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Energy Demand Models for Policy Formulation

A Comparative Study of Energy Demand Models

Subhes C. Bhattacharyya
Govinda R. Timilsina

The World Bank
Development Research Group
Environment and Energy Team
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Abstract

This paper critically reviews existing energy demand forecasting methodologies highlighting the methodological diversities and developments over the past four decades in order to investigate whether the existing energy demand models are appropriate for capturing the specific features of developing countries. The study finds that two types of approaches, econometric and end-use accounting, are used in the existing energy demand models. Although energy demand models have greatly evolved since the early 1970s, key issues such as the poor-rich and urban-rural divides, traditional energy resources, and differentiation between commercial and non-commercial energy commodities are often poorly reflected in these models. While the end-use energy accounting models with detailed sector representations produce more realistic projections compared with the econometric models, they still suffer from huge data deficiencies especially in developing countries. Development and maintenance of more detailed energy databases, further development of models to better reflect developing country context, and institutionalizing the modeling capacity in developing countries are the key requirements for energy demand modeling to deliver richer and more reliable input to policy formulation in developing countries.

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Subhes C. Bhattacharyya
CEPMLP, Dundee University

Govinda R. Timilsina*
Development Research Group
The World Bank

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Acronyms and Definitions

Definitions

A few terms appear recurrently in this report: tool, model, method, methodology, approach and framework. We give the dictionary meaning of these terms and indicate how we have used them in this paper.

A "tool" is "*the means whereby some act is accomplished" or "an implement used in the practice of a vocation"*. In this paper, we use the term to imply an implement or a kit that is used in analyzing energy demand or forecasting demand or in analyzing the energy system in its part or whole.

A "model" is defined as "*a simplified description of a complex entity or process"*. In this paper, we use models to imply a simplified representation of a complex problem or process, often in mathematical terms, that helps us in conceptualizing and analyzing the problem. In this sense, a model can be a tool or can employ a number of tools in a systematic way.

A "framework" is defined as "*a structure supporting or containing something" or "a simplified description of a complex entity or process"*. In this paper, we have used this term interchangeably with a model.

A "method" is defined as "*a way of doing something, especially a systematic way; implies an orderly logical arrangement (usually in steps)"*. We have used the term to mean a logical, systematic approach for accomplishing a task.

An "approach" is defined as the "*ideas or actions intended to deal with a problem or situation"*. We have used this term as a synonym of a method and have used the two terms "approach" and "method" interchangeably.

A "methodology" is defined as "*the system of methods followed in a particular discipline*". We have used this term to imply a clearly defined set of methods following a particular philosophy that are used in analyzing the energy problem.

Acronyms

Term	Meaning
AIM	Asian-Pacific Model
BERR	Department for Business, Enterprise and Regulatory Reform
BESOM	Brookhaven Energy System Optimization Model
CIMS	Canadian Integrated Modeling System
DTI	Department of Trade and Industry (now called Department for Business, Enterprise and Regulatory Reform, BERR)
ECM	Error Correction Model
EFOM	Energy Flow Optimization Model
EGEAS	Electricity Generation Expansion Analysis System
EMF	Energy Modeling Forum
EU	European Union
GDP	Gross Domestic Product
GNP	Gross National Product
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IIASA	International Institute for Applied System Analysis
IPCC	Intergovernmental Panel on Climate Change
ISIC	International Standard Industrial Classification
LEAP	Long-range Energy Alternative Planning
MAED	Model for Analysis of Energy Demand
MARKAL	Market Allocation Model
MEDEE	
NEMS	National Energy Modeling System
OLS	Ordinary Least Squares
POLES	Prospective Outlook on Long-term Energy Systems
RES	Reference Energy System
SAGE	System for the Analysis of Global Energy Markets
SGM	Second Generation Model
US	United States of America
WASP	Wien Automatic System Planning
WEC	World Energy Council

1. Introduction

Since the early 1970s, when energy caught the attention of policymakers in the aftermath of the first oil crisis, research on energy demand has vastly increased in order to overcome the limited understanding of the nature of energy demand and demand response due to the presence of the external shocks encountered at that time (Pindyck, 1979). The lively debate between engineers and economists of that era led to important methodological developments that enriched the energy decision-making process as a whole, and a wide variety of models became available for analyzing and forecasting energy demand (Wirl and Szirucsek, 1990).

Energy demand forecasting is an essential component for energy planning, formulating strategies and recommending energy policies. The task is challenging not only in developing countries where necessary data, appropriate models and required institutions are lacking, but also in industrialized countries in which these limitations are somewhat less serious. Projected energy demands are often found to deviate from the actual demands due to limitations in the model structure or inappropriate assumptions. Reviewing energy demand forecasts in the United States, Craig et al. (2002) show that most of the forecasts overestimated the demand by 100%. The models employed suffer from a long list of limitations. They often bury analytical assumptions in “black boxes” which are difficult to evaluate and reproduce the results. A perception that a complex model with extensive input data produces more accurate results might not be always true. Simple models can sometimes yield results as accurate as more complicated techniques (Armstrong, 2001). As Koomey (2002) points out, energy demand modelers should ask whether the modeling tool is driving or supporting the process of developing a coherent scenario and credence to deal with uncertainties.

There could be several reasons why results coming out energy demand modeling exercises are far from the actual demands. Some of them, according to Laitner et al (2003), are: (i) inaccurate characterization of the behavior of economic agents – most models group consumers into a few representative agents to represent the "millions of decisions made by millions of individuals," and provide relatively stylized descriptions of their decision making; (ii) incomplete coverage of social and environmental impacts; [I can see why this would be a problem in normative modeling, but why does this cause forecasts to miss the mark?] (iii) lack of adequate technological detail; and (iv) unrealistic economic assumptions such as fully employed and efficiently allocated resources, rational individuals, optimizing firms and perfectly functioning markets.

Simultaneously, the importance of developing countries in the world energy scene has grown significantly in the past thirty years. Although energy models have considered developing countries, the basic assumption was that they follow the same features of industrialized countries but with a different time lag (Urban et al 2007). However, this has not turned out to be true. For example, China has sustained a high level of economic growth for decades and has emerged as a major global player. Such global players have now changed the focus of energy sector development from the developed countries to developing countries. At the same time, within these fast growing economies as well as in many lower income countries, access to clean and affordable energy remains a major development issue.

A number of surveys of energy demand models have appeared previously, including, among others, those by Hartman (1979), Bohi (1981), Bohi and Zimmerman (1984), Craig et al (2002), Worrel et al (2004), Wirl and Szirucsek (1990). These studies, however, focus mainly on developed countries. Similarly, Bhatia (1987), Shukla (1995), Pandey (2002), Urban et al (2007) have focused on energy modeling from a developing country perspective. In addition, Dahl (1991, 1994a, 1994b), Cooper (2003), Dahl and Sterner (1991), and Espey (1998) provided energy, particularly oil demand elasticity surveys. As important as they are, most of these reviews have focused on: (i) a single approach -- econometric or end-use; (ii) demand analysis by mainly focusing on the elasticities of demand and their variability among or across studies; and (iii) comparison of the forecast with actual demand in developed country contexts.

As a wide variety of methods is used in energy demand forecasting, there is need for an understanding of the approaches and their relevance in different contexts. This is especially true for developing countries where the quality of information is poor and the future may not just follow the same trajectory as in the past due to structural changes and economic transition. We are unaware of any work that has tried to capture the broad range of approaches and their methodological underpinnings considering the policy perspectives for developing countries.

This study aims to bridge the knowledge gap by providing a systematic review of the literature pertaining to different energy forecasting methods and their applications with a view to understand their working and their usefulness under different circumstances. Further, we analyze how the selection of energy demand model influences energy policy formulations and decision making. Although our focus is on the demand forecasting models and methodologies, we also present a comparative review of selected energy system models in the Appendix to provide the readers with a broader picture.

We seek here to extend existing literature in a number of ways. First, we compare a broad range of energy demand forecasting techniques. Second, we provide an explanatory exposition of the alternative modeling techniques and their application to various sectors, thereby offering a critical appreciation of approaches. Third, we review a selected but commonly used energy demand models and bring out their strengths and weaknesses to facilitate choice of models under different user conditions. Finally, we highlight the possible effects on energy policy formulation and decision making of the selection of energy demand modeling techniques and options for the energy sector in developing countries.

The organization of the paper is as follows: Section 2 presents the special features of the energy systems in developing countries and the review criteria used in this paper. Section 3 recapitulates the theoretical underpinning of energy demand analysis. Section 4 presents a review of literature on demand forecasting applications and identifies the main types of models used in the analysis. Section 5 presents the features of a number of commonly used models and attempts to bring out the strength and weaknesses. Section 6 identifies the policy implications of model choices for developing countries and finally the some concluding remarks are provided in the last section.

2. Energy Demand Modeling Issues from Developing Countries' Perspective

2.1 Specific features of developing countries

Although there is a wide diversity among developing economies in terms of socio-economic conditions (size, economic structure, human resources, and energy endowments, level of urbanization), some common energy system characteristics can be found for most of them (OTA, 1991). These characteristics, according to Urban et al (2007), include: poor performance of the power sector and traditional energies, transition from traditional to modern energies, and structural deficiencies in the economy, society and in the energy systems which result in "urban-rural divide, inadequate investment decisions and misdirected subsidies". Pandey (2002) points out that the existence of large scale inequity and poverty, dominance of traditional life styles and markets in rural areas, transitions of populations from traditional to modern markets, existence of multiple social and economic barriers to capital flow and technology diffusion cause developing countries' energy systems significantly different from that of developed countries.

According to IEA (2002), about 25% of primary energy consumption of developing countries comes from biomass and other traditional energies, although the share varies across different regions and by countries. Although developing economies transit from traditional energies to modern energies as they climb up the income ladder, the speed at which countries move varies and consequently, the number of people relying on such energies even in 2030 is expected to be about 2.6 billions (IEA, 2002). Simultaneously, the reliance on fossil fuels increases, especially in large countries like India and China and the unsustainable resource use practices in developing countries put thus contrasting pressures on development and sustainability (Pandey (2002). The use of traditional energies poses specific problems for energy analysis. Often no estimations for traditional energy demand, prices and supply potential are available and many poor consumers lacking purchasing power may not enter the commercial energy ladder. Ignoring these energies is inappropriate given the critical role of access to affordable, clean and reliable supply of energy for sustainable development (Ailawadi and Bhattacharyya, 2006), but incorporating them is not easy either.

In addition, the changing economic structure due to industrial activities and consequent rapid urbanization of these economies add another dimension to the economic transition where a growing urban sector co-exists with a predominantly rural economy. The nature of economic activities as well as opportunities differs significantly between urban and rural areas. Informal economic activities prevail in rural and semi-urban areas due to the existence of unemployment or part-employment, both of which sometimes produce in-kind payments as compensation and participation in barter rather than monetized transactions. Shukla (1995) and Pandey (2002) point out that the presence of informal sector in the developing economies leads to non-optimal choices. Bhattacharyya (1995) emphasized on the violation of basic assumptions of the neoclassical paradigm because of incomplete markets, costly information and transaction costs in developing countries due to existence of the informal sector and prevalence of traditional use of energies. Pandey (2002) further indicated that the transition dynamics have important implications for energy demand due to changes in life-styles, technology choices and fuel mix, which in turn impact sustainability and the environment. Therefore, understanding these dynamics and their incorporation in the policies and modeling are essential in capturing the transition of developing countries.

Urban et al (2007) point out that the development trajectory of developing countries can be very different from that of the developed economies. While it is generally presumed that an economy will first industrialize from an agrarian economy and then move to service-dominated activities and accordingly, follow a somewhat inverted U-shaped energy intensity curve as the per-capita income increases, this need not be true for developing countries. Citing the Indian example, Urban et al (2007) indicate that the country has fast moved to a flourishing service sector with a modest manufacturing sector. This shows the possibility of leapfrogging and avoiding the mistakes by learning from others' experiences. Many supply-side options such as renewable energies are being adopted by developing countries at the same rate as in most industrialized countries. In fact, promoting such changes could form part of a strategy for a sustainable energy future for developing countries. For example, analyzing the Chinese energy situation Berrah et al (2007) suggest that instead of following a development path that steeply raises energy intensity as per-capita income increases, as exemplified by the industrialized countries, China can leap-frog to an energy efficient path of development. However, setting such an example would "require long-term vision, innovative approaches and strong policies" (Berrah et al (2007)), which in turn requires appropriate characterization of the economies in the policy models.

Supply shortage is quite common in many developing countries, especially for commercial energies in general and electricity in particular, which arise due mainly to inappropriate policies and investment decisions. In such cases, consumption may not represent the actual demand due to the existence of unfulfilled or suppressed demand and the market does not clear through the interaction of supply and demand due to interventions in the market. The existence of large-scale poverty also leads to inequity in consumption behavior, which encourages distorted policies for social reasons (Pandey, 2002). This in turn leads to under-recovery of costs through energy prices, and contributes to poor financial performance of the energy companies, reduced capital availability for investments and perpetuates capacity shortages.

Finally, many developing countries lack adequate capacity in terms of statistical analysis, modeling and data management. While the capacity varies across countries, the human resource constraint is a major constraint in most countries.

The co-existence of modern and traditional activities and the evolving nature of the economies imply a rich juxtaposition of conventional and non-conventional technologies, decision-making processes, cultures and beliefs. There also exists "multiple social and economic barriers to capital flow and technology diffusion" (Pandey, 2002). At the same time, the energy industry is undergoing major changes under the global influence of reform and restructuring. Consequently, a state of transition prevails both in supply and demand sides of the energy industry that makes these economies different from the steady-states of developed markets. Finally, the possibility of learning from others and leapfrogging technological developments renders discontinuities in the development path quite likely.

2.2 Considerations for energy demand modeling

The specific features of developing countries have implications for energy demand analysis and modeling. As early as 1979, Pindyck highlighted the data difficulties for any serious energy demand analysis for developing countries and resorted to a simple log-linear formulation for developing countries because of data constraints. Similarly, Bhatia (1987) had also listed a number of concerns for developing countries. Worrell et al (2004) highlight a number of modeling challenges, including, among others, data quality, capturing technological potential and technology penetration, capturing inter-sectoral and intra-sectoral structural changes, and including external costs of different energy use.

We formulate a set of criteria/ issues that we use in the rest of the paper to ensure a consistent and systematic focus on specific developing country concerns. We divide these into three groups relating to three major sections of this paper, namely, theoretical understanding of demand, review of practical applications and specific models.

Theoretical understanding:

a) Applicability to traditional energies: Does the theory apply to non-traded traditional energies?
b) Inclusion of informal activities: Does the theory apply to informal sector activities?
c) Capability to explain new demand: Can the theory be applied to emerging demands?

d) Adaptability: Is the understanding adaptable to discontinuities in development paths?
e) Non-manifested demand: Does the theory apply to non-manifested demand?
f) Drivers of demand: Are non-price drivers included in the analysis?

Review of analysis of demand:

a) Energy coverage: Does the application include traditional energies?
b) Geographical coverage: Does it distinguish between rural and urban areas?
c) Economic coverage: Are informal activities covered?
d) Non-manifested demand: Is unmet demand covered?
e) Technology coverage: Is technological diversity captured?
f) Economic drivers: Which economic drivers are included?
g) Non-economic drivers: Are non-economic policies and drivers included?
h) Skill requirement: Does it require high skills?
i) Data requirement: Is the data required for the analysis available?

Specific Models:

a) Type: Which modeling tradition does the model follow? Top-down or bottom-up or hybrid approach.
b) Purpose: What is the main objective of the model?
c) Approach: In the given modeling tradition, which method does it follow?
d) Geographical coverage: Does the model consider urban-rural divide?
e) Activity coverage: Does the model cover any specific sector or is it a general purpose model?
f) Level of disaggregation: What is the level of disaggregation used in the model?
g) Technology coverage: How is technology represented, explicitly or implicitly?
h) Data requirement: How much data does the model require? What is the nature of data required for running the model?
i) Skill requirement: Does the model require any special skill set?
j) Versatility: Is it a country-specific model or a general model?
k) Portability to other countries: Is the model portable from one country to another?

l) Documentation: How good and transparent is the model documentation?
m) Capability to analyze price-induced policies: Is the model able to analyze price-induced effects?
n) Capability to analyze non-price induced policies: Is the model capable of analyzing non-price policies?
o) Rural energy: Is rural and traditional energies captured in the model?

3. Understanding Energy Demand

Energy demand is a derived demand that arises for satisfying some needs which are met through use of appliances. Hence, demand for energy then depends on the demand for energy services and the choice of energy using processes or devices. End-use service demand is affected by the cost of energy but also by other factors such as climatic conditions, affordability (or income of the decision-maker), preference for the end-use service, etc. Similarly, demand for end-use appliances depends on the relative prices of the appliances, relative cost of operation, availability of appliances, etc.

The dynamics of energy demand is influenced by the inertia of appliance stocks, which leads to limited flexibility. At any given time any consumer would possess a stock of some particular devices with specific operating characteristics (such as efficiency and costs). The stock cannot be changed immediately and therefore the response to any stimulation would come from behavioral changes (i.e. rate of use of the appliance, acceptance of lower levels of comforts, etc.) while using the same appliances. Over a longer period of time, consumers may find changing the stock of appliances remunerative. Similarly, new procurements would incorporate the characteristics preferred by consumers given the changes in the market conditions. Therefore, in the short run the response is partial while the total response would be cumulate over time.

