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Table of Contents

1. The Need for Classification

This paper serves as a background paper for a research project on local energy planning in developing countries (see Van Beeck, 1999). The project aims at developing a decision support method with which the selection of appropriate energy systems can be facilitated in a region experiencing rapid economic growth. The support method makes use of energy models to assist in projecting future energy demand and supply, assessing the impacts of different energy systems, and finally appraising the energy systems. Underlying question for this paper is therefore which energy models[1] are best suited for these purposes.

In recent years, the total number of available energy models has grown tremendously not in the least because of the expanding computer possibilities. As a consequence, these models vary considerably and the question arises which model is most suited for a certain purpose or situation. A classification scheme can provide insight in the differences and similarities between energy models and thus facilitates the selection of the proper energy models. Over time, numerous classifications have been made[2], but none of them can currently claim to be the best. Although this may have been possible in the early years of model development, today the vast amount of energy models developed for different purposes has clearly made any classification arbitrary. In order to still be able to select the proper models, an overview of the different ways of classification would be useful. However, such an overview is not available in any of the literature examined. Therefore, we will first give an overview of different ways of classification (see Chapter 2). This overview can also be helpful in cases where model developers themselves are looking for a convenient modeling approach. Furthermore, the overview will generally be applicable for other modeling areas related to energy, such as climate change. The choice for exactly these ways is based on the reflections regarding the research project on local energy planning described above. These reflections include:

- What are the purposes of different models, which types address demand, supply, impacts, or appraisal?
- On which assumptions are the models based and are these assumptions valid for rapidly developing regions in developing countries?
- Which type of models can represent small-scale (renewable) energy systems adequately?
- Which methodology should be used for:
  - projecting demand?
  - mapping supply options?
  - matching demand and supply?
  - assessing the impacts?
  - appraising the different options?
- Which implications does the choice for a mathematical approach have on the way of modeling?
- Which type of model addresses the local/ regional level within a country?
- Which sectors are addressed in the model?
- What is the time horizon of the models and which horizon is useful for rapidly developing regions?
- Which impacts are addressed? Can qualitative data also be included in the analysis? Can developing countries meet the data requirements of the models?

In Chapter 3 we will give examples of how existing models fit into the ways of classification described in Chapter 2, and Chapter 4 will address the question which energy models are most suited for local energy planning in developing countries, using the above reflections as guidelines. It should be noted that, although the overview presented in this paper is meant to be comprehensive, it is *not* meant to be complete and will unavoidably be arbitrary.

[1] In this paper a *model* is defined as a mathematical description –usually in the form of a computer algorithm– of a real system and the ways that phenomena occur within that system, and an *energy* model is a model with its focus on energy issues.

[2] See for instance, Vogely (1974), Meier, (1984), APDC (1985), Munasinghe (1988), Kleinpeter (1989), World Bank (1991), Grubb et. al. (1993), IIASA (1995), Kleinpeter (1995), Hourcade et. al. (1996), Environmental Manual (1999).

2. Ways of Characterizing Energy Models

There are general characteristics which are shared by all models. For instance, any model will always be a simplification of reality and includes only these aspects that the model developer regarded as important at that time. Furthermore, Grubb et. al. (1993, 432-433) mention that any model dealing with future situations unavoidably makes use of estimates and assumptions which may or may not turn out to be valid under certain circumstances, but will at the time of application inevitably be uncertain.

The problem with classifying energy models is that there are many ways of characterizing the different models, while there are only few models –if any– that fit into one distinct category. An example of a classification is given by Hourcade et. al. (1996, 283-286) who distinguish three important ways to differentiate energy models, namely regarding the *purpose* of the models, regarding their *structure*, and regarding their *external or input assumptions*. On the other hand, Grubb et. al. (1993, 432-446) use six dimensions to classify energy models, including 1) top-down vs. bottom-up, 2) time horizon, 3) sectoral coverage, 4) optimization vs. simulation techniques, 5) level of aggregation, and finally 6) geographic coverage, trade, and leakage. Other ways of classification include (among others): the applied mathematical techniques, the degree of data intensiveness, the degree of model complexity, and the model flexibility.

In this chapter, an overview is given of nine ways of classifying energy models. The nine ways are based on the reflections mentioned in Chapter 1 and are representations of the main model distinctions found in the literature (see, for instance, Vogely (1974), Meier, (1984), APDC (1985), Munasinghe (1988), Kleinpeter (1989), World Bank (1991), Grubb et. al. (1993), IIASA (1995), Kleinpeter (1995), Hourcade et. al. (1996), Environmental Manual (1999)). The nine ways include:

1. General and Specific Purposes of Energy Models
2. The Model Structure: Internal Assumptions & External Assumptions
3. The Analytical Approach: Top-Down vs. Bottom-Up
4. The Underlying Methodology
5. The Mathematical Approach
6. Geographical Coverage: Global, Regional, National, Local, or Project
7. Sectoral Coverage
8. The Time Horizon: Short, Medium, and Long Term
9. Data Requirements

In the next sections we will discuss each of these ways in more detail. It should be noted that this list of ways is not meant to be exhaustive and that the nine ways of classification are not entirely independent of each other. For example, if a model has a top-down approach, many of the assumptions will frequently be internal, while bottom-up approaches of the toolbox type leave many assumptions to be determined by the model user.

2.1 General and Specific Purposes of Energy Models

Models are usually developed to address specific questions and are therefore only suitable for the purpose they were designed for. Incorrect application of a model may result in significant misinterpretations which cannot be ascribed to poor model functioning but, as the World Bank (1991) –among others– argues, are the responsibility of the model users. For our classification, we will make a distinction between general purposes for energy modeling (forecasting, exploring, backcasting) and more specific purposes such as demand/ supply analysis, impact analysis, or appraisal.

