light on the question *How much should we abate?*, but also require the model users to conceptualize the damage side in more detail, usually via a damage function. As a logical consequence of looking at damages, this means that adaptation and its cost enter the scene. For some, the idea of adapting to damage is as inappropriate as thinking about "unspilling milk", but the concept cannot be dismissed altogether.

Integrated-assessment models of climate change are normative and usually lead to the question of how to implement the solutions found by them. This leads to the following Section 4.7.

4.7. Decision Support Models/Game Theory Models

The fact that there is no global government has a consequence for the tools used to analyze global energy planning. Owing to the lack of global laws and their enforceability, normative models including control variables to steer the system into a desired direction cannot be used as effectively as in a national context. They are often replaced by gaming models, in which individual agents (players) pursue their own goals. Perhaps the best-known of the simple models in game theory is the "Prisoner's Dilemma" model, which can lead to the paradoxical "solution" that an individually "optimal" strategy leaves the players worse off than a "sub-optimal" strategy. This game thus covers the essence of the "free rider" problem, which is central to any scheme aiming at global carbon mitigation.

5. Evaluation/Assessment Criteria for Planning Tools

The most important requirement of energy models is that they must adequately map the real-world system, i. e., they must, first, include all relevant parts of the real-world system, e. g., the environmental impact of policies and measures and, second, provide for a reliable mechanism that translates inputs (energy policies) into outputs (impacts). Model plausibility can be achieved by different means. These include (economic) theory, but often, model relations are identities or formulations that simply appeal to common sense. In either case, the quality of model outputs is a function of both the model and the model inputs, a situation that has been paraphrased by the term GIGO (garbage in – garbage out), which emphasizes the importance of reasonable model inputs. Here we are again referring to the aspect of modeling that is an art, because the most skillfully crafted model can produce worthless results if crucial inputs are not available or only given within wide limits.

The burden of proof of a model's performance in this regard lies on the shoulders of the model developers. Often, model performance is demonstrated by so-called "back-casting", in which the model is applied to cases in which the outcome is known. The model must then be able to reproduce this output. Care must be taken, however, to distinguish between endogenous model variables and exogenous model parameters. Not much is proven by a back-casting exercise if the model parameters can in retrospect be chosen in such as way that they produce actual developments. If, for instance, a "price reaction function" (which uses capacity utilization at a given time to project the price during the next time step) is used to project the price of internationally traded crude oil, and if the admissible range of price reaction is restricted by model input parameters, then a back-casting exercise must carefully discuss the possibility that the *a posteriori* assumed parameters of the price reaction function are the main instrument to produce a known outcome.

As already argued above, an important assessment criterion of long-term models in particular is their ability to handle uncertainties. This means that they must either give ranges of results from the outset or they must provide for an easy handling of multiple cases, each representing one possible outcome.

A secondary requirement of energy planning tools is that they must be suited for use by the model users. This means that they must be responsive to the needs of the users. This includes user friendliness not only allowing users to run pre-set cases, but also to make changes if they want to formulate new cases on the basis of previous results.

So far, we have described criteria that appear like minimum requirements for energy planning models. Once above that minimum, what makes some models better than others? Model quality cannot be measured exactly, of course and, moreover, it depends on the intended purpose of its use. Let us therefore conclude the discussion of model assessment criteria with some general thoughts worth keeping in mind.

Following the lines of argument presented in the introduction, of two models serving the same purpose, the smaller one should generally be considered the better one.

A procedural criterion is that there should be at least a close relation – if not identity – between model builder and model user. One difficulty that can easily arise from using models prefabricated by someone else at a distance is that such models can be formulated in such a general way that the model's input data largely determine the shape of the model. This is a potential quality hazard because such a model with too few input data is not attractive and too many input data can easily entice the model user to use predefined "generic" input data instead of data that are perhaps more appropriate to use in a given application case, but difficult to find.