Energy demand analysis has attempted to capture these aspects in different ways: the traditional economists' approach relies on optimizing behavior within the neoclassical tradition of economics. Another approach follows the engineering tradition and criticizes the limitations of the optimizing and rational behavior assumed in the traditional analysis. Instead, they introduce other behavioral assumptions (such as "satisficing" approach in the sense of Herbert Simon or evolutionary approach for technological change) and beliefs.[1] This divergence in the views has dominated the energy literature in the past and led to the emergence of two distinct traditions of energy analysis – namely the econometric approach and the engineering end-use approach.

3.1 Economic foundations of energy demand[2]

The factors driving energy demand differ across economic agents and sectors. Households consume energy to satisfy certain needs and they do so by allocating their income among various competing needs so as to obtain the greatest degree of satisfaction from total expenditure. Industries and commercial users demand energy as an input of production and their objective is to minimize the total cost of production. Therefore the motivation is not same for the households and the productive users of energy and any analysis of energy demand should treat these categories separately.

3.1.1 Household energy demand

The microeconomic basis for consumer energy demand relies on consumers' utility maximization principles. Such an analysis assumes that consumers know their preference sets and ordering of preferences. It also assumes that preference ordering can be represented by some utility function and that the consumer is a rational one in that she will always choose a most preferred bundle from the set of feasible alternatives.

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[1] See Worrel et al (2004) and Wilson and Dowlatabadi (2007).

[2] This section relies on Bohi (1980), Chapter 2, Estimating the demand for energy: Issues and Methodologies. Similar treatments are also provided in Hartman (1979) and Munasinghe and Meier (1992).

Following consumer theory, it is considered that an incremental increase in consumption of a good keeping consumption of other goods constant, increases the satisfaction level but this marginal utility (or increment) decreases as the quantity of consumption increases. Moreover, maximum utility achievable given the prices and income requires marginal rate of substitution to be equal to the economic rate of substitution. This in turn requires that the marginal utility per dollar paid for each good be the same. If the marginal utility per dollar is greater for good A than for good B, then transferring a dollar of expenditure from B to A will increase the total utility for the same expenditure. It follows that reduction in the relative price of good A will tend to increase the demand for good A and vice versa. (See Box 1 for the mathematical formulation of the problem).

Box 1: Utility maximization and energy demand

Consider that the utility function of a consumer can be written as

Utility $u = U(X_1, X_2, X_3, \ldots, X_n)$ Eq. 1

The consumer has the budget constraint

$I = p_1X_1 + p_2X_2 + \ldots + p_n X_n$ Eq. 2

For maximization of the utility subject to the budget constraint, set the lagrange

$L = U(X_1, X_2, X_3, \ldots, X_n) - \lambda(I - (p_1X_1 + p_2X_2 + \ldots + p_n X_n))$ Eq. 3

Setting partial derivatives of L with respect to X1, X2, X3,…, Xn and λ equal to zero, n+1 equations are obtained representing the necessary conditions for an interior maximum.

$\delta L/\delta X_1 = \delta U/\delta X_1 - \lambda p_1 = 0;$
$\delta L/\delta X_2 = \delta U/\delta X_2 - \lambda p_2 = 0$
.
.
.
$\delta L/\delta X_n = \delta U/\delta X_n - \lambda p_n = 0$
$\delta L/\delta \lambda = I - p_1X_1 + p_2X_2 + \ldots + p_n X_n = 0$

From above, $(\delta U/\delta X_1)/(\delta U/\delta X_2) = p_1/p_2$ or MRS = p_1/p_2
$\lambda = (\delta U/\delta X_1)/p_1 = (\delta U/\delta X_2)/p_2 = \ldots = (\delta U/\delta X_n)/p_n$

Solving the necessary conditions yields demand functions in prices and income.

$X_1^* = d_1(p_1, p_2, p_3, \ldots p_n, I)$
$X_2^* = d_2(p_1, p_2, p_3, \ldots p_n, I)$
.

.

.

$X_n^* = d_n(p_1, p_2, p_3, \ldots p_n, I)$

Source: Bohi (1981).

An individual demand curve shows the relationship between the price of a good and the quantity of that good purchased, assuming that all other determinants of demand are held constant. The market demand function for a particular good is the sum of each individual's demand for that good. The market demand curve for the good is constructed from the demand function by varying the price of the good while holding all other determinants constant.

3.1.2 Industrial and commercial energy demand

In the case of industry and commercial sectors, energy is used as an input to produce an output (or outputs). The theory of the producers is used to determine energy demand in both sectors. Like households, producers face certain constraints:

a) The production process has its own technical limitations that specify the maximum output levels for a given combination of inputs.
b) The capacity of the plant at any given time is fixed and cannot be exceeded.
c) There may be constraints on the availability of certain inputs.

Production of any good is expanded until an additional increment of the good produced in the most efficient manner makes no further contribution to net revenue. Similarly, any factor of production will be increased until, other inputs remaining unchanged, an additional unit of the factor yields no additional net revenue. In order to minimize the cost of any given level of input, the firm should produce at that point for which the rate of technical substitution is equal to the ratio of the inputs' rental prices. The solution of the conditions leads to factor demand functions. Box 2 provides the mathematical formulation of the above.

Box 2: Cost minimization problem of the producer

In the case of producers, the theory of the producers is used to determine the demand for factors of production. Production of any good is expanded until an additional increment of the good produced in the most efficient manner makes no further contribution to net revenue. Similarly, any factor of production will be increased until, other inputs remaining unchanged, an additional unit of the factor yields no additional net revenue.

Consider a firm with single output, which is produced with two inputs X1 and X2. The cost of production is given by

$TC = c_1X_1 + C_2X_2$ Eq. 1

This is subject to

St $q_0 = f(X_1, X_2)$ Eq. 2

The first order conditions for a constrained minimum are:
$\delta L/\delta X_1 = c_1 - \lambda\ \delta f/\delta X_1 = 0$ Eq. 3
$\delta L/\delta X_2 = c_2 - \lambda\ \delta f/\delta X_2 = 0$ Eq. 4

From above, $c1/c2 = (\delta f/\delta X_1)/(\delta f/\delta X_2)$ = RTS (X1 for X2) Eq. 5

In order to minimize the cost of any given level of input, the firm should produce at that point for which the rate of technical substitution is equal to the ratio of the inputs' rental prices.

The solution of the conditions leads to factor demand functions.

3.1.3 Transport energy demand

For energy demand in the transport sector, three types of generic approaches are found: a) identity models, b) structural models and c) the market-share model.

The identity models consider the demand for a transport fuel to be equal to the product of vehicle utilization rate and total stock of vehicles. This can be expressed as

$$D_t = S_t * R_t * U_t, \qquad (1)$$

where D_t is the demand for fuel at time t, S_t is the vehicle stock, R_t is the utilization rate (kilometers per year) and U_t is the unit energy consumption (litre per kilometer). The demand is estimated by estimating the each component separately and the overall demand is obtained using the identity. Uri (1982) provides an early example of application of this model econometrically. This identity is generally used in end-use models as well but applied as a disaggregated level.

The structural model on the other hand considers the demand for the transport services and derives the demand for energy related to those transport services as a derived demand. The demand for transport services is explained using the basic consumer theory assuming that profit maximizing firms choose the transport service to minimize costs of production (see Box 3 for details[3]). For given cost minimizing demands for transport services, the derived demand for specific fuels is developed.

The market-share model on the other hand considers the inter-fuel substitution possibilities. To ensure a consistent outcome, the demand is estimated using a set of simultaneous equation systems.

Clearly, the neo-classical foundation of the above theories of demand analysis assumes the completeness of markets and the participation of energy products in the market. Any energy that remains outside the market system is not covered. Accordingly, traditional energies which are collected by the users and for which no monetary transactions take place will not be covered by these theories. In addition, the external effects of energy use, to the extent they are not captured through the market pricing system, will not enter into the decision-making process, thereby providing incorrect resource allocation information and decisions. Informal economic activities will also not be included, thereby providing inaccurate information and forecasts.

Accordingly, the key assumptions imbedded in the theoretical foundation might be unrealistic in the context of developing countries. The co-existence of market and non-market based energy supplies introduces a complex decision-making which requires considering monetary and non-monetary transactions. Box 4 explains the necessity to

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[3] This follows Berndt and Botero (1985).

incorporate traditional energy in energy demand modeling exercises in developing countries. Ignoring an important energy source from analysis due to data constraints or limitations of the analytical framework does not provide a realistic or correct picture.

Box 3: Structural models of transport fuel demand

The structural models generally determine the transport fuel demand using a two-stage process. In the first stage, the demand for transport services is related to the distance traveled by passengers (indicated by passenger-kilometers) and freight transport (indicated by ton-kilometers). For these two types of transport demand, the basic theories of consumer demand and producer demand are used.

For passenger demand, it is assumed that individuals maximize their utility through optimal selection of their goods and services operating within their budget constraint. The demand function is derived from the constrained optimization of the utility function. This yields the demand function of the following form:

$PT = f1(I, Pp, W, D)$ (1)
Where PT is the passenger transport demand function,
I is the real income
Pp is the price of passenger transport,
W is the price vector for other goods and services,
D is a vector of other demographic variables.

For freight transport, let us assume that the industry using the transport services minimizes its cost. Let the cost function be denoted by

$C(P_f, Po, X, Q)$
where (2)
P_f is the price for freight transport (per ton kilometer)
Po – the price vector for other inputs,
X is a vector of fixed factor quantities,
Q is the level of output.

The cost minimizing demand for freight is obtained by differentiating the cost function with respect to P_f, which yields the demand equations of the following form:
$FT = f2(Q, P_f, Po, X)$ (3)

Given the demand for PT and FT, the demand for specific fuels is obtained assuming appropriate separability of functions. It is now considered that the utility or cost function contains the relevant passenger or freight demand, the price of the relevant fuels and other factor inputs or variables. The demand function for a specific fuel is obtained by differentiating Eq. 3 with respect to its price and takes the following form:

$Demand = g(PT, FT, P)$ (4)
The two-stage econometric model for transport fuel demand is thus obtained.

Source: Berndt and Botero (1985).

Box 4: Rationale for traditional energy use in developing countries

Any energy use involves costs and resource allocation problems. Both traditional energies (TE)[4] which play a crucial role in the energy profile of the poor, and modern energies impose private and social costs. The private cost may be in monetary terms or in terms of time spent by the family members to collect the TEs. For collected TEs, the problem of valuation of the cost arises and the collected fuel is considered as free fuel by many, even perhaps by the poor themselves, as no monetary transactions are involved. However, depending on the quantity of collected fuel, its source and the type of labor used in the collection process, the private cost and social cost can be substantial. The social cost arises due to externalities arising from pollution and other socio-economic problems related to particular forms of energy use.

The entire decision-making process for use of any modern energy form (electricity, kerosene or LPG, or renewable energies) as opposed to any other form of traditional energies revolves around monetary transactions. Any commercial energy requires monetary exchanges and the decision to switch to commercial energies can be considered a three-stage decision-making process. First, the household has to decide whether to switch or not (i.e. switching decision). Second, it decides about the types of appliances to be used (i.e. appliance selection decision). In the third stage, consumption decision is made by deciding the usage pattern of each appliance (i.e. consumption decision).

While the costs do not always lend themselves to monetary-based accounting, the switching decision is largely determined by monetary factors: the amount and regularity of money income, alternative uses of money and willingness to spend part of the income to consume commercial energies as opposed to allocating the money to other competing needs. Appliance selection is affected by similar factors: cost of appliance, the monetary income variables described above and the availability of financing for appliance purchases through formal and informal credit markets. Finally, the consumption decision depends on, among others, family size, activities of the family members, availability of appliances and family income.

This framework of three-stage decision-making helps in analyzing the problem in a logical manner. The poor normally lack regular money income flows due to unemployment or part-employment, both of which sometimes produce in-kind payments as compensation. Moreover, they often participate in informal sector activities, where barter rather than monetized transactions prevail. It is rational for any household or individual to focus on private monetary costs rather than social and/or non-monetized costs due to the inherent subjectivity and complexity of the valuation problem. Moreover, any modern energy has to compete with other goods and services (including saving for the future) procured by the household for an allocation of monetary resources. Given above characteristics and constraints, it is quite logical for the poor to have a natural preference for the fuel that involves no or minimum money transactions. Reliance on firewood and other traditional energies used for cooking, which constitute the major source of energy demand by the poor, can be explained using this logic.

Source: Bhattacharyya (2006).

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[4] We use the term ‘traditional energies’ to ‘non-commercial energies’ to avoid any confusion arising out of monetisation or commercialisation of some of such fuels.

Bhattacharyya (1997) further noted that "The application of economic theories that presuppose the existence of monetized markets and are concerned only with agents involved in such markets faces serious conceptual problems in dealing with economies that do not conform to such stereotypes. Serious conceptual difficulties and incompatibilities arise in the valuation of goods for which no tangible payment is made. For energy goods, the problem is further complicated by the fact that these are not goods for direct consumption but intended to derive certain end-use, which could be satisfied by a number of substitutes. Evaluating the contribution of these energies in monetary terms when some are acquired through non-money activities still rests problematic. Because non-money activities often occupy a far greater share than the monetized part in the rural energy of a developing economy, it is thus imperative that any and every economic indicator for these sectors and the whole economy should take into account both the monetized and the non-monetized sectors, as well as their mutual interaction".

While the theory is capable of capturing non-price variables in principle, the implementation in actual models would show how far this is captured. Similarly, the reliance on consumption data implies that only the satisfied demand is captured in the energy statistics. Using consumption and demand interchangeably implies that the non-manifested demand is not taken into consideration in practice. This again can introduce a bias in the analysis by providing an inaccurate picture in developing countries. Hence, the prescriptions based on standard economic theories can be misleading.

3.2 Energy demand forecasting techniques

A review of the demand forecasting approaches suggests existence of a large variety of techniques used by different sets of users. Werbos (1990) presents the distinction between modeling approaches very succinctly through an example. Let us assume that we want to forecast population in the following year based on present year information. We write the following relationship:

$$POP(t+1) = c.POP(t), \quad (2)$$

Where c is a constant and POP is the population, t is the time period.

If the value of c is obtained by asking the boss, the forecast is based on the judgmental approach. If c is obtained through small-scale studies of controlled population, the model can be called an engineering model. If c is obtained by analyzing the time series of historical population, the model can be called an econometric model or a model estimated using the econometric approach.[5]

Lipinsky (1990) suggested a three dimensional categorization of demand forecasting models based on complexity (simple-complex), dynamics (static-dynamic) and uncertainty (deterministic – probabilistic). In this study we have retained a simple classification of two broad categories: simple approaches and sophisticated approaches. In between there are direct surveys, which are also used for demand forecasting purposes.[6]

3.2.1 Simple approaches

The simple approaches are easy to use indicators that can provide a quick understanding. Such techniques are relatively less common in academic literature although practitioners rely on them in many cases. Four such simple indicators commonly used for forecasting are: growth rates, elasticities (especially income elasticity), specific or unit consumption and energy intensity (See Box 5 for details). In addition, trend analysis that finds the growth trend by fitting a time trend line is also commonly used. All of these approaches rely on a single indicator and the forecast is informed by the assumed changes in the indicator during the forecast period. Clearly these methods lack explanatory power and

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[5] See Werbos (1990) for a highly readable, non-technical introduction to econometric approach of demand forecasting. See also Munasinghe and Meier (1993), Siddayao (1986), Codoni et al (1985), Donnelly (1987) for further details.

[6] See Codoni et al (1985), Siddayao (1986), Munasinghe and Meier (1992), Craig et al (2002) for further discussions on some of these models.

being based on extrapolation or arbitrary assumption, their attractiveness for any long-term work is rather low.

Despite their weaknesses, this approach is used for its simplicity. Westoby and Pearce (1984) note that most of the earlier work on energy forecasting in the UK used the “energy ratio” (which is popularly known as energy intensity”) and the “energy coefficient” (i.e. the elasticity of energy demand with respect to national income or GDP). This practice was discontinued only in the early 1980s when the reliance on sophisticated models started to rise. Similarly, Codoni et al (1985) reported the use of income elasticity of demand for an energy assessment study of Korea. Grover and Chandra (2006) report that Indian state agencies rely on income elasticities for forecasting primary energy and electricity demand[7]. In two recent reports on energy policies of India and China[8], simple measures of GDP-elasticity and energy intensities have been used for demand forecasting for ten or more years. Some studies [e.g. in Armstrong (2001), Craig et al (2002), and Westoby and Pearce (1984)] argue that simple models can sometimes produce accurate results similar to those obtained from sophisticated ones. Many sophisticated models also retain simple techniques in some of their sub-components. For example, intensities or gdp-elasticities are commonly used in engineering-economic models while growth rates and elasticities are often used for forecasting independent variables in econometric approaches. In addition, these techniques can be used both at the aggregated and disaggregated levels. The virtue of simple models is that the skill and data requirement is low and such models are more tractable rather than the hidden assumptions of complex models (Brown, 1984). This is further supported by Craig et al (2002) who found that many long-term forecasts using sophisticated models for the USA produced inaccurate forecasts in the past. Armstrong (2001) echoes the same view and states that “simple models can sometimes yield results as accurate as more complicated techniques.”