2.1.1 General Purposes

General purposes are the purposes that reflect how the future is addressed in the model. Hourcade et. al. (1996, 283-284) identify three general purposes of energy models:

I. *To predict or forecast the future*
Because prediction is based on extrapolation of trends found in historical data, forecasting models are usually only applied for analyzing relatively short-term impacts of actions. A prerequisite for such an extrapolation is that critical underlying development parameters (e.g., elasticities) remain constant. This approach requires an endogenous representation of economic behavior and general growth patterns and is most found in short-term, econometrically driven economic models.

II. *To explore the future (scenario analysis)*
Exploring the future is done by scenario analysis, in which a limited number of "intervention" scenarios are compared with a "business as usual" reference scenario. The alternative intervention scenarios are only relevant in the context of the reference scenario and rely on assumptions rather than parameters extracted from past behavior. Generally, assumptions must be made about economic behavior, physical resource needs, technical progress, and economic or population growth. Economic behavior is usually represented or simulated either by a "least cost optimization" (utility) approach or in terms of technology adoption processes. Sensitivity analyses are crucial to provide information on the effects of changes in the assumptions. The scenario analysis approach can be used in the so-called "bottom-up" models as well as the "top-down" models[3].

III. *To look back from the future to the present ("backcasting")*
The purpose of backcasting models is to construct visions of desired futures by interviewing experts in the fields and subsequently look at what needs to be changed to accomplish such futures. This approach is often used in alternative energy studies and can also be seen as a separate methodology (see Section 2.4). However, it is possible to use this methodology as an analytical tool for assessing the long run (economic) consistency of the alternatives. This way, the "bottom-up" models can be linked with the "top-down" models.

2.1.2 Specific Purposes

More specific or concrete purposes of energy models are the aspects on which the models focus, such as energy demand, energy supply, impacts, or appraisal.

I. *Energy Demand Models*
Demand models focus on either the entire economy or a certain sector and regard demand as a function of changes in population, income, and energy prices.

II. *Energy Supply Models*
Supply models focus mainly on the technical aspects concerning energy systems and whether supply can meet a given demand, but may include financial aspects using a least-cost approach.

III. *Impact Models*
Impacts can be caused by using certain energy systems or enact certain policy measures. Impacts may include changes in the financial/ economic situation, changes in the social situation (distribution of wealth, employment), or changes in health and the environment (emissions, solid or liquid waste, bio-diversity). Impact models assess the consequences of selecting certain options.

[3] See Section 2.3 for an explanation of bottom-up and top-down models.

IV. *Appraisal Models*
If there are several options they need to be compared and appraised in order to select the most suited option. Even if there seems to be only one option to be appraised there will always be the other option of *not* selecting the option which has consequences as well. The consequences or impacts of each option are compared and appraised according to one or more preset criteria of which efficiency (technical as well as cost) is the most commonly used.

Although there exist models that focus on one aspect only (such as some utility expansion models or environmental impact models) recent models generally have an integrated approach in the sense that they combine several specific purposes. Demand-supply matching models and impact-appraisal models are common examples of integrated models, but an integrated approach is also required to study energy-economy-environmental interactions. Also, almost all models include some indication of costs as a means for appraisal. Some models are constructed as a modular package, which enables the user to select only those modules (submodels) that are relevant.

Another aspect concerning the purpose is what form of energy the model addresses. Not all models include all forms. In fact, there exist many models which focus on electricity exclusively. On the other hand, some models that address “energy” as a whole, can not differentiate between different forms of energy and thus do not deal with the fact that not all energy forms are suited for certain purposes (e.g., there is no use in supplying more heat to the end-users if people want to use more electrical appliances.

2.2 The Model Structure: Internal and External Assumptions

Besides the purpose of models, the models can also be distinguished according to their structure, more specific the assumptions on which the structure is based. For each type of model, a decision has to be made on which assumptions will be embedded in the model structure (the implicit or internal assumptions) and which are left to be determined by the user (i.e., external or input assumptions). Hourcade et. al. (1996, 284-285) distinguish four independent dimensions with which the structure of models can be characterized:

I. *The degree of endogenization*
Endogenization means the attempt to incorporate all parameters within the model equations so as to minimize the number of exogenous parameters. Predictive models have endogenized behavior, while exploring or backcasting models use external (or input) assumptions about behavior which make them more suited to simulate the effects of changes in historical patterns.

II. *The extent of the description of the non-energy sector components of the economy*
Non-energy sector components include investment, trade, consumption of non-energy goods and services, income distribution, and more. The more detailed the model’s description of the non-energy sectors, the more suitable the model is for analyzing the extent to which energy policy measures affect the entire economy.

III. *The extent of the description of energy end-uses*
The more detailed the model’s description of energy end-uses, the more suitable the model is for analyzing the technological potential for energy efficiency.

IV. *The extent of the description of energy supply technologies*
The technological potential for fuel substitution and new supply technologies can best be analyzed if the model allows for a detailed description of technologies. Most models with an economic background represent technology only in a highly aggregated manner, treating it as a black box. This makes them less suited for analyzing different supply technologies.

For each of the four dimensions there is a range from “more” to “less” and each energy model can be ranked somewhere on that range. Hourcade et. al. state that, because the dimensions are independent, it is practically impossible to classify existing models in only one classification scheme or dimension that uses only one range.

As far as parameter values are not assumed within the energy model, the model users themselves will have to make external assumptions about these parameters. According Hourcade et. al. (1996, 286), external assumptions often include assumptions about:

I. *Population growth*
Other things being equal, population growth increases energy demand.

II. *Economic growth*
Economic growth generally causes an increase in activities for which energy is needed (this does not have to imply, however, that energy demand increases because energy efficiency might increase at the same time). Another consequence of economic growth is that it reduces the economic lifetime of energy-using equipment.

III. *Energy demand*
Energy demand is influenced by structural changes in an economy because different sectors have different energy intensities. Furthermore, the choice of technology and the associated energy efficiency affect the demand for energy.