6. Concluding Remarks

The attention paid to modeling "soft" aspects of energy planning – such as the uncertainty surrounding model inputs and outputs – has increased over the past few years. The insufficient regard paid to uncertainty in so many earlier modeling efforts went along with the view that models could be built to map the real-world process as accurately as desired if only enough effort would be spent on the modeling process, and that models can directly calculate optimal decisions. This must be a fallacy on account of the observation that, after all, the extreme degree of realism of a computer model would be a real-time one-to-one scale model, an absurd proposition.

Meanwhile, it has become conventional wisdom that the accuracy of model results – and thereby a model's suitability to provide the user with optimal decisions – not only depends on the model detail but also on the accuracy and the availability of input data and model parameters, which often describe unknown quantities such as future costs or consumption levels. Accordingly, the role of energy models in decision-making has become that of a supporting tool that can be used for describing the consequences of alternative actions under various scenarios of future developments. Such a tool can therefore be used to assess the robustness of policy measures.

It should also be noted that accuracy of model results is not necessarily the same as model usefulness. The difference comes from the observation that insights into the relationship between policy action and systems response can also be gained in way that does not rely on a particular model. It is this ability to gain insights that makes the combination of a skillful model user with a poor model a much more promising proposition than the combination of an inexperienced model user with a sophisticated model.

The latter is perhaps only a variation of the observation that tools have their inherent limitations. We are perhaps still very far away from a situation in which computerized tools can replace human decision makers. Professional human judgment in evaluating the model results is and will remain an indispensable master of computer programs.

Glossary

E3 models:	Energy-economy-environment models.
Elasticity:	Percentage change of a dependent variable (energy demand), given a change of the independent variable (GDP, price) of 1 percent. An elasticity of energy demand with respect to income (=GDP) of 0.8 expresses says that a growth GDP by one percent is accompanied by an energy demand growth of 0.8 percent.
Experience (learning) curve:	In the most common form of this concept, technological progress is expressed in terms of specific technology costs as a regular function of cumulative experience, measured as total (cumulative) installed capacity of that technology. The regularity lies in specific technology costs decreasing by a fixed amount (the learning rate) with each doubling of cumulative capacity of this technology.
Production function:	A mathematical formula explaining (economic) output as a function of a number of independent variables, the production factors.
Reference energy system (RES):	A schematic and aggregated representation of all energy conversion technologies and the flows between them. A RES is not uniquely defined, but rather depending on the level of aggregation considered in a particular analysis.
Stochastic models:	Models that include uncertainty by replacing certainty (of parameters and functional relations) by probability distributions.

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Biographical Sketch

Leo Schrattenholzer has been affiliated with IIASA (International Institute for Applied Systems Analysis) since 1973, after graduating from the Technical University of Vienna. Presently he is Leader of ECS (Environmentally Compatible Energy Strategies) Project at IIASA.

The focus of his present work in the ECS project is in the field of energy technology assessment, including the analysis of the role of research and development in enhancing technological progress.

Dr. Schrattenholzer received his master's degree in mathematics in 1973 and his Ph.D. in energy economics in 1979, both from the Technical University of Vienna. His Ph.D. thesis was on modeling long-term energy supply strategies for Austria. From 1972 to 1974, he was a research and teaching assistant with the Institute of Mathematics I of the Technical University of Vienna. He has worked as a consultant to the Energy Sector Management Assistance Program sponsored by the World Bank and UNDP, for which he conducted a major project assessing personal computer models for energy planning in developing countries. He has also been a consultant to governmental institutions on national strategies to reduce greenhouse gas emissions. Other consultancy work has included the design and implementation of a computerized information system about space heating demand in the city of Vienna. He has represented IIASA-ECS in international teams working for three major projects co-sponsored by the European Commission and has lectured at universities and other educational centers. He is a Lead Author of the IPCC's (Intergovernmental Panel on Climate Change) Second Assessment Report. He is also the member of editorial board of the Pacific and Asian Journal of Energy (PAJE) and the International Journal of Global Energy Issues (IJGEI).

His scientific interests include the development, implementation and application of energy-economy-environment models, energy forecasting, and scenario analysis.

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