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[7] Grover and Chandra (2006) also made long-term electricity demand forecasts (up to 2052) for India based on certain assumptions about GDP-elasticity of electricity demand.

[8] See GOI (2006) and Berrah et al. (2007).

Box 5: Simple approaches for energy demand forecasting

Growth-rate based method

Let g be the growth rate in demand and D_0 is the demand in year 0, then D_t can be obtained by

$$D_t = D_0 (1+g)^t \qquad (1)$$

Elasticity-based demand forecasting

Elasticity is generally defined as follows:

$$e_t = \frac{(\Delta EC_t / EC_t)}{(\Delta I_t / I_t)} \qquad (2)$$

where
t is a period given
EC is energy consumption
I is the driving variable of energy consumption such as GDP, value-added, price, income etc.
Δ is the change in the variable.

In forecasting, output elasticity or income elasticity is commonly used. The change in energy demand can be estimated by assuming the percentage change in the output and the output elasticity. Normally, the elasticity is estimated from past data or gathered using judgment. The output change is taken from economic forecasts or planning documents.

Specific consumption method

Energy demand is given by the product of economic activity and unit consumption (or specific consumption) for the activity.
This can be written as E = A x U (3)
Where A is level of activity (in physical terms)
U is the energy requirement per unit of activity
These two factors are independently forecast and the product of the two gives the demand.

Ratio or intensity method

Energy intensity is defined as follows:
EI = E/Q (4)
Where EI – energy intensity,
E = energy demand
Q = output
This can be rearranged to forecast energy demand E = EI.Q
Using the estimates for Q for the future and assumptions about future energy intensity, the future energy demand can be estimated.

Clearly, simple methods can be applied for both commercial and traditional energies and can be used both in urban and rural areas. They could be used to include the effects of informal activities and unsatisfied demand. However, they neither explain the demand drivers, nor consider technologies specifically. They only rely on the value judgments of the modeler, wherein lies the problem. Further, these methods do not rely on any theoretical foundation and accordingly, they are ad-hoc approaches.

3.2.2 Sophisticated approaches

Sophisticated models employ more advanced methodologies. Such models can be classified using alternative criteria: for example, a common method of classification is the top-down and bottom-up models. Top-down models tend to focus on an aggregated level of analysis while the bottom-up models identify the homogeneous activities or end-uses for which demand is forecast. Another classification relies on the modeling philosophy:

- econometric models are grounded in the economic theories and try to validate the economic rules empirically;
- engineering-economy models (or end-use models on the other hand attempt to establish accounting coherence using detailed engineering representation of the energy system; and
- combined or hybrid models attempt to reduce the methodological divergence between the econometric and engineering models by combining the features of the two traditions.[9]

Some other models are also indicated in the literature – system dynamics models, scenario approaches[10], decomposition models[11], process models,[12] input-output models, and artificial neural networks[13].

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[9] See Reister (1990) for an example. We also discuss the POLES model in section 4, which can also be considered a hybrid model.

[10] See Ghanadan and Koomey (2005) for an example.

[11] See Sun (2001). The results of the study show a significant divergence with actual EU15 demand.

[12] See Munasinghe and Meier (1993) and Labys and Asano (1990).

[13] Al-Saba and El-Amin (1999) for an application.

This section briefly introduces these techniques to facilitate a review of modeling literature in section 4 below.

3.2.2.1 Econometric approach

This is a standard quantitative approach for economic analysis that establishes a relationship between the dependent variable and certain chosen independent variables by statistical analysis of historical data. The relationship so determined can then be used for forecasting simply by considering changes in the independent variables and determining their effect on the dependent variable.

This approach has the theoretical appeal because of its close link with the theory of consumers and the production theory. The set of potentially important variables to be tested in the model can be drawn from the appropriate theory and the influence of these factors is evaluated statistically. Normally the statistically relevant factors are considered and included in the estimated demand function. It is usual to test alternative functional forms to identify the most appropriate one but as the number of independent variables increases, the set of possible combinations increases exponentially, making the choice more difficult.

The degree of sophistication of econometric estimations varies widely: the single equation, reduced form estimations forms the basic level of analysis. The market share approach is also used in certain cases, especially for transport fuels. In such a case, the total demand is estimated jointly through one equation and the market share of each fuel is then estimated separately through another set of equations. More complex estimations based on simultaneous equation expenditure share models are also used. This approach has been applied to total aggregate energy demand as well as demand in individual sectors (industry, transport, residential, etc.). Even the econometric analysis has been applied to the entire energy system using the energy balance framework (e.g. Adams and Shachmurove, 2008).

The econometric approach has seen significant developments over the past three-four decades. In the 1970s, the main aim was to understand the relationship between energy and other economic variables. Pindyck (1979) succinctly captures this as follows:

> "We have had a rather poor understanding of the response of energy demand in the long run to changes in prices and income, and this has made it difficult to design energy and economic policies. By working with models of energy demand rather different from those that have been used before and by estimating these models using international data, we can better understand the long-run structure of energy demand and its relationship to economic growth".

Hartman (1979) summarizes the developments during the 1970s as follows:

> "Many early attempts in residential, commercial and/ or industrial demand modelling were aggregate, single equation, long-run equilibrium demand models focusing on a single fuel. Such models, in general, utilised only fuel price as a decision variable; they paid little attention to the characteristics of fuel-burning equipment and the differences between long-run and short-run demand. In the face of a growing awareness of the inadequacies of these models, the equilibrium models gave way first to more dynamic partial-adjustment demand models for a single fuel and then to partial-adjustment inter-fuel and inter-factor substitution models for residential, commercial and industrial energy demand."

Griffin (1993) has identified three major developments since 1970s, namely, the trans-log revolution, panel data methodology and the discrete choice method. Wirl and Szirucsek (1990) remarked that the trans-log function emerged as the preferred choice of researchers due to its flexible properties. This allowed investigations into capital energy substitutability and technical change questions. A large number of studies appeared in the 1970s and 1980s that applied the trans-log model at the aggregated level and disaggregated level, including Brendt and Wood (1975 and 1979), Pindyck (1979), Uri (1979a and 1979b), Siddayao et al (1987), Saicheua (1987), Christopoulos (2000), Dahl and Erdogan (2000), and Buranakunaporn and Oczkowsky (2007). The panel data analysis approach allowed capturing interregional variations that can be considered to reflect the long-term adjustment process as opposed to short term adjustment reflected in the time series data. The discrete choice method on the other hand relies on the stock and its utilization decision to determine demand. Despite its appeal this method found limited econometric use due to lack of capital stock data. The development of multinomial logit model represented a break-through in this regard.

In the 1980s the assumption of stationarity of economic variables assumed in the standard ordinary least square (OLS) method of estimation was questioned. It was suggested that many variables used in energy demand analysis (e.g. energy consumption, real energy prices, and real income) have a root close to unity and are integrated of degree 1. Using non-stationary data in regression results spurious results unless the variables are cointegrated.[14] The problems include non-stationary error process, autocorrelation of explanatory variables, non standard distribution of coefficient estimates and endogeneity problem. As a solution to the problem, tests for co-integration and estimation of vector error correction models have emerged. This development in the econometric analysis has significantly influenced the energy demand studies in the 1990s and brought the "unit-root revolution". It is now a routine exercise in the academic literature to test for stationarity and co-integration of variables before undertaking any forecasting exercise econometrically.

However, Harvey (1997) criticized this over-reliance on co-integration as "unnecessary or misleading or both". Harvey (1997) argued that "The use of autoregressive models and associated unit root tests forces the researcher into a specific way of modeling which effectively excludes forecasting and decomposition procedures which may be more effective and have a more natural interpretation". He also suggests that the statistical properties of the method are poor and consequently, there is limited justification for such a systematic use of this method. Instead, he has proposed an alternative method called the Structural Time Series models, which have been applied to the energy demand, among others, by Hunt et al (2003) and Adeyemi and Hunt (2007).

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[14] See Engsted and Bentzen (1997) for a non-technical review of these developments. See also Bentzen and Engsted (1993).

Moreover, these studies have generally focused on the aggregated demand and considered a limited driver variables such as GDP and price, and do not capture the technological changes or other non-price related policies. Even the results from these sophisticated methods seem to depend on model specification and the strategies for data analysis. For limited sample sizes, these methods are unlikely to produce appropriate results. Consequently, simple OLS estimates still continue, perhaps in the belief that even if they are non-stationary, there exists a co-integration relationship so that the simple regression yields super-consistent results.

3.2.2.2 End-use approach

The end-use approach or engineering-economy approach (also known as the “bottom-up” approach) is another widely used energy demand forecasting tradition that focuses on end-uses or final needs at a disaggregated level. Although this tradition has its origin in the process-type energy systems models, the first systematic elaboration of the method and an application to France was reported by Chateau and Lapillonne (1978). Since then, this approach gained prominence through works at the International Institute of Applied Systems Analysis (IIASA), International Atomic Energy Agency (IAEA), Lawrence Berkeley Laboratory (LBL) and elsewhere and has emerged as an alternative method of energy demand forecasting (See Lapillonne (1978), Lapillonne and Chateau, (1981), Finon and Lapillonne (1983), among others). Wilson and Swisher (1993) suggest that the motivation for the “bottom-up” movement arose from the high demand forecasts in the 1970s that raised eyebrows of researchers who were wondering where so much energy would be used. This resulted in a different type of investigation that led to the realization that economic growth and high quality of life could be maintained even with lesser energy supplies.

Worrel et al (2004) argue that although price clearly matters and significantly influences energy use decisions, it is not all that matters. The wider non-price policies and industry interactions require (Worrel et al (2004)):

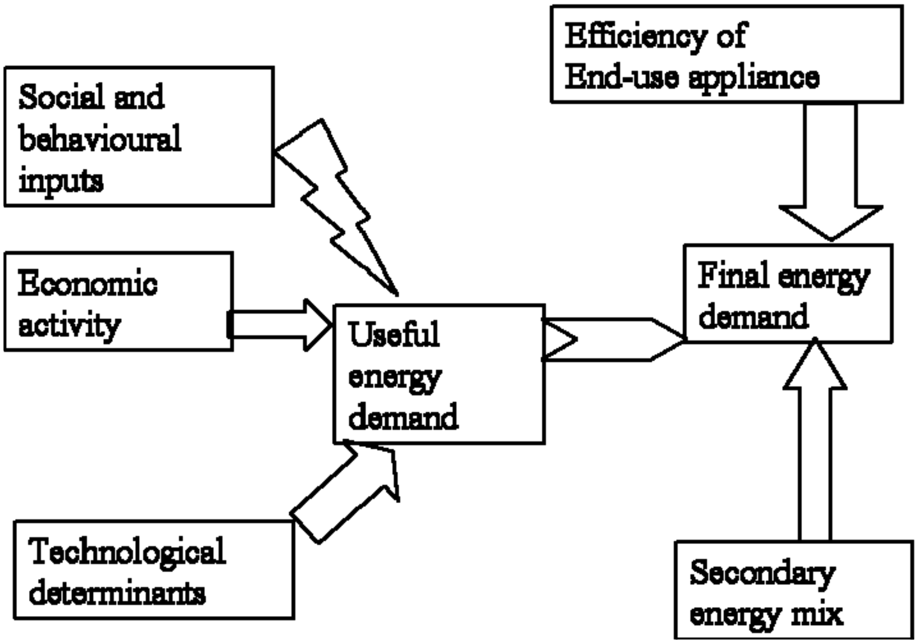
> "a comprehensive assessment of policy impacts and program effects, effectiveness, and efficiency. The variety also means that the standard neoclassic economic framework is insufficient for energy models aiming to explore the different dimensions of potential policy impacts."

Bottom-up models offer such an alternative option for capturing different policy dimensions more closely.

This method involves the following general steps [UN (1991) and IAEA (2006)]:
- Disaggregation of total energy demand into relevant homogenous end-use categories or modules;
- A systematic analysis of social, economic and technological factors
    - to determine the long-term evolution
    - Identification of interrelationships
- Organization of determinants into a hierarchical structure
- Formalization of the structure in mathematical relationships
- Snap-shot view of Reference year
    - foundation of the forecasting exercise
    - All relevant data and mathematical relationships developed
    - Reference year is taken as the most recent year for which data is available
- Scenario design for the future
- Quantitative forecasting using mathematical relations and scenarios

These steps are presented in a visual form in Fig. 1. The formulation of a demand model for electricity can be found in Swisher et al (1997).

Fig. 1: Generic end-use approach



A wide variety of models have been developed following this alternative approach but the models differ in terms of their level of disaggregation, technology representation, technology choice, model goal, and the level of macro-economic integration (Worrel et al, 2004). Generally end-use models either follow a simulation approach or an optimization goal, while the technology representation can be either explicit (where specific technologies are considered) or stylistic. The macro-economic linkage is often restricted to ad-hoc or judgmental use of key driver variables but some models are driven by a separate macro-model that captures the interaction with the macro-economy. Table 1 provides a few examples of such models, while Appendix 1 provides more information about some end-use models.

Table 1: Examples of end-use models

Characteristics	Technology representation	Models
Simulation models without macro-links	Explicit	MEDEE/MAED, LEAP, ENUSIM,
Simulation models without macro-links	Stylistic	LIFF
Optimisation models without macro-links	Explicit	EFOM, MARKAL, MESAP
Optimisation models with macro-links	Explicit	MARKAL-MACRO,

Source: This study.

Most of the end-use models emerged after the first oil price shock in the 1970s but many have undergone major evolution to reach their present state. For example, the technological representation in MARKAL is supported by a detailed database. Similarly, the case examples and the modeler community have grown and sharing of experience is often possible through dedicated reference libraries, discussion forums and training. Further, most of the models now run on PC versions and can operate on a stand-alone basis.

As most of the end-use models do not rely on the neo-classical economic paradigm, it brings a very different perspective on energy system analysis. These models are capable of capturing rural-urban divide and can include informal activities. They can also capture the diversity of actual processes and technologies of energy conversion and use, and accordingly need not rely on stylistic, aggregate and a single vintage representation of technologies. As these models do not rely only on past history or evolution, they can capture structural changes and new technological developments. In fact, this is one of the major strengths of this category of models. Through the formulation of different scenarios these models try to capture different development trajectories and the influences of policies on economic development. However, accounting-type end-use models suffer from their inability to capture price-induced effects alongside non-price policies, thereby reducing their effectiveness for certain policy analyses. Moreover, the issue of overall consistency of the isolated assumptions used in the models looms large in models which do not include a macro-linkage.

3.2.2.3 Input-output models

The input-output method has long been used for economic analysis. It provides a consistent framework of analysis and can capture the contribution of related activities through inter-industry linkages in the economy. Thus the input-output method is able to capture the direct energy demand as well as indirect energy demand through inter-industry transactions. This feature makes this method an interesting analytical tool. Box 6 provides the basic mathematical relationships used in the Input-Output models. Some recent studies using this approach for energy demand forecasting include Wei et al (2006), Tiwari (2000), Liang et al (2007), and O'Doherty and Tol (2007).

The data requirements of basic input-output analysis are very demanding. They are even more demanding if individual fuel, energy services and relative price variables are explicitly incorporated. Specific problems may include nonexistent data, inaccurate data, inappropriately classified data and data collected for inconsistent time intervals. The assumption of constant input-output coefficient which implies that the input and output changes are both strictly proportional and invariant over time is a restrictive assumption. These restrictions prohibit an analysis of inter-fuel substitution possibilities and allowance for substitution among non-energy inputs. The assumptions implied about relative prices remaining constant can be quite restrictive if relative prices were to vary significantly in practice. This may or may not be crucial, depending on the particular developing country. The static input-output models do not contain theory of investment behavior or treatment of technical change behavior.

Although this is a disaggregated approach, the details normally pertain to the industrial activities, while other actors or agents are normally represented by a single representative entity. Thus despite its detailed analytical structure, the rural-urban divide is hardly captured. Similarly, the technological diversity is difficult to capture within a given sector of activity. Moreover, as these tables are based on national accounting information, they exclude informal activities and non-monetary transactions. It is also difficult to use this approach for new demand or technologies as the input-output relations have to be established across sectors. However, price-induced policies are easily captured through these models.

Box 6: Energy demand analysis using Input-Output approach

The value of output relations in a set of inter-industry accounts can be defined as:

$$X_i = \sum_{j=1}^{n} X_{ij} + \sum_{k=1}^{r} F_{ik}\,;\; i = 1,\ 2, \ldots n \qquad (1)$$

where X_i is the value of total output of industry i, X_{ij} is the value of intermediate goods' output of industry i sold to industry j, and F_{ik} is the value of final goods' output of industry i sold to final demand category k (net of competitive import sales).

The final demand arises from a number of sources, which is shown in Eq. 2:

$$\sum_{k=1}^{r} F_{ik} = C_i + \Delta V_i + I_i + G_i + E_i - M_{Fi} \qquad (2)$$

where C_i is the value of private consumer demand for industry i final output, V_i is the value of inventory investment demand for industry i final output, I_i is the value of private fixed investment demand for industry i final output, G_i is the value of government demand for industry i final output, E_i is the value of export demand for industry i final output and M_{Fi} is the value of imports of industry i final output (and often referred to as competitive imports).