IV. *Energy supply*
Energy supply is determined by the short-term availability of alternative resource supplies as well as by backstop technologies which give an indication of the cost at which an infinite alternative supply of energy becomes available (and thus provide information on the maximum cost of a policy).

V. *Price and income elasticities of energy demand*
Elasticities measure the relative change in energy demand, given relative changes in energy prices and in incomes. Higher elasticities imply larger changes in energy use.

VI. *Existing tax system and tax recycling*
Taxes can have large impacts on the total costs of energy systems.

If all the parameters of a model have to be determined exogenously, the model would be no more than a computational device, albeit an extremely flexible one. On the other hand, there will always have to be at least one external parameter. In practice, energy models will be placed somewhere between these two extremes.

2.3 The Analytical Approach: Top-Down vs. Bottom-Up

The distinction between top-down and bottom-up models is particularly interesting because they tend to produce opposite outcomes for the same problem. Hourcade et. al. (1996, 281-289) and in particular Grubb et. al. (1993, 432-446) provide useful information on this subject. According to Hourcade et. al., the differences in outcomes of top-down and bottom-up models stem from the distinct manners in which these two types of models treat the adoption of technologies, the decision-making behavior of economic agents, and how markets and economic institutions actually operate over a given period of time.

Grubb et. al. (1993, 433-437) state that the top-down approach is associated with –but not exclusively restricted to– the “pessimistic” *economic paradigm*, while the bottom-up approach is associated with the “optimistic” *engineering paradigm*. Therefore, the latter is also referred to as the *engineering approach*.

Economics regards technology as a set of techniques by which inputs such as capital, labor, and energy can be transferred into useful outputs. The “best” or most optimal techniques (defined by efficient markets) determine the so-called economic “production frontier” (see Figure 1) which can be constructed by observing actual behavior. No investments are possible beyond this frontier. However, it is possible to move the frontier towards the origin by means of technological progress.

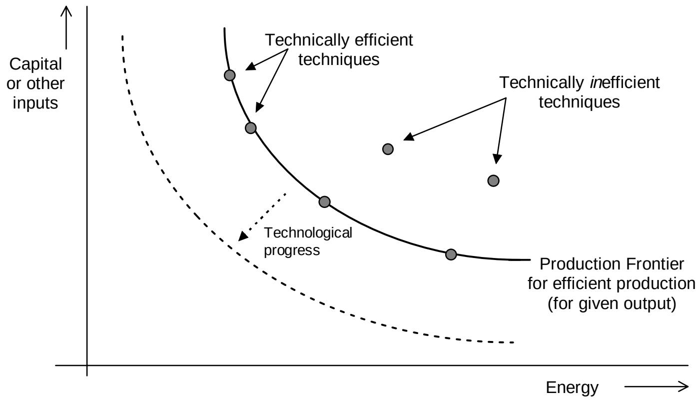

Figure 1. The production frontier from an economical perspective. Derived from Grubb et. al. (1993, 434).

A purely economic model has no explicit representation of technologies, but uses elasticities which implicitly reflect the technologies. Hourcade et. al. (1996, 287) state that technological change in most economic models is represented by the “autonomous energy efficiency index” (AEEI) and the “elasticity of substitution” between the aggregate inputs to households and firms. Stated otherwise, technology is treated as a black box, which makes it difficult to convert detailed technological projections into the production functions of these models.

Engineering studies, on the other hand, are independent of observed market behavior. They describe the techniques, the performances, and the direct costs of all technological options in order to identify possibilities for improvement. In practice, the technological potential differs from the “best” technologies that represent the economic production frontier in economic models. The difference arises due the fact that the engineering approach tends to ignore existing constraints, while the economic production frontier is based on market behavior. According to Grubb et. al. (1993, 434-435), these constraints include hidden costs, costs of implementation measures, market imperfections, macro-economic relationships (multiplier effects, price effects), and macro-economic indicators (GNP, employment). Market behavior can be regarded as a result of the existence of these constraints. Therefore, models which are based on data derived from actual behavior are believed to automatically include existing constraints. However, promoters of the bottom-up approach argue that appropriate policy measures would reduce the constraints substantially, making existing consumer behavior no longer an adequate measure.

Another characteristic of top-down models is that they use aggregated data to examine interactions between the energy sector and other sectors of the economy, and to examine the overall macro-economic performance of the economy. This is done by endogenizing behavioral relationships as much as possible. Past behavior can then be extrapolated into the future, which makes top-down models suitable for predictive purposes on the short term.

In contrast, bottom-up models usually focus on the energy sector exclusively, and use highly disaggregated data to describe energy end-uses and technological options in detail. According to Hourcade et. al. (1996), bottom-up models can be further subdivided into descriptive and prescriptive models. Descriptive models try to provide a practical estimate of the technology mix that would result from actual decisions, based on factors such as complex preferences, intangible costs, capital constraints, attitudes to risk, uncertainty, and market barriers. Prescriptive studies, on the other hand, provide an estimate for the technological potential by examining the effects of acquiring only the most efficient existing technologies (or of minimizing explicit costs for a given service at a system level). As a consequence, descriptive models are typically less optimistic than prescriptive studies. In a sense, the purpose of descriptive models tends towards prediction and it can be seen as an attempt to bridge the gap between the engineering paradigm and the economic paradigm, while the purpose of prescriptive models tends more towards exploration.

So, as Hourcade et. al. summarize (1996, 281), in general top-down models can only be used “if historical development patterns and relationships among key underlying variables hold constant for the projection period” i.e., there is no discontinuity in historical patterns. Bottom-up models, on the other hand, are suited only “if there are no important feedbacks between the structural evolution of a particular sector in a strategy and the overall development pattern” i.e., if interactions between the energy sector and the other sectors are negligible.

The very first energy models for policy making were probably of a highly aggregated top-down kind with a purely economic approach used for predictive purposes. The production functions which were used in these models dealt with technology as a black box and included only a general variable to represent energy demand. As a response, the early bottom-up models were developed specifically for purposes that could not be performed by the early top-down models, such as simulation and backcasting. These bottom-up models are assumed to originate from the engineering models that were used by utilities for planning their energy production. Regarding the model structure (see the previous Section 2.2), early top-down models score typically high on the dimensions I (degree of endogenization) and II (description of other sectors), while early bottom-up models score high on dimensions III (description of energy end-use) and IV (description of energy supply technologies). Today, the clear distinction between top-down and bottom-up is diminishing as more "hybrid" models become available in which the two approaches have been merged. For instance, many top-down models now also allow for simulations. This implies that different outcomes must then be ascribed to differences in external or input assumptions rather than differences in model structure.

Concluding, the distinction between top-down and bottom-up can generally be typified as the distinction between aggregated and disaggregated models respectively, or as the distinction between models with a maximum degree of endogenized behavior and models with a minimum degree. Furthermore, (early) top-down models are generally used for prediction purposes, while bottom-up models are mainly used for exploring purposes. The different aspects associated with top-down and bottom-up models are summarized in Table 1.

Table 1. Characteristics of top-down models and bottom-up models.

Top-Down Models	Bottom-Up Models
use an "economic approach"	use an "engineering approach"
give pessimistic estimates on "best" performance	give optimistic estimates on "best" performance
can not explicitly represent technologies	allow for detailed description of technologies
reflect available technologies adopted by the market	reflect technical potential
the "most efficient" technologies are given by the production frontier (which is set by market behavior)	efficient technologies can lie beyond the economic production frontier suggested by market behavior
use aggregated data for predicting purposes	use disaggregated data for exploring purposes
are based on observed market behavior	are independent of observed market behavior
disregard the technically most efficient technologies available, thus underestimate potential for efficiency improvements	disregard market thresholds (hidden costs and other constraints), thus overestimate the potential for efficiency improvements
determine energy demand through aggregate economic indices (GNP, price elasticities), but vary in addressing energy supply	represent supply technologies in detail using disaggregated data, but vary in addressing energy consumption
endogenize behavioral relationships	assess costs of technological options directly
assumes there are no discontinuities in historical trends	assumes interactions between energy sector and other sectors is negligible

2.4 The Underlying Methodology

Methodologies used for the concrete development of energy models can be found in, among others, APDC (1985), Grubb et. al. (1993), IIASA (1995), Kleinpeter (1995), Hourcade et. al. (1996). Below, an overview is given of commonly used methodologies found in the above literature. These methodologies include 1) econometric, 2) macro-economic, 3) economic equilibrium, 4) optimization, 5) simulation, 6) spreadsheet, 7) backcasting, and 8) multi-criteria methodologies. In practice, the distinction is not always clear. For instance, the literature make a distinction between simulation, optimization, and spreadsheet methods usually only when referring to bottom-up models, while recent economic top-down models use optimization and simulation techniques as well. On the other hand, econometric, macro-economic, and economic equilibrium methods are generally only applied in top-down models, although there are exceptions here also.

I. *Econometric Models*

Econometrics is defined as "applying statistical techniques in dealing with problems of an economic nature" (Kleinpeter, 1995, p. 177). Econometric methodologies are methodologies that apply statistical methods to extrapolate past market behavior into the future. They rely on aggregated data that have been measured in the past to predict the short- or medium-term future in terms of labor, capital, or other inputs. They are also frequently used to analyze energy-economy interactions. So, generally, the purpose of econometric models is to predict the future as accurately as possible using measured parameters. Although early energy (demand) models were purely econometrics based, nowadays econometric methodologies are mainly used as parts of macro-economic models.

A disadvantage of this methodology is that it does not have a representative set of technology options, in fact it does not represent specific technologies at all. Also, since variables are based on past behavior, a reasonable stability of economic behavior is required. Finally, Munasinghe (1988) as well as the APDC (1985) state that econometric models can only be used by experienced econometricians and have rather high data requirements. Long term effects can only be addressed by increasing the aggregation level in order to reduce the fluctuations over time.

The APDC (1985) mentions another methodology similar to the econometric one, namely "trend analysis". Trend analysis also extrapolates past trends of energy-economic activity and energy per capita ratios but has less stringent data (and formal) requirements. However, trend analysis is not suited for policy analysis partly due to the fact that it requires highly aggregated data (to reduce fluctuations in behavior over time) and does not allow for energy-economy feedbacks. It cannot capture structural change and does not explain determinants of energy demand.

II. *Macro-Economic Models*

The macro-economic methodology focuses on the entire economy of a society and on the interaction between the sectors. It is often applied in energy demand analysis when taken from a neo-Keynesian perspective (i.e., output is demand determined). Input-Output tables are used to describe transactions among economic sectors and assist in analysis of energy-economy interactions. The Input-Output approach can be used only when the assumptions of constant returns to scale as well as the possibility of perfect aggregation hold. Macro-economic models are often developed for exploring purposes, using assumed parameter and scenarios which do not necessarily have to reflect reality.

Often macro-economic models do not concentrate on energy specifically but on the economy as a whole, of which energy is only a (small) part. Therefore, some do not regard macro-economic models as energy models.

Similar to the econometric methodology, the macro-economic methodology has the disadvantage that it does not represent specific technologies and requires a relatively high level of expertise. Also, effects of intertemporal preferences and long-term expectations are not taken into account, which results in a rather static representation of technical change.

III. *Economic Equilibrium Models*

Where econometric and macro-economic methods are mainly applied to study the short or medium term effects, economic equilibrium methodologies focus on the medium to long term. They are used to study the energy sector as part of the overall economy and focus on interrelations between the energy sector and the rest of the economy. Economic equilibrium models are sometimes also referred to as resource allocation models.