It is assumed that intermediate input requirements are a constant proportion of total output, which is expressed as:

$$a_{ij} = \frac{x_{ij}}{X_j} \qquad (3)$$

where a_{ij} is the fixed input-output coefficient or technical coefficient of production.

Equations 1, 2 and 3 can be written more concisely in matrix form as

$$X = AX + F \qquad (4)$$

F = vector of final demand,
A = matrix of inter-industry coefficients
X = vector of gross outputs

The well-known solution for gross output of each sector is given by

$$X = (I-A)^{-1}F \qquad (5)$$

Where I is the identity matrix, and $(I-A)^{-1}$ is the Leontief inverse matrix.

Thus, given the input-output coefficient matrix A, and given various final demand scenarios for F, it is straightforward to calculate from equation 5, the corresponding new values required for total output X, and intermediate outputs x_{ij} of each industry.

For energy analysis, the basic input output model is extended to include energy services. It is considered that the input-output coefficient matrix can be decomposed and expanded to account for energy supply industries (e.g. crude oil, traditional fuels, etc.), energy services or product equations (e.g. agriculture, iron and steel, water transportation).

Equation 5 is modified to a more general system as shown in equation 6.

$$A_{ss}X_s + A_{sp}X_p \qquad + F_s = X_s$$

$$A_{ps}X_s \quad + A_{pi}Xi \quad + F_p = X_p$$
$$A_{is}X_s \quad + A_{ii}X_i \quad + F_i = X_i \qquad (6)$$

Where X_s = output vector for energy supply,
X_p = output vector for energy products,
X_i = output vector for non-energy sectors,
F_s = final demand for energy supply,
F_p = final demand for energy products,
F_i = final demand for non-energy sectors.
A_{ss} = I/O coefficients describing sales of the output of one energy/ supply conversion sector to another energy conversion sector.
A_{sp} = I/O coefficients describing how distributed energy products are converted to end-use forms.
A_{si} = 0 implying that energy supplies are not used by non-energy producing sectors. Energy is distributed to the non-energy producing sectors via energy product sectors.
A_{ps} = I/O coefficients describing how energy products – final energy forms – are used by the energy supplying industries.
A_{pp} = 0 implying that energy products are not used to produce energy products
A_{pi} = I/O coefficients describing how energy products – final energy forms are used by non-energy producing sectors.
A_{is} = I/O coefficients describing the uses of non-energy materials and services by the energy industry.
A_{ip} = 0 implying that energy product sectors equipment require no material or service inputs. This is because they are pseudo sectors and not real producing sectors.
A_{ii} = I/O coefficients describing how non-energy products are used in the non-energy producing sectors.

If we rewrite Eq. 6 in the summary form,
$X^E = A^E X^E + F^E$, where the superscript E indicates energy input-output matrices, the equivalent equation of equation 5 is

$$X^E = (I-A^E)^{-1}F^E \qquad (7)$$

We could then calculate the various alternative final energy demand scenarios, the corresponding new total output requirements for non-energy industry and energy supply industry and energy services output and their respective intermediate outputs. Some perspective on inter-fuel substitution could also be gained, if one were satisfied that prices would not significantly influence the substitution process and if one were satisfied that the assumption of constant input output relationships would be true in practice.

Source: Based on Chapter 7, Macro-Demand Analysis, of Codoni et al (1985). See also Miller and Blair (1985).

3.2.2.4 Scenario approach

The scenario approach has been widely used in climate change and energy efficiency policy making (Ghanadan and Koomey, 2005). The scenario approach has its origin in the strategic management where it has been used since 1960. In the energy and climate change area, the use of scenarios by the Intergovernmental Panel of Climate Change (IPCC) has played an important role in the policy debate. Similarly, studies by the World Energy Council (WEC), Inter-laboratory Working Group of US and similar studies in Australia have brought the approach to limelight. See for example Jefferson (2000)[15], Brown et al (2001), Saddler et al (2007 and 2004) and Shell Studies[16] (Shell (2008)), among others. Scenarios are an integral part of the end-use approach as well and accordingly, they are not new to energy analysis.

"A scenario is a story that describes a possible future" (Shell, 2003). In simple terms, scenarios refer to a "set of illustrative pathways" that indicate how "the future may unfold" (Ghanadan and Koomey, 2005). Evidently, they do not try to capture all possible eventualities but try to indicate how things could evolve. It is a particularly suitable approach in a changing and uncertain world (Leydon, et al, 1996).

> "Scenarios give the analyst the opportunity to highlight different combinations of various influences, so that alternative future contexts can be sketched out, and the energy implications examined" (Leydon et al., 1996, p.5).

"Scenarios are based on intuition, but crafted as analytical structures…They do not provide a consensus view of the future, nor are they predictions" (Shell, 2003). Clearly, "scenarios are distinct from forecasts in that they explore a range of possible outcomes

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[15] This paper presents a brief history of the WEC efforts in energy understanding the future energy demand and describes the scenarios used in a number of studies. In 1978 study, the Council called for actions to ensure a sustainable future. Until 1989 the Council used two scenarios – high growth and middle course. Since 1993, an ecologically driven scenario was added which were further refined subsequently in 1998 to develop six scenarios – three high growth, one middle course and two ecologically driven scenarios. The fully integrated scenarios present a range of possible rational outcomes and forecast energy and environmental indicators up to 2100.

[16] Shell was active in using scenario technique for strategic management and planning. It is the ex-Shell planners who have brought this method to the wider public (Ghanadan and Koomey, 2005). Shell produced its first energy scenario studies in the 1992 and produced the catch phrase "There is no alternative" (TINA). This was followed by a number of studies in 1995, 1998, 2002 and 2005 (see http://www.shell.com/home/content/aboutshell/our_strategy/shell_global_scenarios/previous_scenarios/previous_scenarios_30102006.html for details). In its latest scenario study, Shell has introduced the new catch phrase "There are no ideal answers" (TAN!A) in 2008.

resulting from uncertainty; in contrast, forecasts aim to identify the most likely pathway and estimate uncertainties" (Ghanadan and Koomey, 2005).

The strength of the scenario approach is its ability to capture structural changes explicitly by considering sudden or abrupt changes in the development paths. The actual level of disaggregation and inclusion of traditional energies and informal sector activities depend on model implementation. Theoretically it is possible to include these aspects but how much is actually done in reality cannot be generalized. Moreover, the development of plausible scenarios that could capture structural changes, emergence of new economic activities or disappearance of activities is not an easy task.

3.2.2.5 Hybrid approaches

This, as the term indicates, approach relies on a combination of two or more methods discussed above with the objective of exploring the future in a better way. The hybrid methods have emerged to overcome the specific limitations of individual approaches. These models have become very widespread now and it is really difficult to classify any particular model into a specific category. For example, econometric models now adopt disaggregated representation of the economy and have internalized the idea of detailed representation of the energy-economy activities. Similarly, engineering-economy models use econometric relationships at the disaggregated levels thereby taking advantages of the econometric estimation method. The end-use approach heavily relies on the scenario building approach to enrich itself.

There is a growing interest in the hybrid energy models in recent times with the objective of reconciling the differences between the top-down and bottom-up approaches. This is evident from a set of recent studies: [17]

- To reconcile the "efficiency gap", models with top-down structure are using bottom-up information to estimate parameters. See for example Koopmans and te Velde (2001) for such an exercise.

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[17] See for example Special Issue of Energy Journal (November 2006) on this theme.

- To capture the technological details of bottom-up models and micro- and macro-economic details of econometric models, the hybrid option is being adopted. NEMS falls in this category. NEMS is the model used by the U.S. Department of Energy for its Annual Energy Outlook. NEMS uses the details found in engineering-economic models but retains the behavioral analysis found in top-down models, making it a hybrid model. Other examples include the CIMS model (see Bataille et al (2006)).
- To enhance the capability of price-induced policies in a bottom-up model, price information is explicitly included in the bottom-up structure. The POLES model is such an example, which is widely used by the European Union for its long-term energy policy analysis.

This approach has now been extended beyond demand analysis and forecasting to include energy-economy interactions and even more recent concerns such as renewable energy penetration and technology choice.

Clearly, the objective of these models is to enhance interactions among dominant modeling paradigms to achieve a better result. Accordingly, the hybrid models capture technological diversity in a greater detail and some try to ensure macro-economic consistency of the model assumptions. In principle, it is possible to capture traditional energies and informal economic activities in some of the models. It is also possible to capture rural-urban divide by taking a spatially differentiated approach. However, the practical implementation varies depending on the model objectives. Evidently, the skill and resource requirements increase as the model complexity increases. As discussed in Section 5, these models become less portable and user unfriendly, thereby reducing their appeal for developing countries.

4. Energy demand modeling in practice

This section presents to a review of selected literature on energy demand forecasting with a view to take stock of the evolution in the knowledge and modeling preferences. This would also enable us to identify and select a few models for further examination to understand the mechanics of the models. Accordingly, we have resisted the temptation of compiling a list of studies indicating the variables used and elasticities obtained.[18] In addition, although some attempt has been made to compare the forecasts with actual demand wherever possible, no systematic assessment or comparison of models is attempted here.[19]

We cover the entire gamut of energy demand forecasting – from aggregate energy demand to the sector level studies. We also cover fuel-specific studies within each sector as well as studies covering fuel demand for electricity generation.

4.1 Aggregate energy demand forecasting

Aggregate energy demand generally refers to what is known as primary energy demand in energy accounting terminology. This normally relates to a country or a region or can be global in its coverage and is normally obtained by combining the demand for various sectors and the energy needs for the transformation sector.[20] In the end-use tradition, the aggregated demand is obtained by summing demand at the disaggregated levels and accordingly, in methodological terms, there is nothing specific here. In contrast, in the econometric approach, some studies have focused on the aggregate demand only. In addition, there are some econometric studies which forecast energy demand by fuel or by sector but focus on the sectors or the fuels as a whole. We have considered such studies under this heading as well.

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[18] Interested readers can see Bohi (1981), Bohi and Zimmerman (1984), Dahl (1991), Dahl (1994), and Espey (1998), among others, for this purpose.

[19] See Sweeney (1983) for a systematic approach to comparison.

[20] This follows the energy accounting framework. For a basic understanding of energy accounting, see IEA (2004).

4.1.1 Primary energy demand forecasting

In the past, when data availability was restricted, especially in developing countries, and access to computing facilities was limited, aggregated studies were common using reduced form specifications (see Dahl (1994a) for a long list of such studies). Dahl (1994a) suggests that although models are found to test per capita energy and/or total energy consumption in the reduced form versions with or without dynamic elements, "aggregation can cause heteroscedasticity when the population varies across the sample." [See Box 7 for further explanation.]

Box 7: Difference between the total and per capita specifications of energy demand

Consider a simple log-linear demand specification with price and income as dependent variables as shown in Eq. 1

Eq. 1: $\ln Q = \alpha + \beta \ln P + \gamma \ln Y$,
where Q is the total energy demand, P is the price of energy and Y is the GDP of the country.

The per-capita specification can be written as Eq.2.

Eq.2: $\ln(Q/pop) = \delta + \varepsilon \ln(P) + \zeta \ln(Y/pop)$
Where pop represents population. Equation 2 can be rewritten as

Eq. 3: $\ln Q = \delta + \varepsilon \ln(P) + \zeta \ln(Y) + (1-\zeta)\ln(pop)$

Comparing Eq. 1 with Eq. 3, it becomes clear that the two specifications are equivalent, if the income elasticity is equal to 1. When the income elasticity is different from one, the two specifications are not equivalent because of the last term in Eq. 3. When $\zeta>1$, the last term in Eq. 3 is negative and when $\zeta<1$, the last term is positive. This would affect the income elasticity estimation and the forecast.

Source: Dahl (1994a).

Westoby and Pearce (1984) present a brief history of the evolution of the single equation energy demand estimation. They report that the initial attempts were either to establish a linear relationship between output and energy adjusted for calorific content or to study linear relationships between energy and income. Subsequently, more variables, including price, were included in the single equation models. Moreover, instead of considering just energy as the dependent variable, energy intensity has also been modeled in single equation form by linking it to price, fuel share and economic structure. The study reviews 12 single equation models [See Box 8] and subjects them to post-sample period projection test. The study finds that simple energy-output relationships break down during the periods of unstable energy prices. However, single equation models that include a structure component of the GDP and specify a dynamic adjustment process can provide robust forecasts. These models are “cheap and transparent” and can still play a role in policy and planning decision-making processes. This view is echoed by Bohi and Zimmerman (1984) who found that reduced form models produced comparable results as obtained from structural models and performed well.

Box 8: Typical examples of single equation econometric models

The following equations provide examples of specifications used in simple econometric analyses. E is energy consumption, Y is income (GDP), P is price, POP is population, EMP is employment of labour, a, b, c, d, e, f, - are coefficients to be determined through the estimation process, t is time period t while t-1 represents the time period before t.

(a) Linear relation between energy and income (GDP)
$E_t = a + bY_t$

This implies an (income) elasticity that tends asymptotically to unity as income increases. Note that b is not the elasticity in this specification, which has to be determined from the basic definition of elasticity.[21]

(b) Log-linear specification of income and energy
$\ln E_t = \ln a + b \ln Y_t$
Here b represents the elasticity of demand, which is a constant by specification.

(c) Linear relation between energy and price and income variables
$E_t = a + bY_t + cP_t$
This is not a popular specification however.

(d) Log-linear specification of income, price and energy
$\ln E_t = \ln a + b \ln Y_t + c \ln P_t$

As with model (b), the short-run price and income elasticities are directly obtained here.

(e) Dynamic version of log-linear specification of energy with price and income variables

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[21] This turns out to be (1-a/E) and as E tends to infinity, the elasticity tends to 1.

$\ln E_t = \ln a + b \ln Y_t + c \ln P_t + d \ln E_{t-1}$
The short run and long-run price and income elasticities are obtained here.

(f) log-linear model of price and other demographic variables
$\ln E_t = \ln a + b \ln P_t + c \ln EMP_t + d \ln POP_t$

(g) log-linear model of energy, price, income, fuel share and economic structure variables
$\ln E_t = \ln a + b \ln P_t + c \ln Y_t + d \ln F_t + e \ln S_t$

(h) dynamic version of the above model
$\ln E_t = \ln a + b \ln P_t + c \ln Y_t + d \ln F_t + e \ln S_t + f \ln (E_{t-1})$

(i) linear relation between per capita energy and income
$E_t/POP_t = a + b\, Y_t/POP_t$

(j) Log linear relation between per capita energy and income
$\ln(E_t/POP_t) = \ln a + b \ln (Y_t/POP_t)$

(k) log-linear relation between energy intensity and other variables
$\ln(E_t/Y_t) = \ln a + b \ln P_t + c \ln F_t + d \ln S_t$

(l) Dynamic version of log-linear energy intensity relation
$\ln(E_t/Y_t) = \ln a + b \ln P_t + c \ln F_t + d \ln S_t + e \ln (E_{t-1}/Y_{t-1})$

Source: Westoby and Pearce (1984).

Ibrahim (1985) has reviewed the energy demand forecasting efforts in Arab countries and their performance. He noted that time series, single equation models, and aggregated approach were commonly used in most of the earlier studies. His review suggested that most of the efforts were quite primitive at that time and did not meet the requirements of policy analysis. Similarly, Chern and Soberon-Ferrer (1986) analyzed the structural changes in energy demand in developing countries.

Ishiguro and Akiyama (1995) have analyzed energy demand in five Asian countries, namely China, India, South Korea, Thailand and Indonesia both at the aggregate level and the sector level using a simple econometric model. They have used the model for forecasting energy demand in these countries up to 2005. Their main focus was to analyze the effect of different policies on energy demand growth. The analysis was presented for the base case and two alternative scenarios (high GDP growth and high energy price). Al-Azam and Howdon (1997) apply a dynamic OLS approach to forecast energy demand in Jordan. The objective of this study is to show whether modern econometric approaches can be used to forecast energy demand in developing countries. However, this does not provide any forecasts. Erdogan and Dahl (1996) analyzed aggregated energy demand for the Turkish economy as well as industrial energy demand using three specifications – the static model, lag adjustment model and the Almon lag model.

The main objective of such studies was to identify any statistically significant relationships between commonly known economic variables and aggregate energy demand. Clearly, they do not capture the spatial dimension or the traditional energies or technological diversity. As the measured consumption information is used in the analysis, the unsatisfied demand is not captured. Non-pricing policies are not captured and the relationships provide only the basic elasticity information but the skill requirement as well as the data requirement is generally low for such exercises.

In the 1990s, the single equation approach returned to prominence but most of these new studies consisted of applying co-integration techniques, often with error correction methods. Two essential reasons behind this return are: (Adeyemi and Hunt, 2007)

- The simplicity of the models, straightforward interpretation and limited data requirements was favored in contrast to the complex estimation procedures.
- These models often outperformed complex specifications.

Some have considered time trends (either deterministic or stochastic) while others did not consider the time trend specifically.[22] A few examples include Hunt and Manning (1989), Bentzen and Engsted (1993), Al-Muriati and Eltony (1996), Fouquet et al (1997), Pesaran et al (1998), Hunt and Nonomiya (200%), Crompton and Wu (2005), etc.[23] Hunt and Manning (1989) analyzed the aggregate energy demand in the UK. Pesaran et al (1998) was a major study that analyzed energy demand in 11 Asian developing countries using Autoregressive Distributed Lag Model to co-integration both at the aggregate and sector levels. The main result of the study was the long-run price and income elasticity estimates for countries analyzed. They also investigate the effect of pooling the data on

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[22] See Adeyemi and Hunt (2007).