There is a distinction between partial equilibrium models on the one hand, and general equilibrium models or optimal growth models on the other. Partial equilibrium models only focus on equilibria in parts of the economy, such as the equilibrium between energy demand and supply. General equilibrium models are particularly concerned with the conditions which allow for simultaneous equilibrium in all markets, as well as the determinants and properties of such an economy-wide set of equilibria. According to Slesser (1982), general equilibrium models consider simultaneously all the markets in an economy, allowing for feedback effects between individual markets. Economic equilibrium methodologies are used to simulate very long-term growth paths and do not systematically rely on econometric relationships but are instead benchmarked on a given year in order to guarantee consistency of parameters. They rely on (neo-classical) perfect market equilibrium assumptions; output is determined by supply and markets "clear" (there exists no structural unemployment). The disadvantage of these models is that they do not provide adequate information on the time path towards the new equilibrium, implying that transition costs are understated.

IV. *Optimization Models*

Optimization methodologies are used to optimize energy investment decisions endogenously (i.e., the results are directly determined by the input). The outcome represents the best solution for given variables while meeting the given constraints. Optimization is often used by utilities or municipalities to derive their optimal investment strategies. Furthermore, in national energy planning, it is used for analyzing the future of an energy system. Underlying assumption of optimization methodologies is that all acting agents behave optimal under given constraints. According to DHV (1984), disadvantages are that optimization models require a relatively high level of mathematical knowledge and that the included processes must be analytically defined. Optimization models often use linear programming techniques[4].

V. *Simulation Models*

According to the World Energy Conference (1986), simulation models are descriptive models based on a logical representation of a system, and they are aimed at reproducing a simplified operation of this system. A simulation model is referred to as static if it represents the operation of the system in a single time period; it is referred to as dynamic if the output of the current period is affected by evolution or expansion compared with previous periods. Simulation models are especially helpful in cases where it is impossible or extremely costly to do experiments on the system itself. A disadvantage is that simulation models tend to be rather complex. They are often used in scenario analysis.

VI. *Spreadsheet Models (Tool Boxes)*

In the literature the spreadsheet methodology is often mentioned as a separate (bottom-up) methodology (see, for instance, Grubb (1993), Hourcade (1996)). Although the models all make use of spreadsheets (as the term suggests), this term may cause some confusion because other methodologies also frequently use spreadsheet programs as a basis. What is meant by spreadsheet models is a highly flexible model which, according to Munasinghe (1988,30) is actually more like a software package to generate models than a model per se. The World Bank (1991, 6-9) refers to spreadsheet models as "tool boxes" which often include a reference model that can easily be modified according to individual needs.

[4] see Section 2.5 for an explanation of linear programming.

VII. *Backcasting Models*
The backcasting methodology is used to construct visions of desired futures by interviewing experts in the fields and subsequently by looking at which trends are required or need to be broken to accomplish such futures. This approach is often used in alternative energy studies. For instance, the Dutch interdepartmental research program Sustainable Technological Development (STD) uses backcasting to explore the (technological) requirements for certain desired futures (STD, 1998).

VIII. *Multi-criteria Models*
The multi-criteria methodology can be used for including other criteria than just economic efficiency alone. It enables you to include quantitative as well as qualitative data in the analysis. This approach is not yet widely applied in energy models. Two examples of application can be found in studies conducted by Georgopoulou (1997) and Georgopoulou (1998).

2.5 The Mathematical Approach

At the level of concrete models, a further distinction can be made regarding the mathematical approach or procedures applied in the models (see, for example, IIASA (1995), and Kleinpeter (1995)). Commonly applied techniques include linear programming, mixed integer programming, and dynamic programming. Of course, combinations of techniques within a model are also possible. Mathematical techniques that only recently have been applied to energy planning, such as multi-criteria techniques and fuzzy logic, are not addressed here.

I. *Linear Programming (LP)*
Linear programming is a practical technique for finding the arrangement of activities which maximizes or minimizes a defined criterion, subject to the operative constraints (Slesser, 1982). All relationships are expressed in fully linearized terms. Linear Programming can be used, for instance, to find the most profitable set of outputs that can be produced with given type input and given output prices. The technique can deal only with situations where activities can be expressed in the form of linear equalities or inequalities, and where the criterion is also linear. That is, if x_1 and x_2 are inputs and y is the output, the technique is only applicable if their relationship is of the form $y \leq ax_1 + bx_2$. LP is a relatively simple technique which gives quick results and demands little mathematical knowledge of the user. Disadvantages are that all coefficients must be constant and that LP results in choosing the cheapest resource up to its limits before any other alternative is used at the same time for the same item (World Bank, 1991). Also, LP models can be very sensitive to input parameter variations. This technique is used for almost all optimization models, and applied in national energy planning as well as technology related long-term energy research.

II. *Mixed Integer Programming (MIP)*
Mixed Integer Programming (MIP) is actually an extension of Linear Programming which allows for greater detail in formulating technical properties and relations in modeling energy systems. Decisions such as Yes/No or (0/1) are admitted as well as nonconvex relations for discrete decision problems. MIP can be used when addressing questions such as whether or not to include a particular energy conversion plant in a system. By using MIP, variables that cannot reasonably assume any arbitrary (e.g., small) value –such as unit sizes of power plants– can be properly reflected in an otherwise linear model. (World Bank, 1991).

III. *Dynamic Programming*
Dynamic programming is a method used to find an optimal growth path. The solution of the original problem is obtained by dividing the original problem into simple subproblems for which optimal solutions are calculated. Consequently, the original problem is than optimally solved using the optimal solutions of the subproblems.

2.6 Geographical Coverage: Global, Regional, National, Local, or Project

The geographical coverage reflects the level at which the analysis takes place, which is an important factor in determining the structure of models. The global models describe the world economy or situation, the regional level frequently refers to international regions such as Europe, the Latin American Countries, South-East Asia, etc., although the literature uses the term “regional” in some cases to refer to regions within a country. In this paper, we will use the term “local” in these cases. National models treat world market conditions as exogenous, but encompass all major sectors within a country simultaneously, addressing feedbacks and interrelationships between the sectors. Examples of national models are econometric models for the short term and general equilibrium models for the long term. The local level is subnational, referring to regions within a country. The project level is a somewhat special case. It usually refers to a subnational level focusing at a particular site. However, the project level can also encompass a project on a national or even international scale, although specific “project models” generally do not focus on these large scale projects.

The comprehensiveness of models focusing on the global, regional, or national level generally requires highly aggregated data and models focusing on one of these levels often include all major sectors and macro-economic linkages between those sectors, implying a considerable simplification of the energy sector. Local and project models, on the other hand, usually require a bottom-up approach using disaggregated data.

2.7 Sectoral Coverage

A model can be focused on only one sector, as many early bottom-up models do, or include more sectors. How the economy is divided into certain sectors is crucial for the analysis. Multi-sectoral models can be used at the international, national, as well as subnational level and focus on the interactions between these sectors. Single-sectoral models only provide information on a particular sector (in our case the energy sector) and do not take into account the macro-economic linkages of that sector with the rest of the economy. The rest of the economy is represented in a highly simplified way. Nearly all bottom-up models are sectoral, but not all sectoral models use bottom-up methodologies. For instance, top-down partial equilibrium models focus on the long term growth path of a distinct sector.

2.8 The Time Horizon: Short, Medium, and Long Term

There exists no standard definition of the short, medium, and long term. However, Grubb et. al. (1993, 437) mention a commonly noticed period of 5 years or less for the short term, between 3 and 15 years for the medium term, and 10 years or more for the long term. The time horizon is important because different economic, social, and environmental processes are important at different time scales. Thus, the time scale determines the structure and objectives of the energy models. Long run analyses may assume economic equilibrium (i.e., resources are fully allocated or markets “clear”), while short run models need to incorporate “transitional” and disequilibrium effects (e.g., unemployment).

2.9 Data Requirements

Models require certain types of data. For instance, most models will require data of a quantitative, cardinal type, some even require aspects to be expressed in monetary units. However, sometimes data are not available or unreliable (for instance in developing countries), in which case it might be important that the energy model can handle qualitative or ordinal data as well. Furthermore, data may be aggregated or disaggregated. Long-term global and national models will necessarily need highly aggregated data with little technological detail. Great detail in representing energy supply and consumption is only possible in models that are specific for the energy sector.

3. Classifying Existing Energy Models

In this chapter we will give an overview of the main energy models existing today, including EFOM-ENV, ENERPLAN, ENPEP, LEAP, MARKAL, MARKAL-MACRO, MESAP, MESSAGE-III, MICRO-MELODIE, and RETscreen. For more information on these models we refer to the World Bank website "Computer Tools for Comparative Assessment" (1999), United Nations (1985), and CEDRL (1998). The models are characterized according to the nine classification ways mentioned in Chapter 2:

1. *Purposes of Energy Models*
   General: forecasting, exploring, backcasting
   Specific: energy demand, energy supply, impacts, appraisal, integrated approach, modular build-up

2. *The Model Structure: Internal Assumptions & External Assumptions*
   Degree of endogenization, description of non-energy sectors, description end-uses, description supply technologies.

3. *The Analytical Approach*
   Top-Down or Bottom-Up

4. *The Underlying Methodology*
   Econometric, Macro-Economic, Economic Equilibrium, Optimization, Simulation, Spreadsheet/Toolbox, Backcasting, Multi-Criteria.

5. *The Mathematical Approach*
   Linear programming, mixed-integer programming, dynamic programming.

6. *Geographical Coverage*
   Global, Regional, National, Local, or Project

7. *Sectoral Coverage*
   Energy sectors or overall economy.

8. *The Time Horizon*
   Short, Medium, Long Term

9. *Data Requirements*
   Qualitative, quantitative, monetary, aggregated, disaggregated.

EFOM-ENV

Developers:	European Commission DDG-XII F/1, Belgium
1. Purposes	
General:	Exploring
Specific:	Energy supply, subject to technical, environmental and political constraints. Detailed description of (renewable) technologies possible. Appraisal through cost-effectiveness analysis. The objective includes energy and environment policy analysis and planning in particular regarding emission reduction.
2. Assumptions:	Low degree of endogenization, no interaction between non-energy sectors, detailed decsription of energy supply and end-uses technologies. Endogenous analysis of generation expansion. Input needed: demand projections/ scenarios, supply costs, (environmental) constraints.
3. Top-Down vs. Bottom-Up:	Bottom-Up
4. Methodology:	Optimization
5. Mathematical Approach:	Linear Programming/ Dynamic Programming
6. Level:	National
7. Sectoral Coverage:	Energy producing and consuming sectors
8. The Time Horizon:	Medium to long term
9. Data Requirements:	Quantitative, monetary, disaggregated

ENERPLAN

Developers:	Tokyo Energy Analysis Group, Japan
1. Purposes	
General:	Forecasting or exploring (depending on mode)
Specific:	Energy supply, energy demand, matching demand and supply
2. Assumptions:	Depends on mode
3. Top-Down vs. Bottom-Up:	Top-Down
4. Methodology:	Econometrics and simulation (depending on mode)
5. Mathematical Approach:	Not available
6. Level:	National
7. Sectoral Coverage:	Energy sector
8. The Time Horizon:	Short to medium
9. Data Requirements:	Quantitative

ENPEP	
Developers:	International Atomic Energy Agency (IAEA), Autstria
1. Purposes	
General:	Forecasting, exploring.
Specific:	Energy demand, supply, matching demand and supply, environmental impacts. Detailed analysis for electricity based on least cost optimization. Integrated approach. Allows for energy policy analysis, energy tariff development, investment analysis, generation expansion planning, environmental policy analysis.
2. Assumptions:	Demand: high degree endogenization, description of all sectors in economy. Supply: detailed description of end-uses and (renewable) technologies.
3. Top-Down vs. Bottom-Up:	Hybrid. Top-down for demand analysis and bottom-up for supply.
4. Methodology:	Macro-economic for demand, economic equilibrium for total energy system.
5. Mathematical Approach:	Not available
6. Level:	Local, National
7. Sectoral Coverage:	Entire economy
8. The Time Horizon:	Short (1-3 yrs), medium, long (max 50 yrs).
9. Data Requirements:	Quantitative, monetary, aggregated and disaggregated.