[23] There is a long list of studies that have used this approach. For a review see Engsted and Bentzen (1997).

the elasticities. While these studies use more advanced statistical approaches for analysis, the focus remains on long-term price and income elasticities of energy demand. Yet, the results of these studies are neither conclusive nor significantly different from the simple studies. In addition, most of these studies find that price does not play a significant role in influencing demand in developing countries where income drives the demand. Focusing on price-based policies in such cases may not be helpful. Further, these studies do not consider traditional energies, informal economic activities and being aggregated studies ignore rural-urban divide and technological diversities existing in developing countries. While such studies employ state-of-the-art econometric knowledge, the outcomes may prove to be of limited use for policy-making in developing countries.

4.1.2 Sector or fuel-level aggregate studies

A number of aggregate studies focusing on specific fuels or specific sectors are also found in the literature. For example, Suganthi and Jagadeesan (1992) and more recently Iniyan et al (2006) have reported aggregate demand models for India. The 1992 study considered three fuels (coal, oil and electricity) and presented estimations and forecasts for each fuel for 1995-96 and 2000-01. However, as this study used coal replacement equivalent as the unit of energy and the term was not adequately clarified, it was not possible to check how their forecast fared compared to the actual demand.

Their 2006 study presents a system of three models for India for configuring energy systems for three years 2010-11, 2015-16 and 2020-21. The first model named as Modified Econometric Mathematical Model (MEM) to predict energy demand for coal, oil and electricity using two-stage least square error principle. The demand is forecast using the previous year's demand, price, gross national income, technological factor and environment quality. The model parameters are estimated using data for the past four decades. The outcome of this model is fed into the Mathematical Programming Energy-Economy-Environment (MPEEE) model. This model determines optimal allocation of commercial energy based on environmental limitations. The model maximizes the GNP/ energy ratio subject to emission constraints. This model gives an outcome of energy use that is lower than the predicted outcome. The balance will then be supplied from renewable energies. The Optimal Renewable Energy Mathematical (OREM) model then selects the renewable energy technology options by minimizing the cost/ efficiency ratio subject to social acceptance, reliability, demand and potential constraints. 38 renewable energy options for various end-uses have been considered to generate realistic distribution of renewable energy use. Similar modeling efforts are reported in Suganthi and Williams (2000).

Paga and Birol (1994) used a log-linear relationship to estimate aggregate oil demand in 8 developing countries using data for the 1971-1991 period. They then projected the oil demand for 2000.

Pokharel (2007) has developed static log-linear Cobb-Douglas functions for Nepal for different fuels (8 fuels) and energy consuming sectors (5 sectors). Energy demand has been estimated using economic variables (such as GDP, prices) and demographic variables (population) and the estimation was based on data for the period 1988-2002. The estimated relationships were used to forecast demand for 2007 and 2012. Although the actual data for 2007 is not yet available, it appears that the reliability of the forecasts made here is not very high. In the case of fuel wood, the demand appears to be underestimated as the IEA data for combustible renewable energies for 2005 is much higher than the wood fuel forecast.

Sharma et al (2002) have developed econometric models for forecasting electricity, coal and petroleum products for the Indian State of Kerala. Electricity demand was estimated at the sector level while for other products only aggregate product demand functions were estimated. Single equation models for each sector/ product using OLS was estimated but corrected for auto-correlation. Demand forecasts were presented for four periods, 2005/06, 2010/11, 2015/16, and 2021/21. Unlike other studies where forecasting of independent variables is summarily presented, this study contains a detailed documentation of this aspect.

Since the 1990s, some studies analyzing specific fuel demand at the aggregate level have also used cointegration and error correction methods. For example, Chan and Lee (1997) have analyzed coal demand in China using three alternative specifications, namely Engle-Granger's error correction model, Hendry's error correction model and Hendry's general-to-specific approach. Similarly, Moosa (2002) analyses oil demand in developing countries to find the correct specification and importance of oil price in the demand relation.

While aggregate demand analysis studies have been widely used in the past, they often lack explanatory power due to aggregation across fuels, sectors and/ or countries. Such studies do not allow a careful consideration of rural-urban dichotomy and often do not go beyond identifying the price and income elasticities as the drivers. The role of technology is hardly considered and structural change does not appear as a main concern. Given that all developing countries are aiming at breaking away from the past demand trend, attempts to find better or closer fit with the past data may not bear much importance for the future. There lies the problem with the econometric approach of demand analysis in the context of developing economies.

4.2 Energy demand forecasting at the sector level

As industry, transport, households and the commercial sector are the major energy consumers at the sector level, the presentation is organized along these sectors following the above sequence. In each sector, we shall present how alternative approaches have attempted energy demand forecasting.

4.2.1 Industrial energy demand

As industrial energy consumption often accounts for a major share of final energy demand of a country, this sector has received attention of the energy analysts from an early date. As with any energy demand modeling, industrial energy demand can be forecast using alternative approaches discussed above.

Econometric approach

As Brendt and Wood (1975) reported, earlier studies of industrial energy demand either focused on outputs solely and did not consider the influence of price on demand or failed to take inter-fuel and inter-factor substitution possibilities. Brendt and Wood (1975) pioneered the tradition of using trans-log cost function for analyzing industrial energy demand [See Box 9 for the basic properties of the Translog cost function]. This functional form has been extensively used in subsequent studies, notably by Pindyck (1979), Uri (1979a, 1979b), Siddayao et al (1987), etc. Most of these studies are at the aggregate level, focusing on industrial demand as a whole using country-specific or cross-country data.

Box 9: Translog cost function

The translog cost function is considered to be the second order approximation of an arbitrary cost function. It is written in general form as follows:

$$\ln C = \alpha_0 + \sum \alpha_i \ln P_i + 0.5 \sum_i \sum_j \gamma_{ij} \ln P_i \ln P_j + \alpha_Q \ln Q + 0.5 \gamma_{QQ} (\ln Q)^2 + \sum_i \gamma_{Qi} \ln Q \ln P_i$$

where C = Total cost, Q is output, P_i are factor prices, i and j = factor inputs. (1)

This cost function must satisfy certain properties:
- homogeneous of degree 1 in prices;
- satisfy conditions corresponding to a well-behaved production function.
- Cost function is homothetic (separable function of output and factor prices) and homogeneous.

Accordingly, the following parameter restrictions have to be imposed:

$\sum \alpha_i = 1$

$\gamma_{ij} = \gamma_{ji}, i \neq j$

$$\sum_i \gamma_{ij} = \sum_j \gamma_{ij} = 0$$

$$\sum_i \gamma_{Qi} = 0$$

$\gamma_{Qi} = 0$ and

$\gamma_{QQ} = 0$

The derived demand functions can be obtained from Shepherd's lemma

$$X_i = \delta C / \delta P_i \tag{2}$$

Although these functions are non-linear in the unknown parameters, the factor cost shares ($M_i = P_i X_i / C$) are linear in parameters.

$$M_i = \alpha_i + \sum_j \gamma_{ij} (\ln P_j) \quad \text{for i = factor inputs, j = factor inputs, i \# j} \tag{3}$$

These share equations are estimated to obtain the parameters. Only n-1 such equations need to be estimated as the shares must add to 1.

The own price elasticity of factor demand is obtained as follows:

$$E_{ii} = \partial \ln X_i / \partial \ln P_i \tag{4}$$

$$X_i = \frac{C}{P_i} (\alpha_i + \sum_j \gamma_{ij} (\ln P_j) \tag{5}$$

$$\begin{aligned} \ln X_i &= \ln C - \ln P_i + \ln(\alpha_i + \sum \gamma_{ij} (\ln P_j) \\ &= \ln C - \ln P_i + \ln M_i \end{aligned} \tag{6}$$

$$\begin{aligned} \partial \ln X_i / \partial \ln P_i &= \frac{\partial \ln C}{\partial \ln P_i} - 1 + \frac{\gamma_{ii}}{M_i} \\ E_{ii} &= M_i + \frac{\gamma_{ii}}{M_i} - 1 \end{aligned} \tag{7}$$

$$E_{ii} = (M_i^2 - M_i + \gamma_{ii}) / M_i \tag{8}$$

The cross-price elasticity can be derived similarly as

$$E_{ij} = (\gamma_{ij} + M_i M_j) / M_i \tag{9}$$

Allen partial elasticity of substitution is given by:

$$\sigma_{ij} = (\gamma_{ij} + M_i M_j) / M_i M_j \tag{10}$$

Source: Pindyck (1979).

Many studies routinely used this flexible functional form in demand studies until late 1980s.[24] The preference for this functional form derived from the theoretical underpinning of the function, the flexibility of avoiding pre-specification of any particular relationships, and the imposition of minimum restrictions on the parameters.

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[24] See Borges and Pereira (1992), Christopolous (2000), Dahl and Erdogan (2000), Siddayao et al (1987), Saicheua (1987), Kim and Laby (1988), Mahmud and Chisti (1990), and Buranakunaporn and Oczkowsky (2007).

However, the disadvantages of this function include: a) local approximation of the demand that may not be plausible globally, b) loss of degrees of freedom, and c) complicated estimation techniques (Wirl and Szirucsek, 1990). Further, many of them relied on pre-1970 data, thereby missed the opportunity to consider the sudden price changes in the 1970s. In addition, the static translog model does not describe the adjustment process to the long-term.

Adeyemi and Hunt (2007) remark that despite their strict neo-classical orientation and intuitive results, these models were at odds with data and were incorrect. As Griffin (1993) and Jones (1994) indicate, the differences between in the results from times series and cross-sectional studies and the failure of the models to identify the effects of technical progress became important issues. Subsequent econometric modeling efforts used dynamic versions of translog model and other functional forms (such as the logit model).[25] However, such studies were more concerned with the suitability of the functional forms and specifications rather than in better understanding industrial energy demand.

Parallel to the developments in the translog approach, the use of multinomial logit models became popular in the energy studies. The logit model is not derived from the utility maximization theory but derives its appeal from its interesting properties (Pindyck, (1979), Urga and Walters (2003)):

- it is relatively easy to estimate;
- it ensures that the outcomes are non-negative and add to one;
- as the share of a component becomes small, it requires increasingly large changes to make it smaller.
- Flexible for incorporating a dynamic structure.

In the case of industrial energy use this has been used to analyze fuel shares or market shares of fuels. Some details about the logit model are presented in Box 10.

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[25] See for example Urga and Walters (2003), Jones (1994) and Jones (1996).

Box 10: Logit model description

The logit model for fuel share, Si, can be written as

$$\frac{Q_i}{Q_T} = S_i = \frac{\exp(f_i)}{\sum_{j=1}^{n} \exp(f_j)} \qquad (1)$$

Where Q_i is the quantity of fuel i, $Q_T = \sum Q_i$, and f is the function representing consumers preference choices.

The share equation for any two fuels can be written as

$$\log\left(\frac{Q_i}{Q_j}\right) = \log\left(\frac{S_i}{S_j}\right) = f_i - f_j \qquad (2)$$

As the sum of the shares adds up to one, only (n-1) equations need to be estimated simultaneously.

For estimation purposes, a specific functional form has to be chosen. This is often done arbitrarily and we use a linear specification of relative fuel pries, income and temperature as given below.

$$f_i = a_i + b_i \tilde{P}_i + c_i Y + d_i T \qquad (3)$$

Where $\tilde{P}$ is (P_i/P_E) – ratio of price of fuel i to the aggregate fuel price P_E
Y is income,
T is the temperature.

Substitution of (3) in (2) yields the equations to be estimated:

$$\log\left(\frac{S_i}{S_n}\right) = (a_i - a_n) + b_i \tilde{P}_i - b_n \tilde{P}_n + (c_i - c_n)Y + (d_i - d_n)T \qquad (4)$$

Where i = 1, 2, 3, …(n-1)

A dynamic version of the equation can be easily written by including the lagged shares in the functional form

$$f_i = a_i + b_i \tilde{P}_i + c_i Y + d_i S_{i,t-1} \qquad (5)$$

The equations for dynamic estimation in that case turns out as

$$\log\left(\frac{S_i}{S_n}\right) = (a_i - a_n) + b_i \tilde{P}_i - b_n \tilde{P}_n + (c_i - c_n)Y + d_i S_{i,t-1} - d_n S_{n,t-1} \qquad (6)$$

Where i = 1, 2, 3, …, (n-1)

Source: Pindyck (1979).

As noted earlier, the trend changed to the reliance on single equations following the cointegration revolution in the 1990s. This marked a remarkable turning point in the econometric research when earlier methods were almost abandoned. These studies often adopted an aggregated analysis but used more advanced time-series data analysis techniques. Examples for the industrial sector include Hunt and Lynk (1992), Hunt et al (2003), Dimitriopoulos et al (2005), Kulshrestha and Parikh (2000), and Adeyemi and Hunt (2007). Adeyemi and Hunt (2007) summarize the developments in the econometric tradition of energy demand analysis as follows: "there is no consensus on how to estimate industrial energy demand, in particular how the effect of technical change and (possible other important exogenous factors) is captured."

Although our review finds that the econometric analysis has been applied to the industrial energy demand of developing countries, their occurrences are rather limited and often restricted to more advanced developing countries with a large industrial base. We also note that the more recent studies have focused on OECD countries in general and even in such studies, the issues of structural change and technological improvements have not been sufficiently captured. The focus remained on the elasticity estimates and the identification of better specifications. In the case of developing countries, the change in the industry structure and the evolution of technological mix of the industry are two essential factors that affect future energy demand. Inadequate representation of such issues in the econometric tradition provides limited help for better policy-making to develop a sustainable energy future. The extrapolation of past trends provides little help where the emergence of new activities not known previously has to be considered. The quality of data and the availability of long time series to ensure correct estimation of econometric parameters are also doubtful in many cases. Finally, the human resources required for such analyses may not be available in many developing countries. Therefore, this approach may not be suitable for many developing countries.

End-use approach

The end-use approach to industrial energy demand focuses on the disaggregated demand analysis and retains at least 2-digit level classification of industries following ISIC codes (International Standard of Industrial Classification) to take care of the diversity of industrial activities and fuel use (see table 2 for an example). This decision is highly influenced by data availability; degree of industrialization and the environmental setting, but higher levels of disaggregation are preferred to an aggregated analysis.

Table 2: Usual disaggregation of the industrial sector

First level	Second level	Third level
Mining		
Manufacturing	Food	Sugar, edible oil, etc.
	Textile	
	Wood	
	Paper	
	Chemicals	Fertilizers,
	Non-metallic minerals	Cement,
	Primary metals	Steel, Aluminium.
	Engineering	Electronics, Cars, etc.
	Miscellaneous	
Construction		

Source: UN (1991).

Following the basic principle of this approach, energy demand from various end-uses is considered next. These generally include motive power, heat, cooling, chemical energy, lighting, etc. Depending on the nature of the industry, these end-use demands could be analyzed for industrial processes and for buildings. Normally, the process energy demand would be significant for energy intensive industries while the building-related energy demand could be important for labor intensive industries. The method tries to capture the essential features of the production system through a detailed description of the technologies and practices prevalent in a region or country.

Various determinants of the end-use demand are then identified: the level of industrial activity (expressed as value added) is considered to be the main factor. However, for energy intensive industries, physical level of output can also be considered. For forecasting purposes a mechanism for determining the output of each industry and the changes in the industrial output composition would have to be developed. Finally, energy demand is estimated by linking the output from the industry to specific consumption or energy intensity. Figure 2 presents this scheme is a diagrammatic form.

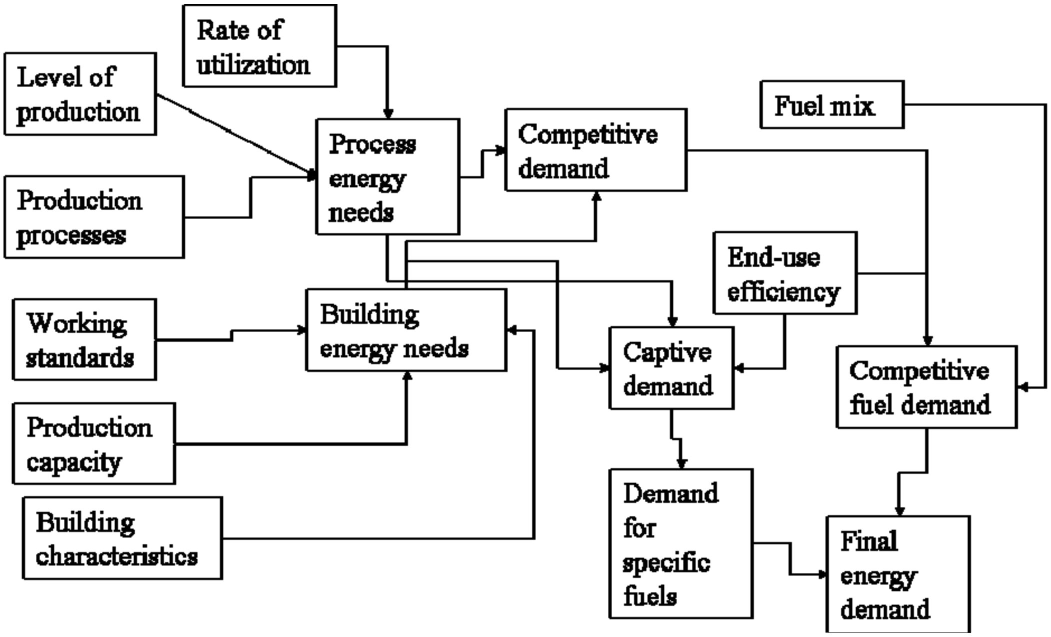
The end-use model has been widely used in energy demand forecasting and analysis throughout the world. Some examples of end-use engineering models with rich technological representation are presented in table 3.