LEAP	
Developers:	Stockholm Environmental Institute Boston, USA
1. Purposes	
General:	Exploring, forecasting
Specific:	Demand, supply, environmental impacts. Integrated approach. the objective includes energy policy analysis, environmental policy analysis, biomass- and land-use assessment, preinvestment project analysis, integrated energy planning, full fuel cycle analysis. Applicable to industrialized as well as developing countries.
2. Assumptions:	Demand: rather high degree of endogenization and description of all sectors in economy Supply: simple description of end-uses and supply technologies, including some renewable.
3. Top-Down vs. Bottom-Up:	Demand: top-down, supply: bottom-up.
4. Methodology:	Demand: econometric or macro-economic. Supply: simulation
5. Mathematical Approach:	Not available.
6. Level:	Local, national, regional, global.
7. Sectoral Coverage:	All sectors.
8. The Time Horizon:	Medium, long term
9. Data Requirements:	Quantitative, monetary, aggregated/ disaggregated.

MARKAL

Developers: International Energy Agency (IEA)/ ETSAP

1. *Purposes*
   - *General:* Exploring
   - *Specific:* Energy supply with constraints. The objective includes target-oriented integrated energy analysis and planning through a least cost approach.
2. *Assumptions:* Low degree of endogenization, focuses only on the energy sector, detailed description of end-uses and (renewable) energy technologies possible.
3. *Top-Down vs. Bottom-Up:* Bottum-up.
4. *Methodology:* Toolbox/ Optimization
5. *Mathematical Approach:* Linear programming, dynamic programming.
6. *Level:* Local, national.
7. *Sectoral Coverage:* Energy sector only
8. *The Time Horizon:* Medium, long term.
9. *Data Requirements:* Quantitative, monetary, disaggregated.

MARKAL-MACRO

Developers: Brookhaven National Laboratory, USA.

1. *Purposes*
   - *General:* Exploring
   - *Specific:* Demand, supply, environmental impacts. Integrated approach for economy-energy-environmental analysis and planning. The objective is to maximize utility (discounted sum of consumption) from a neo-classical macro-economic perspective.
2. *Assumptions:* Neo-classical growth model with nested substitution (CES) between capital/ labor aggregate and energy. Energy is represented as the weighted sum of useful energy demands in the MARKAL submodel. Detailed description of (renewable) technologies is possible.
3. *Top-Down vs. Bottom-Up:* MACRO part is top-down, MARKAL part is bottom-up.
4. *Methodology:* Macro-economic for MACRO and partial equilibrium through optimization for matching demand and supply in MARKAL.
5. *Mathematical Approach:* Dynamic programming (non-linear).
6. *Level:* Local, National
7. *Sectoral Coverage:* All sectors.
8. *The Time Horizon:* Medium, long term.
9. *Data Requirements:* Qualitative, monetary, aggregated, disaggregated.

MESAP

Developers:	IER, University of Stuttgart, Germany.
1. Purposes	
General:	Exploring, forecasting
Specific:	Modular package. Demand, supply, environmental through different modules: ENIS = database PLANET/ MADE = demand which can be coupled to supply module INCA = comparative economic assessment of single technologies WASP = generation expansion based on least-cost analysis MESSAGE = integrated energy systems analysis
2. Assumptions:	Depends on module.
3. Top-Down vs. Bottom-Up:	Top-down (demand) and bottom-up (supply).
4. Methodology:	Econometric (demand), simulation or linear programming (supply).
5. Mathematical Approach:	(among others) linear programming, dynamic programming
6. Level:	Local, national.
7. Sectoral Coverage:	All sectors through PLANET/ MADE.
8. The Time Horizon:	Medium, long term.
9. Data Requirements:	Quantitative, monetary, aggregated, disaggregated.

MESSAGE-III

Developers:	International Institute for Applied System Analysis (IIASA), Austria.
1. Purposes	
General:	Exploring
Specific:	Energy demand and supply, environmental impacts. Modular package. the objective includes generation expansion planning, end-use analysis, environmental policy analysis, investment policy.
2. Assumptions:	Detailed description of energy end-uses and (renewable) energy technologies.
3. Top-Down vs. Bottom-Up:	Bottom-up.
4. Methodology:	Optimization.
5. Mathematical Approach:	Dynamic programming
6. Level:	Local, national.
7. Sectoral Coverage:	Energy sector.
8. The Time Horizon:	Short, medium, long term.
9. Data Requirements:	Quantitative, monetary, disaggregated.

MICRO-MELODIE

Developers:	CEA, France
1. Purposes	
General:	Exploring
Specific:	Energy demand, supply, environment. Integrated approach. The objective includes an analysis of macro-economic energy and environment linkages.
2. Assumptions:	Multi-sectoral analysis with a description of conventional energy technologies only, in particular for the electricity sector.
3. Top-Down vs. Bottom-Up:	Top-down with a detailed description of the energy sector.
4. Methodology:	Macro-economic based on price equilibrium.
5. Mathematical Approach:	Not available
6. Level:	National.
7. Sectoral Coverage:	All sectors, with a detailed description of the energy sector.
8. The Time Horizon:	Medium, long term
9. Data Requirements:	Quantitative, monetary, aggregated, disaggregated.