Table 3: Energy end-use models for industrial energy demand analysis

Name of the model	Country of origin	Technology representation	Modelling approach
AMIGA	US	Explicit	Simulation
EERA	New Zealand	Unknown	Simulation
ENUSIM	UK	Explicit	Simulation
ENPEP	US	Explicit/ stylistic	Simulation
MAED	Austria	Explicit	Simulation
MEDEE	France	Explicit	Simulation
LEAP	US	Explicit	Simulation

Source: Worrel et al (2002) and Fletcher and Marshall (1995).

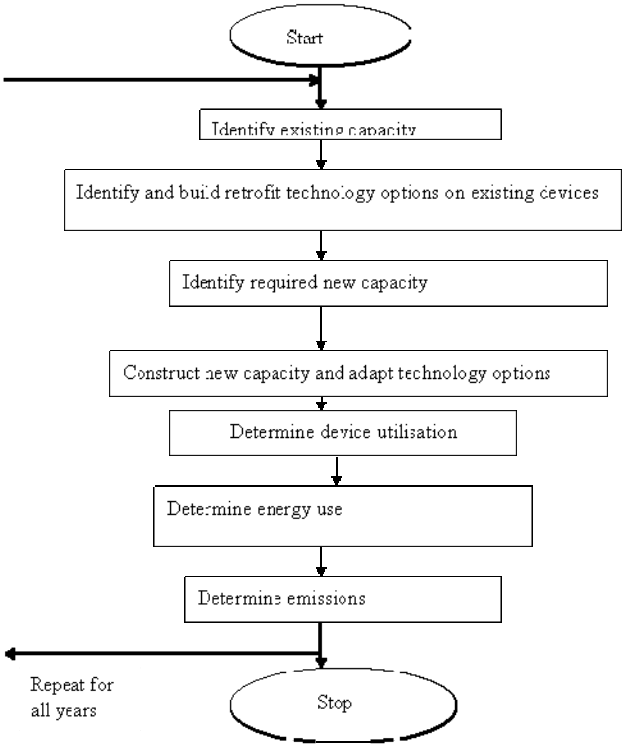
Fig. 2: Industrial energy demand estimation in end-use method



Source: UN (1991).

Fletcher and Marshall (1995) present a study of industrial energy demand forecast of an English region using a disaggregated end-use model, ENUSIM. “This is a technology-based, ‘bottom-up’ industrial energy use simulation model which considers both economic and behavioral factors affecting investment in new technology and plant replacement” (Fletcher and Marshall (1995)). The economic factors considered in the model include industrial output growth, relative prices of fuels and investment discount rate, which are used to determine the potential for technological change affecting industrial energy demand. The speed and extent of change is conditioned by a set of behavioral factors. Figure 3 presents the ENUSIM methodology. The model was used to forecast industrial energy demand up to 2009. But given the regional nature of the demand forecast, it is somewhat difficult to compare the results with actual demand.

Fig. 3: ENUSIM methodology



Source: Fletcher and Marshall (1995).

More recently, OEF (2006) has used ENUSIM for forecasting energy demand in the UK industry following the introduction of EU-Emissions Trading System. This approach has been used in specific industries as well. For example, Ozlap and Hyman (2006) have used it for the paper industry in the US. Similarly, Price et al (2001) have analyzed the steel industry in five developing countries using end-use methodology. Hainoun et al (2006) have analyzed the energy demand in Syria using MAED model where the industrial demand has been analyzed in detail.

The end-use approach pays special attention to the technological aspect of the industrial sector, although the details vary from one case to another. When a particular industry is being analyzed (e.g. the steel industry as done by Price et al (2001)), the level of details is expected to be much greater compared to a study focusing on industry as part of an economy-wide analysis (as in the Syrian case mentioned above). This approach also allows the regional dimension to be taken into consideration and the analysis can be performed at the region-specific level. Additionally, the focus shifts to capturing structural changes, technological improvements and policy-induced effects rather than devoting entire effort to elasticity estimation or determining the correct specification. The skill requirement is often not too onerous and the data can be developed using expertise and judgments.

Other approaches

EMF (1987) reported a comparison of results of US industrial energy demand from a variety of forecasting models using alternative approaches – econometrics, input-output approach and process analysis. The study also used a standard base case and a variety of alternative scenarios to examine how the model results differ. To analyze the historical demand trend, the study used a diagram to plot the actual energy demand in the US industry over 1960-85 period and compared four trend lines for the period between 1985 and 2000 based on the following assumptions:

a) 1973 energy output ratio and historical output growth;
b) 1973 energy output ratio applied to a 2% annual growth in output;
c) 1985 energy output ratio applied to a 2.5% annual growth in output and
d) 1973-1985 energy output trend applied to a 2.5% annual growth in output

These assumptions were also applied to fossil fuel demand and electricity demand as well and the possible alternative paths of demand growth were visually examined. The study then compared six models using different methodologies and compared their results using a set of common assumptions and scenarios. The results suggested a decline in industrial energy intensity in the US but the overall demand was forecast to grow modestly due to increase in the activity level. Energy demand for heat and power in industry was projected to grow between 40 to 80% of the 1985 level by 2010. However, the actual growth up to 2006 was just 12% (including electricity, but only 10% if only primary energies are considered).

Ang (1987) used a disaggregated approach of forecasting industrial energy demand in Taiwan and Singapore, where the intensity effect and the structural effects are considered at the sub-sector level. Using growth rates for industrial output as the driving variable, he developed three alternative scenarios to forecast energy demand and energy saving potential in 2000.

Schenk and Moll (2007) use physical indicators to develop industry energy demand scenarios. Instead of using energy intensities, this method relies on physical outputs of the industry and its relation with energy consumption. The authors indicate that this formulation has not been used in energy demand forecasting before and their effort explores the possibility with application to two regions: Western Europe and Centrally Planned Asia and China. The authors claim that this method offers meaningful insights, a possibility for reality check and intra-sectoral structural change poses limited problems.

Murphy et al (2007) used a hybrid model, CIMS, to analyze the industrial energy demand in Canada. This model retains the technological richness of an end-use model, adds behavioral realism and captures equilibrium feedbacks of top-down models. This has been used to forecast demand for 2030 and determine carbon emissions.

4.2.2 Transport energy demand

The transport sector accounts for a significant amount of commercial energy use in most countries and has often been a target for policy intervention. As energy demand in the transport sector is directly related to the mode of transport (domestic air, water, rail and road transport) and because a number of fuels are used in this activity, different levels of analysis can be noticed. Most of the studies focus on the dominant mode of transport – the road transport and often two dominant fuels – gasoline and diesel – are considered.

A number of approaches are used for energy demand forecasting for this sector. As the stock of vehicles, their utilization pattern and the average efficiency greatly influence energy demand, studies generally try to capture these elements in the analysis. We consider the econometric and end-use methods in detail. As before, we neither focus on the elasticity estimates, nor present tables comparing such studies.[26] Moreover, in the case of transport sector there are studies related to transport demand which are not necessarily concerned about energy demand in the transport sector.[27] We exclude such studies from our scope of review.

Econometric approach

The single equation, reduced form of demand estimation either at the aggregate transport fuel level or for particular fuels (gasoline, diesel, etc.) remains the basic form of econometric analysis. Many studies are reported in the literature, including Paga and Birol (1994) and Chakravorty et al (2000), while Sterner (1991) analyzed model specification for pooled estimation. Hughes et al (2008) retain this simple specification in their study because "it provides a good fit to the data and allows for direct comparison with previous results from the literature."

As indicated in Section 3.1.3, two common approaches used to estimate transport energy demand are the identity approach and the structural approach. Research from as early as 1970s has recognized the importance of stock of cars, car utilization and the average car efficiency in the transport energy demand. This is captured through the demand identity:

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[26] A number of studies have reviewed transport related elasticities. See for example, Goodwin et al (2004), Graham and Gleister (2004), Graham and Glaister (2002a), Graham and Glaister (2002b), Hanly et al (2002), Dahl (1995), Dahl (1994) and Espey (1998).

[27] See Trujillo et al (2000) for a review of such studies.

$E = C.U.Eff$ (3)

Where E is the fuel demand,

C is the stock of automobiles

U is the annual utilization rate (km/year), and

Eff is the vehicle efficiency (l/km)

Early studies such as those by Adams et al (1974) and Pindyck (1979) have attempted to formulate transport fuel demand taking these variables into account. The fuel demand is obtained as a product of the above three variables, each of which is estimated using a function of other explanatory variables. Accordingly, the demand is not obtained from the utility or cost functions or from the perspective of any optimization process (Pindyck, 1979, p.61).

Hoffman and Wood (1976) discuss the gasoline demand model developed by Sweeney as follows:

> "Vehicular gasoline consumption for any time period is a derived demand that depends on the total number of miles driven and the average number of miles per gallon (mpg) for the fleet in operation during the period. The demand for vehicle miles is estimated by a function of real disposable income per capita, the unemployment rate, and the cost per mile of automobile travel, including the cost of gasoline and time (permitting introduction of speed limits). The average mpg for the fleet is first estimated by prediction of new car purchases per capita as a function of lagged automobile purchases per capita, total vehicle miles per capita, real disposable income per capita, and the unemployment rate. A sales-weighted average mpg of new cars is estimated by a function of automobile efficiency and the price of gasoline. The mpg for the fleet is then estimated by formation of a weighted harmonic mean of the mpg estimates for new cars and each vintage of old cars where the weights are the shares of each vintage in the total vehicle miles estimated."

The implementation of the above identity for estimation purposes can take alternative paths. We present two examples: one from Pindyck (1979) in Box 11 and the other from Johansson and Schipper (1997) (in Box 12)[28]. Although the choice is somewhat arbitrary, Pindyck (1979) is a widely read study and an early attempt to analyze global transport energy demand, while Johansson and Schipper (1997) is a more recent work employing a simple framework. However, data availability often has restricted such detailed analysis even in developed countries, forcing the researchers to adopt simpler forms of specifications. For example, Pindyck (1979) and Uri (1982) have used detailed form for gasoline demand but an aggregated form for diesel demand. More recently, Hughes et al (2008) have analyzed gasoline demand in the US for two different periods using a simple log-linear formulation. A detailed review of the demand models and econometric methods can be found in Graham and Glaister (2002b).

Box 11: Transport energy demand model in Pindyck (1979)

The study used the identity model for gasoline demand estimation. Three equations were used to determine stock of vehicles, while two other relations described the depreciation rate, transport volume and vehicle efficiency.

The stock of vehicle is obtained from an accounting identify which reflects the depreciation of stock and addition of new vehicles to the stock. This is written as in Eq. 1.

$$STK_t = (1-r)STK_{t-1} + NR_t \qquad (1)$$

Where STK is the stock of automobiles,
R is the depreciation of the stock, and
NR is new registrations.

New registrations bring the stock to the desired stock level, where the desired stock is a function of explanatory variables such as car price (P_c), fuel price (P_f) and income. Per capita new registrations can be expressed as

$$\frac{NR_t}{POP_t} = w\left(\frac{STK_t^*}{POP_t} - \frac{STK_{t-1}}{POP_{t-1}}\right) + r\frac{STK_{t-1}}{POP_{t-1}} + \lambda\frac{NR_{t-1}}{POP_{t-1}} \qquad (2)$$

Assuming STK* to be a linear function of P_i, P_f and Y, equation 2 can be rewritten as

$$\frac{NR_t}{POP_t} = a_0 + a_1P_c + a_2P_f + a_3\frac{Y}{POP} - (w-r)\left(\frac{STK_{t-1}}{POP_{t-1}}\right) + \lambda\frac{NR_{t-1}}{POP_{t-1}} \qquad (3)$$

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[28] Some other studies include Baltagi and Griffin (1983), Dunkerley and Hoch (1987), McRae (1994), Garbacz(1989).

The depreciation rate r can be expected to increase with higher per capita income and fall with higher car prices. This can be captured through a linear function as given in equation 4.

$$r = b_0 + \frac{b_1 Y}{POP} + b_2 P_c \qquad (4)$$

Equations 1, 3 and 4 define the stock of vehicles.

The vehicle utilization is normally expressed in kilometers driven per year per car. It can be expected to depend positively on the per capita income but negatively on the price of fuel. This is captured through the log-linear relationship given in equation 5.

$$\ln(U_t) = c_0 + c_1 \ln(Y/POP) + c_2 \ln P_f + c_3 \ln(U_{t-1}) \qquad (5)$$

The average fuel efficiency is expected to change with fuel price but with a lag. Another log-linear relationship, equation 6, captures this.

$$\ln(Eff_t) = d_0 + d_1 \ln P_f + d_2 \ln(Eff_{t-1}) \qquad (6)$$

Box 12: Johansson and Schipper (1997) model

As before, the fuel demand is defined as the product of three factors:

$$E = S.\ I.\ D. \qquad (1)$$

Where S is the automobile stock per capita,
I is fuel consumption per kilometer driven (or fuel intensity), and
D is the distance travelled per year per car.

The authors have chosen a *recursive* system approach where the variable D is estimated as a function of S and I and other variables, but I and S are estimated solely as functions of other variables. Moreover, they estimate all three demand components using log-linear relationships which are most widely used functional forms that yield constant elasticities and provide easy-to-interpret results. However, for tax and population density, semi-log specification was used to avoid the problems arising from near zero values.

The following dynamic pooled model relationships were estimated:
for vehicle stock:

$$\ln S_{it} = \alpha_0 + \alpha_1 \ln S_{i,t1} + \alpha_2 \ln P_{it} + \alpha_3 \ln Y_{it} + \alpha_4 T_i + \alpha_5 G_i + u_{it} \qquad (2)$$

for fuel intensity:

$$\ln I_{it} = \beta_0 + \beta_1 \ln I_{i,t1} + \beta_2 \ln P_{it} + \beta_3 \ln Y_{it} + \beta_4 T_i + \beta_5 G_i + u_{it} \qquad (3)$$

for distance traveled (4)

$$\ln D_{it} = \gamma_0 + \gamma_1 \ln D_{i,t1} + \gamma_2 \ln(P_{it} I_{it}) + \gamma_3 \ln Y_{it} + \gamma_4 T_i + \gamma_5 G_i + \gamma_6 \ln S_{it} + u_{it} \qquad (4)$$

Where

P is the fuel price,
Y is the income (GDP)
G is the population density

The authors remark that the distance traveled equation is the most difficult to estimate as there exist a large number of possible explanatory variables. The estimated relationships can be used to forecast future demand.

A more common approach is to rely on the market shares and forecast the demand ensuring consistency. Miklius et al (1986) provides an early example of this approach for analysis petroleum demand in several Asian countries. Box 13 provides the details of methodology used in that analysis, to explain the market share approach.

Box 13: A simple model for transport fuel demand estimation

Consider that two substitutable fuels diesel and gasoline are used for transport purposes. The market share approach is used to estimate the demand. The model has two components: first, the total fuel demand for transport is estimated; then, the demand for individual fuels is estimated using their market share.

The total demand for diesel and gasoline is considered to be a function of weighted average price of fuels in real terms, real per capita GDP and the total consumption of both fuels in the previous year. The equation in log-linear form can be written as

$$\ln TC = a0 + a1 \ln P + a2 \ln GDP + a3 \ln TC_{-1}, \qquad (1)$$

where $P = (DC/TC).DP + (GC/TC).GP$

where, TC = total consumption of diesel and gasoline, P is the average price, GDP is the real per capita GDP, DC is the diesel consumption, GC is the gasoline consumption, DP is the price of diesel and GP is the price of gasoline.

The market share of a fuel is assumed to be a function of its real price, the price of the substitute fuel, the per capita GDP and the share of the fuel in the previous year. The equation for gasoline can be written as follows:

$$\ln(GC/TC) = b0 + b1 \ln DP + b2 \ln GP + b3 \ln GDP + b4 \ln(GC/TC)_{-1} \qquad (2)$$

As there are two fuels in this case, the total share has to be 100. The diesel share is thus obtained

$$DC/TC = 100 - \exp[\ln(GC/TC)] \qquad (3)$$

Source: Miklius et al (1986).

Bouachera and Mazraati (2007) have forecast transport fuel requirement for India using the econometric approach. They determine the aggregated fuel demand from car stock in a given year and the average fuel requirement per car per year. Per capita car ownership has been forecast using alternative non-linear functions such as logistic, Gompertz and power. The goodness of fit of functions was verified to find out the best relation between per capita income and per capita car ownership. The vehicle fleet was then forecast using these relationships and by combining the forecast with assumptions about average fuel consumption per vehicle, overall transport fuel demand was estimated. Clearly, the above approach does not make any distinction between different types of fuels and vehicles used in the transport sector.