RETscreen

Developers:	CEDRL/Natural Resources Canada
1. Purposes	
General:	Exploring
Specific:	Energy supply. Specially designed for renewable energy technologies.
2. Assumptions:	Detailed description of supply technologies for generation expansion.
3. Top-Down vs. Bottom-Up:	Bottom-up
4. Methodology:	Spreadsheet/ Toolbox.
5. Mathematical Approach:	Not available.
6. Level:	Local, national.
7. Sectoral Coverage:	Energy Sector.
8. The Time Horizon:	Not avaliable
9. Data Requirements:	Quantitative, monetary, disaggregated.

4. The Choice of Energy Models for Local Energy Planning

In this chapter we come back to the original intention for writing this paper. As discussed in Chapter 1, this paper should provide information on the most suited energy models for local energy planning. So, which models are most suited to support local energy planning, in particular the selection of appropriate energy systems for regions experiencing rapid economic growth? To answer this question we need to keep in mind that there are 4 issues for which we seek an answer:

1. The future amount and types of energy demand. If we do not know future demand we do not know how much energy has to be supplied, thus how many new systems are needed.
2. The relevant energy systems that can meet the demanded forms of energy.
3. The impacts of using the energy systems.
4. How (according to which criteria) the energy systems should be appraised.

For each issue a separate model can be chosen. What is clear beforehand is that all models used must be developed for local level analyses. The four issues mentioned above will be discussed in more detail below.

I. *Energy Demand*

As we have seen in Chapter 3, existing models frequently use forecasting methods (econometrics) for projecting future energy demand. However, in regions which experience a rapid economic growth, historical data may not provide a satisfactory forecast. Due to rapid growth, a discontinuity occurs in the trends derived from past behavior. Therefore, scenario analysis is believed to be more suited in this case. Of course, past experiences in regions which have experienced a similar rapid development may serve as a basis for the scenarios.

Furthermore, it is not enough to know that energy demand will increase by, for instance, 10%. In a region where the energy infrastructure is underdeveloped, it is important to know what forms of energy (e.g., heat, electricity, transport fuels) are demanded by the end-users. For this, we need to know for what purposes the energy is used i.e., what the desired the energy services are. The desired energy services should be the starting point of the analysis. This implies a bottom-up approach rather than a top-down approach to allow for a detailed, disaggregated analysis.

II. *Energy Supply Systems*

Because the focus is on selecting appropriate energy systems, the supply model must have a bottom-up approach to allow for a detailed description of the available energy technologies for conversion of conventional resources (oil, coal, gas) as well as renewable resources (sun. wind, water, biomass) available.

III. *Impact Assessment*

Most existing models assess only technical aspects and financial and economic consequences of energy systems. More and more models now also include an environmental impact assessment, but only those that can be expressed in quantitative terms. Many (qualitative) social impacts are ignored as well because impacts that cannot be quantified are excluded from the analysis. However, these impacts may play a crucial role in the viability of an energy system. Therefore, we promote the use of impact models which have a multi-criteria approach, allowing for the inclusion of both quantitative (physical, monetary) as well as qualitative data. This way it is ensured that the energy systems' impacts can be assessed according to all possible preferences or criteria of the energy planners.

Since most existing impact models are integrated in the supply and/or demand models, they cannot be easily modified to include other (qualitative) criteria. This is not the case with a modular package because each module can operate separately from the others. A modular package is therefore preferred.

IV. *Appraisal*
The use of multiple criteria –of which some may be qualitative– also requires that the appraisal model is able to take all the criteria into account. The appraisal model should thus be of a Multi-Criteria Analysis (MCA) type.
A very important aspect concerning the appraisal of impacts is the sensitivity of the outcomes to (small) changes in the input variables. The sensitivity analysis might result in the choice for less (or, of course, more) stringent criteria which, in turn, will influence the scores of a system on other criteria. For instance, relaxing the criterion of system reliability from 100% to 90% may reduce the system costs considerably. For the planner it is important to know how the scores on other criteria are affected if one of the criteria is altered.
A question which remains unanswered is whether it would be better to not use an appraisal model at all. Especially in cases where the energy planner is not the actual decision maker. In these cases it might be preferable if only a clear overview is presented of the different options and their consequences (including the outcomes of a sensitivity analysis) rather than presenting one option which is believed to be the most appropriate. Even a ranking may not be desirable in such cases. If a clear overview is presented the decision makers themselves can then select the options that they regard as most appropriate.

So the set of models for local energy planning should consist of a modular package of models with exploring purposes and should at least include models for energy demand, energy supply, and impacts. The inclusion of an appraisal model depends on whether the planner is the same person or group as the decision maker, but because of the modular build-up an optional module for appraisal is easily added. The approach will have to be bottom-up to allow for a detailed description of the energy forms needed to provide the energy services that end-users desire. The bottom-up approach is also necessary to enable a detailed description of the different supply technologies (conventional as well as renewable). The focus will be on those sectors that are the main consumers of energy.

A flexible toolbox is believed to be the most suited methodology because this makes an optimal adjustment to local circumstances possible. Another reason for choosing a toolbox methodology is that the methodology should be kept as accessible as possible for the local planners. As far as the mathematical approach is concerned, there is no distinct preference, although linear programming has a clear advantage in that it allows for simple programming and can easily be understood by planners because no special expertise is needed. As for the time horizon, the model should allow for short as well as medium term planning. The long term planning may be of less use in a rapidly developing region with constantly changing circumstances.

5. Conclusions

Concluding we can say that in developing countries, local energy planning for regions experiencing rapid development can best be supported with a modular package of models. This package should include models for assessing energy demand, supply, and impacts at the local level. The inclusion of an appraisal model is optional. The general purpose of these models must be exploring and the approach has to be bottom-up rather than top-down to allow for a detailed description of, on the one hand, energy services and the resulting demand for energy forms, and supply technologies on the other hand. A flexible toolbox is believed to be the most suited methodology for adjustments to local circumstances. The time horizon should include the short and medium term.

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