Like industrial energy demand, recent econometric studies on transport demand forecasting have relied on cointegration and error correction models.[29] These models focus on the technical properties of the time series and try to avoid misspecification of the models. But often these models are at an aggregated level and do not consider the efficiency or vehicle stocks explicitly. Most of these models focus on a particular fuel rather than considering the entire set of transport fuels or modes, thereby ignoring the substitution possibilities.

In developing countries, where fuel prices are regulated by the government, the transport fuel demand is generally more influenced by income and the price sensitivity of demand is often limited. Studies that consider demand at the aggregate level without considering the growth of transport vehicle stocks or the modes of transport cannot really capture the developing country features. In addition, as the traditional modes of transport play an important role in the developing countries, any study that ignores such options may not truly reflect the demand growth. Moreover, the spatial dimension is particularly important in the developing country context as the demand growth often takes place in the urban areas while the rural transport demand remains neglected. The aggregate level of analysis, while useful for obtaining the big picture, is less appropriate for a developing

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[29] See for example Ghosh (2006), Polemis (2006), Ramanathan (1999), Eltony and Al-Mutairi (1995), and Bentzen (1994), Samimi (1995), Dahl and Kurturbi (2001), and Kulshresthra et al (2001).

country transport policy context. This turns out to be the main issue with the econometric analysis of transport energy demand.

End-use approach

While the econometric approach has focused on the elasticities of fuel demand and other variables that influence fuel demand, the end-use approach has focused on forecasting demand by capturing the diversity of transport modes, types of vehicles, efficiency and other drivers. The usual disaggregation of the transport sector is shown in table 4.

Table 4: Disaggregation of the transport sector in end-use studies

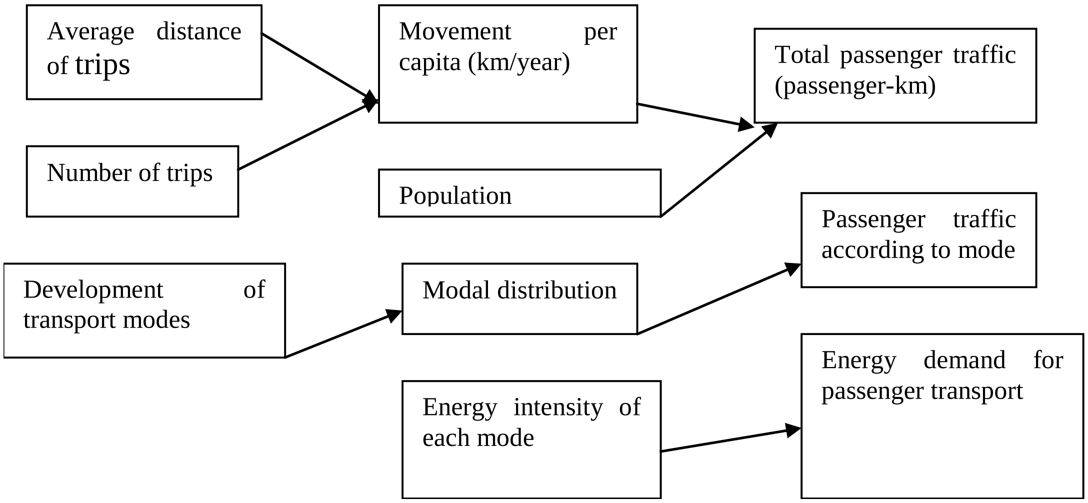
Need	Modes	Vehicles	Fuel use
Public passenger transport	Road	Taxis	Gasolene, Diesel, LPG, CNG
		Minibuses	Diesel, CNG
		Urban buses	Diesel, CNG
		Intercity buses	Diesel
		Others	Gasolene, Diesel, LPG, CNG
	Rail	Tramways, tube rails	electric
		light rails	electric
		Commuter trains	coal, diesel, electric
		Intercity trains	coal, diesel, electric
	Dom. Air		Jet fuel
	Dom water		Fuel oil, gasolene,
Private passenger transport	Road	Motorcycles	
		Cars	
Freight transport	Road	Pick-ups	Diesel
		Light trucks	Diesel
		Heavy trucks	Diesel
	Rail		coal, diesel, electric
	Dom water	Barges, ships	Fuel oil, gasolene,

Source: This study.

It is a conventional practice for the transport sector's energy demand analysis to divide the sector into passenger and freight transports. The determinants of energy demand and the units of measurement of outputs are different in these two types of transport activities. On a macro or national level, energy consumption for passenger transport depends on the number of passengers traveling, the frequency and average length of trips, the distribution of trips among various modes of transport (i.e. air, sea, rail, road) and the technical characteristics of the carriers and their conditions of use. Figure 4 presents these determinants in a schematic form.

In the transport sector, energy is mainly used for passenger transport and freight transport. In less developed countries, the frequency of passenger trips and volume of shipment of freight are low. Moreover, traditional methods such as human and animal-powered transport systems co-exist in these countries alongside modern systems. The energy demand both for passenger and freight transportation tends to increase rapidly, often at a rate higher than the growth rate of GDP, due to economic growth. This also leads to growth in ownership of cars and personalized transportation modes. The increase in demand for vehicles in turn causes higher demand for oil.

Fig. 4: Determinants of passenger transport demand

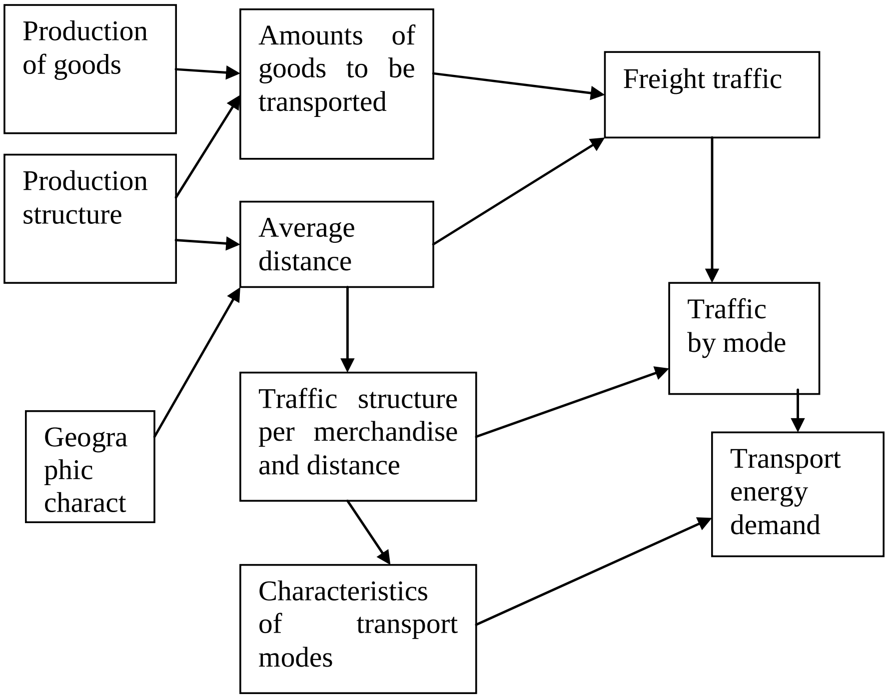


The development of transport modes and the modal distribution of a country are greatly affected by energy as well as general economic policy. The energy consumption per passenger-km varies greatly by mode of transformation. The energy consumption per unit of driving (i.e. liters/km) is in principle a function of the power of the engine and of engine efficiency. The weight of the vehicle, traffic, speed, and driving style are further important factors affecting the energy intensity of the modes. If all these remain constant over time, the determinant of the energy intensity of each mode reduces the fuel consumption efficiency.

Energy demand for freight transport depends on the volume of commodities, average distance of shipping, the modal structure of freight transport, and the economic and technical characteristics of each transport mode. The relationship among these variables is shown in Figure 5.

Many policy-oriented forecasting studies of the transport sector have relied on the end-use approach. Studies using the end-use related often rely on a standard model or computer package and contrary to the econometric studies end-use studies are hardly reported in the academic journals. However, examples of application of various popular models such as MEDEE, LEAP or other specially developed end-use applications can be found in, among others, Dhakal (2003) and Dakhal (2006), Dutton and Page (2007), and Zhou (2007).

Fig. 5: Determinants of energy demand for freight transport



The end-use oriented studies of transport demand attempt to capture the fuel demand by considering individual components contributing to demand and accordingly, they tend to cover the relevant demand drivers for the developing countries. The disaggregated approach also allows a detailed representation of the vehicle stock, vehicle vintages, and changes in the fuel mix, modal mix and technologies, as well as rural-urban dichotomy. This method is also capable of capturing introduction of new technologies or fuels, and traditional modes of transport. This method has been applied to the developing countries in the past. Although most of the end-use models do not consider price-induced effects, the problem may not be acute due to inelastic demand of transport fuels. The use of hybrid end-use models can also address this specific problem.

Other approaches

In line with the general trend in energy model developments, the use of hybrid models in the transport sector in gaining ground. Jaccard et al (2004) provide an example of a hybrid model where the rich technological representation of the transport system is complemented by using a top-down behavioral choice model. Similarly, Robert et al (2007) apply forecasting and back-casting approaches to analyze energy demand in the Stockholm transport system in 2030 after oil peak is reached.

4.2.3 Residential demand

Residential sector generally accounts for a substantial share of final energy demand in many countries. As energy sector policies or energy market conditions tend to have serious welfare consequences for the households, this sector has traditionally been well analyzed. Given that both aggregated and disaggregated demand forecasting has been carried out, we shall present the application of econometric method first, followed by that of the end-use approach.

Econometric approach

The pioneering work of Houthakker (1951) on the British urban electricity consumption perhaps initiated the econometric investigation of residential energy demand in a formal way. Since then, and as with other applications, a wide variety of applications of the econometric approach to the residential sector has appeared in the literature. According to Bohi and Zimmerman (1984) and Madlener (1996), more studies have been done on this sector than any other area thereby providing an opportunity for detailed comparisons. Similarly, the focus on electricity demand is significantly higher than any other fuels.[30] However, in line with our preoccupation with forecasting models, we present a brief review here highlighting the major methodological developments. A more detailed recent review can be found in Madlener (1996), while Bohi and Zimmerman (1984) provide a somewhat older but excellent review of the US studies.

Residential energy demand studies have covered individual fuels (such as electricity, natural gas) or aggregate demand or the entire set of energies used. The reduced-form, single equation demand specifications are quire common for fuel-level analysis[31]. The log-linear specification is most commonly used in such studies for the ease of estimation and simplicity.[32] Although residential energy demand depends on the stock of energy-using appliances and other economic variables, in the short-run the demand is expected to be constrained by the existing capital stock, which in turn would influence the consumer response to any changes in the economic variables. To capture this aspect, some attempts were made to use two-stage demand analysis – one for the short-term and the other for the long-run. However, the data on appliance stocks is often poor and leads to problematic results.

The trans-log wave of the 1970s has also fed to the publication of a number of studies, including Pindyck (1979). In his study, Pindyck (1979) considered that consumers make

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[30] Some recent studies include the following: Ziramba (2008), Nasr et al (2000), Filippini and Pachauri (2004), Bose and Shukla (1999), Beenstock et al (1999) and Al-Faris (2002).

[31] See for example, Taylor (1975) for a survey of electricity related studies.

[32] Some recent studies of this type include Rapanos and Polemis (2006), Rijal et al (1990) and Blackmore et al (1994).

two simultaneous utility-maximization decisions – how much to allocate for different fuels and what fraction of the budget to be spent on energy as opposed to other needs. He used indirect translog utility function for the two-stage model and estimated the model using pooled time-series cross-section data for nine OECD countries.

A new trend in energy modeling and for residential energy demand studies started with the pioneering works of McFadden (1973).[33] Prior to his works and even now most models assume a continuum of decision options. However, in reality, many a times we are confronted with discrete choices: unless an appliance (say electric oven) is purchased, the demand for that end-use energy cannot exist for that consumer. Moreover, consumers do not buy more than one such item at a time, thereby putting a limit on the growth as well. In energy studies, logit models became quite popular – often as an alternative to the translog models. The other feature of these studies is their use of micro-data from survey or similar sources – which initiated a further new trend in the demand modeling.

More recent academic studies have relied on cointegration approach (and other advanced econometric methods) for demand analysis of the residential sector. Most of these studies tend to focus on the aggregate demand in the sector and are preoccupied with identifying the cointegrating relationships. Studies of this variety include, among others, the following: Clements and Madlener (1999), Beenstock et al (1999), Ziramba (2008), Holtedahl and Joutz (2004), Halicoglou (2007), Narayan and Smyth (2005) and Hondroyiannis (2004). In addition, studies using household survey data have also appeared (see for example Hirst et al (1982), Tuan and Lefevre (1996), and Pachauri (2004)).

A common problem with the studies on the residential energy demand using the econometric approach is the assumption of a representative consumer. Although in disaggregated models one representative consumer per group is used, still the process remains arbitrary and judgmental. Assimakopoulos (1992) suggested an approach of endogenously obtaining homogeneous groups of consumers using a two stage process: a

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[33] See Dubin and McFadden (1984), Baker and Blundell (1991) and Baker et al (1989) as well.

structural analysis of households using statistical techniques and then modeling demand equations. Although this method was applied to a case study, there is no evidence that this has been widely used. Although the survey-based studies tend to capture the diversity of demand by income and location, they provide insight at a given point in time. While these studies surely add value in understanding the demand, the frequency of such surveys and the cost of gather such data could be a hurdle for many developing countries.

Although a large number of econometric studies exist for the developed countries, limited focus has been given on residential energy demand in developing countries and especially for rural areas. The main difficulty often faced by the residential and commercial sectors in analyzing energy demand is the availability of data, especially of end-use breakdowns of energy consumption. Moreover, traditional fuels play a vital role in many countries to meet the energy demand of residential and commercial sectors but data is often not available in a systematic and regular manner. In addition, as the end-use efficiency of traditional fuel use is comparatively low, the final energy consumption including traditional energies may hide certain changes taking place within the sectoral energy consumption pattern. The conventional econometric analysis tends to ignore the non-priced transaction of traditional energy use in rural areas, especially due to the lack of a reliable time series. However, such omission can be difficult to justify given that a large section of the rural population is expected to continue to rely on traditional energies even in 2030 (IEA, 2002).

Further, the single equation models or aggregated analysis do not capture the technological diversity and the spatial difference in energy demand. The problem can be worse where energy prices are controlled by the government because the econometric relations may not prove statistically significant or meaningful.

End-use models

Changes in energy demand in the residential sector are often related to the population change, and changes in demand per capita. Measuring activity is difficult since there are many different energy-using activities that take place in homes but no single measure. For that reason, population is used as an indicator of residential activity.

For example, energy consumption can be considered as follows:

$$E = POP*S*EI; \tag{4}$$

Where E = total energy demand;

POP = population

S = structural parameter indicating per capita ownership of energy-using appliance or dwelling area per person;

EI = energy intensity expressed in terms of energy use per unit of an application.

As there are different end-uses (e.g. space heating, water heating, lighting, electric appliances, etc.) and different appliances or applications within end-uses, the total energy demand is obtained by summing all applications in an end-use and then adding demand in all end-uses.

$$E = POP\sum_i \sum_j S_{ij} EI_{ij} \tag{5}$$

Total energy demand in the end-use approach is estimated by summing up end-use energy demands for space heating, air conditioning, water heating, cooking and use of electrical appliances including lighting. Total energy consumption for space heating and air-conditioning of a country for a given year is determined by the average energy consumption per household and per building for those purposes, and the total number of households and buildings for that year. Similarly, energy demand for cooking is related to unit demand per household and number of households. The lighting requirement can be expressed as a function of household area, lighting requirement per unit area and the number of households.

As the demand pattern in households vary with income level and geographical location (rural/ urban), better results are obtained by disaggregating the demand by income level and rural/ urban areas. The total demand in that case would be sum of demands by all categories and locations.

Studies using this approach include:
a) McAleer (1982) for a study of Northern Ireland to perform forecasting for 30 years and analyse what-if question,
b) Farahbakhsk et al (1998) for the residential sector of Canada using an end-use model,
c) Tanatvanit et al (2003) who used LEAP for analyzing demand in Thailand including the residential sector, etc.
d) Liao and Cheng (2002) analyzed the space heating and water heating demands by the aged people in the USA.

A number of studies by Lee Schipper and his associates (e.g. Schipper et al (1985), IEA (1997), Haas and Schipper (1998), etc.) use end-use approach but focus mainly on the indicators and the decomposition approach for analyzing the residential energy demand at the international level. While these are not forecasting studies per se, the later studies focusing on the climate change issues incorporate forecasting elements.

Michalik et al (1997) used a structural model based on the bottom-up approach considering consumer characteristics and appliance- stock and usage information at a detailed level for residential energy demand in Australia.

The disaggregated approach to residential demand analysis allows better representation of the specific features of developing countries. Spatial differences in housing stocks, consumption behavior and technological choices are commonly captured in these studies. They also cover traditional energies as well as differences in demand by income class. Moreover, the end-use approach reflects the transition of energy use in the residential sector due to income- and policy-induced effects. Accordingly, this approach appears to better suit the developing country needs.

4.2.4 Commercial sector

Perhaps the energy demand in the commercial sector is less analyzed compared to other sectors. Denton et al (2000) ascribe this lack of analysis to the following factors:

- defining the coverage of the sector in an unambiguous manner;
- availability of consistent data for analytical purposes;

Like the residential sector, this sector is quite heterogeneous, widely dispersed and can be at different levels of development in different countries.

As the commercial sector uses different types of energies, studies have focused on aggregate fuel demand or specific fuel demand (electricity or natural gas). In the econometric tradition, state or country level information as well as micro data have been used for this sector, although the later variety is less common. Similarly, discrete choice theory has also been applied to analyze the conditional nature of energy demand decision-making process.

Eltony and Al-Awadhi (2007) has analyzed the energy demand of the commercial sector of Kuwait. They have used cointegration technique and the error correction model (ECM) for forecasting the demand. They retained customary variables of income and price as explanatory variables and first established that all the variables are first difference stationary. Then they estimated cointegration and ECM equations. Using the established relationships, they projected the electricity demand for 2010 and 2015 under three alternative scenarios (base case, and two alternative price change cases). However, there is a significant divergence between the electricity consumption in the commercial sector for 2005 with the information reported in this study. The validity of their results remains questionable.

Newell and Pizer (2005) use the discrete-continuous choice analysis of multi-fuel demand for the US commercial sector. They use a multinomial log-it specification and use 1995 Commercial Buildings Energy Consumption Survey of 1995 to produce a detailed end-use and fuel-level analysis.

End-use method

The approach taken by the end-use models for commercial sector analysis is similar to that of the residential sector. However, instead of population other activity variable is used as demand determinant because of the heterogeneity of the sector activities. Example include: floor space for commercial areas, sales or economic output for business activities, number of patients or students or room occupancy for hospitals, schools/ colleges, and hotels respectively, etc. Generally, disaggreation at an appropriate level is considered to capture different activities covered by the sector. The demand is forecast by the product of activity and unit consumption (or specific consumption).

Energy demand for various end-uses such as space heating, air conditioning, water heating, cooking and use of electrical appliances including lighting is taken into consideration.

The issues related to the commercial sector are same as in the case of residential energy demand and are not repeated here.

5. Features of Specific Energy Demand Forecasting Models

This section considers specific models with either detailed country-level coverage or a regional/ global coverage. Clearly, the selection of models has been guided by the information available on the model and the usual constraints of time and resources. The section is organized as follows: the first sub-section provides a brief description of the models; this is followed by a comparison of the models in terms of a set of criteria such as their coverage, data requirements, complexity, skill requirement, etc.

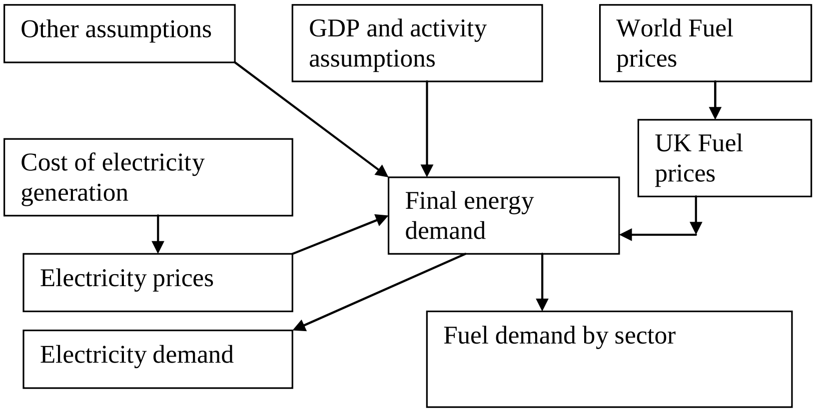
5.1 Brief descriptions of selected energy demand models

5.1.1 Country-specific models

UK energy forecast model[34]

For its energy forecasts and future carbon emission estimations, the Department of Business, Enterprise and Reform of the United Kingdom relies on an econometric model. Although the model covers both supply and demand sides, the demand is fairly elaborate. It contains 150 econometric relationships to determine the demand in various sectors of the economy. The model follows the Error Correction Modeling approach and uses price and economic activity as main variables although time trends are used in some sectors. The model has 13 final users who are then grouped into four major sectors, namely industry, transport, services and domestic. Each final user sector is further disaggregated by fuels. The model structure of the model is shown in Fig. 6, while the main demand drivers are indicated in Table 5.

Fig. 6: DTI energy model overview



Source: Based on DTI (2005)[35]

However, a comparison of the forecasts made in DTI (2000) with the actual data shows that the model did not succeed in making correct projections (see Table 6). In fact, the

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[34] Based on DTI (2000),

[35] See (http://www.berr.gov.uk/files/file26611.ppt).

forecasts for 2005 were systematically lower and even the actual demand was close the forecasts for 2010. This shows the underestimation and underperformance of the model even in mature economy with little demand surprises.

Table 5: Demand drivers of DTI model

Sectors	Activity variable	Price variable	Appliance stock	Weather	Other
Domestic	Real personal disposable income	Domestic energy prices	Major appliance take up	External temperatures	Number of households
Transport	GDP, OECD GDP	Petrol price, other fuel prices	Car ownership level, goods lifted, track length		Population and number of households
Service	GDP	Service sector energy prices		External temperatures	Public sector share, employment
Industry	GDP	Industrial sector prices, fossil fuel prices, electricity prices			Physical output

Source: DTI (2005)

Table 6: Comparison of actual demand with projected demand for the UK (Mtoe)

Description	2005	2010
Centre growth low price scenario	239.9	247.4
Central growth high price scenario	235.6	242.8
Actual-2004	246.0	
Actual demand 2005	247.4	
Actual demand 2006	243.8	

Source: DTI (2000) and BERR (2007)

NEMS [National Energy Modeling System]

The National Energy Modeling System (NEMS) was designed and primarily used by the US Department of Energy for preparing the Annual Energy Outlook. It is a model of energy-economy interaction that is used to analyze the functioning of the energy market under alternative growth and policy scenarios. The model uses a time horizon of about 25 years (up to 2030 for the present version).

The model is fairly detailed and explicitly represents the economic decision making at various levels (production, consumption, etc.) as well as technologies. The demand analysis component is divided into four modules (residential, commercial, industrial and transport) and each module captures the diversity at the regional level to a great extent (see table 7).

Table 7: Demand representation in NEMS

Energy activity	Categories	Regions
Residential demand	Sixteen end-use services Three housing types Thirty–four end–use technologies	Nine Census divisions
Commercial demand	Ten end–use services Eleven building types Ten distributed generation technologies Sixty–four end-use technologies	Nine Census divisions
Industrial demand	Seven energy–intensive industries Eight non–energy–intensive industries Cogeneration	Four Census regions, shared to nine Census divisions
Transportation demand	Six car sizes Six light truck sizes Sixty–three conventional fuel-saving technologies for light–duty vehicles Gasoline, diesel, and thirteen alternative–fuel vehicle technologies for light-duty vehicles Twenty vintages for light-duty vehicles Narrow and wide–body aircraft Six advanced aircraft technologies Medium and heavy freight trucks Thirty–seven advanced freight truck technologies	Nine Census divisions

Source: EIA (2003).

The residential demand module forecasts energy demand using a structural model based on housing stock and the appliance stock. The demand is driven by four drivers: economic and demographic factors, structural effects, technology, and market effects. The housing stock and appliance stock information from the Residential Energy Consumption Survey is used to capture the diversity of stock holding and usage patterns across the country. It projects the demand for various end-uses by fuel type.

The commercial sector demand module projects energy demand in the commercial sector by taking into account building and non-building demand. It also captures the appliance stock and technological advancements and their effects on energy demand for three major fuels, namely electricity, natural gas and distillate oil. For the remaining minor fuels, the demand is projected using a simple econometric method. The demand by fuels for various end-uses is projected by the module.

The industrial demand module projects energy demand in the industrial sector using a hybrid approach: it uses the technological representation found in the end-use method and incorporates the behavioral aspects of a top-down approach. The demand is analyzed at a disaggregated level – with a greater focus on energy intensive industries which are analyzed at the 3-digit level of industrial classification. Within each industry, three elements of demand are considered – building, boiler and process/ assembly activities. The demand for each element is estimated separately using a combination of approaches ranging from simple growth rates to more involved methods.

The transport demand module projects the fuel demand in the transport sector by mode and includes alternative energy demand. A disaggregated approach is used in demand forecasting where personal car usage, light truck, freight transport, air transport and miscellaneous transport are considered separately. A nested multinomial logit model is used to predict the vehicle sales by technology. The vehicle miles per capita is estimated based on fuel costs of driving, disposable income per capita and an adjustment for men to women driving ratio. The model captures the regional variation in transport demand as well.

EIA (2007) presented a retrospective review of the projections contained in the Annual Energy Outlooks between 1982 and 2007. The review shows that the overall energy demand was quite close to the actual demand but the difference was somewhat high for natural gas demand and energy price forecasts. The main driving variable, GDP, was less accurately forecast, which influenced other outcomes directly.

Although NEMS is a detailed model, its use has remained confined to government agencies and a limited number of research laboratories because of the model's reliance on costly proprietary software packages and complex model design.

ERASME model

ERASME is a short-term energy model that is used by the European Commission for quarterly forecasting of energy demand at the Community level (Deimeizis, 1995). It also has a supply-side forecasting and the model produces the forecasts of energy balance. The results of the model feed into the Short-Term Energy Outlook of the Commission. The model contains 55 behavioral relations and a large number of identities capturing the European energy system. The model uses the data obtained from the Statistical Office of the Community and the equations are re-estimated twice a year. The estimation process relies on OLS except for electricity where a three stage lease square approach is used.

The demand-side of the model relies on the following logic:
Final energy prices are considered to be a function of international oil prices, coal import prices, exchange rate, changes in the fiscal regime and seasonal factors.

$$P_f = f(PM, XR, T, SF) \quad (6)$$

Where
P_f = fuel price
PM = price of imported fuel (coal or oil)
XR = exchange rate

T = fiscal regime
SF = seasonal factors

Energy demand by fuel is considered to a function of exogenous macro and sectoral variables (such as GDP, private consumption, industrial production, etc.) and real energy prices.

$$D_f = f(Q, P_f, P_s, DD, SF, ..) \qquad (7)$$

Where
D_f = demand for fuel f
Q = economic activity
P_s = price of competing fuel
DD = Climatic conditions (degree-days)

The dynamic adjustment process is introduced generally through Kyock lags, although the lag system is redesigned for each re-estimation of the model.

Fuel substitution is captured through relative prices of fuels and technological progress/ structural change is captured through a trend.

5.1.2 Generic energy forecasting models

MAED model

This is a widely used bottom-up model for forecasting medium to long-term energy demand. MAED (acronym for Model for Analysis of Energy Demand) falls in the MEDEE family of model developed by B. Chateau and B. Lapillonne (IAEA (2006), Lapillonne (1978)) but has been modified now to run on PCs and using EXCEL.

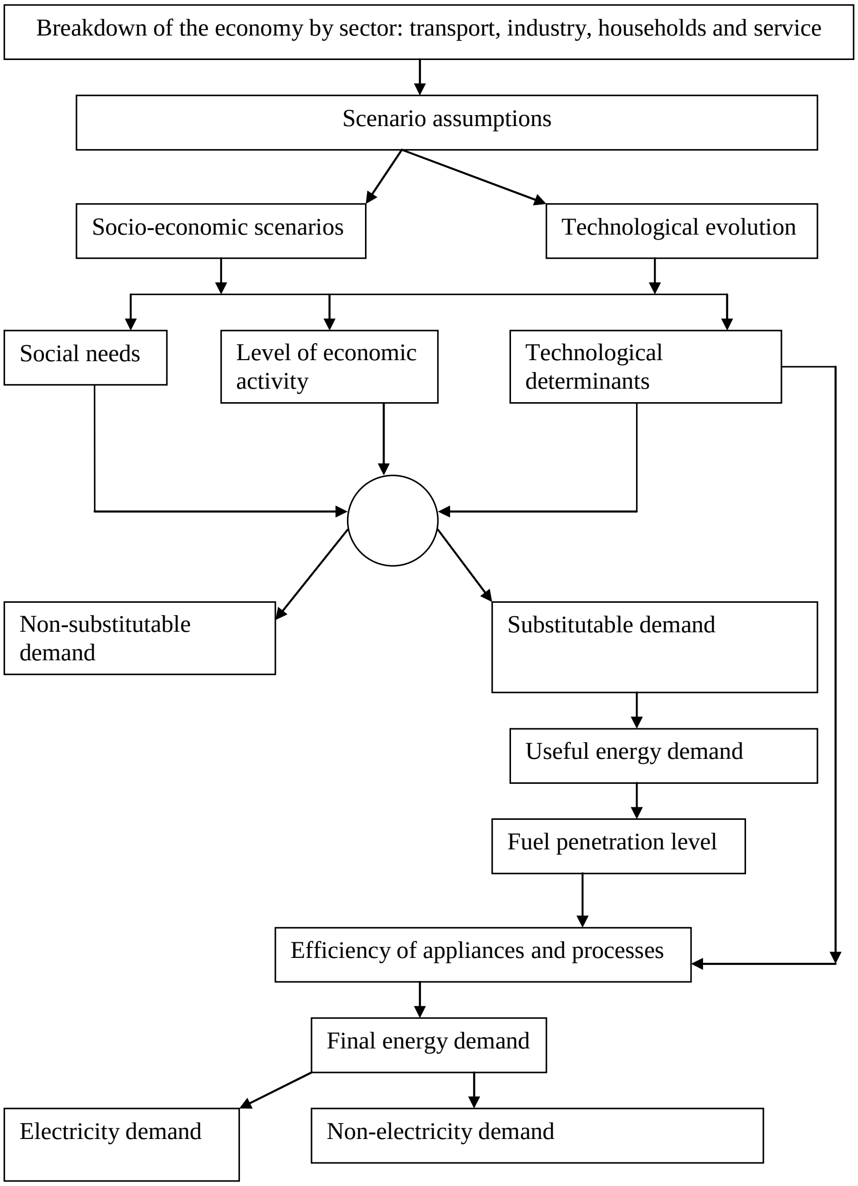
The earlier versions of the model were built around a pre-defined set of economic activities and end-uses. Manufacturing industry was broken into four sub-sectors while the transport sector considered passenger and freight transports separately. Various types of households could also be considered but they were aggregated at the national or regional level. An aggregated representation was used for other sectors.

Given the diversity of needs of the users from across different countries around the world, the more recent version has been developed to provide a more flexible structure where the user can add more sub-sectors, transport modes and fuel types, and household types.

The model follows the end-use demand forecasting steps typical for an engineering-economy model as indicated in Sec. 4. It relies on the systematic development of consistent scenarios for the demand forecasts where the socio-economic and technological factors are explicitly taken into consideration. Through scenarios, the model specifically captures structural changes and evolution in the end-use demand markets. For competing forms of energies, the demand is first calculated in useful energy form and the final demand is derived taking market penetration and end-use efficiency into consideration. The model does not use pricing and elasticity information for the inter-fuel substitution as is common in the econometric tradition. This is a deliberate decision of the model developers as the long-term price evolution is uncertain, the elasticity estimates vary widely and because energy policies of the governments tend to influence demand significantly.

The energy demand is aggregated into four sectors: industry, transport, households and service. The industrial demand includes agriculture, mining, manufacturing and construction activities (or sub-sector). The demand is essentially determined by relating the activity level of an economic activity to the energy intensity. However, the demand is determined separately for non-substitutable energy forms (electricity, motor fuels, etc.) and substitutable forms (thermal energies). The need for feedstock or other specific needs can also be considered.

Fig. 7: MAED Framework of analysis



Source: IAEA (2006)

The demand is first determined at the disaggregated level and then added up using a consistent accounting framework to arrive at the overall final demand. The model focuses only on the final demand and does not cover the energy used in the energy conversion sector. The general framework of analysis of the MAED model is presented in Fig. 7. The detailed list of principal equations used in the model is provided in IAEA (2006).

MEDEE Model

As indicated earlier, the MEDEE model was developed initially by Chateau and Lapillonne (1978) and has been expanded through additional research at IIASA and elsewhere (see Lapillonne (1978), Lapillonne and Chateau (1981), and Finon and Lapillonne (1983)). The MAED model described above is essentially derived from the MEDEE model. The main difference between MAED and MEDEE is that MAED was based on an earlier version of MEDEE which has been further developed by IAEA into its present form, while MEDEE remains the model of the original authors and is supported by their energy consulting firm ENERDATA. Thus the modeling approach remains the same but the development of the two products has taken different paths in the recent times. To avoid duplication, MEDEE model is not elaborated any further here.

5.1.3 Energy forecasting as part of an integrated model

LEAP Model

The Long-range Energy Alternatives Planning (LEAP) is a flexible modeling environment that allows building specific applications suited to particular problems at various geographical levels (cities, state, country, region or global). As an integrated energy planning model LEAP covers both the demand and supply sides of the energy system. However, we briefly outline the demand forecasting features of the LEAP model here.

The model follows the accounting framework approach to generate a consistent view of energy demand (and supply) based on the physical description of the energy system. It also relies on the scenario approach to develop a consistent storyline of the possible paths of energy system evolution. Thus for the demand forecasting, the model does not optimize or simulate the market shares but analyses the implications of possible alternative market shares on the demand.

The demand analysis, following the end-use approach, is carried out as follows (Heaps, 2002):

- The analysis is carried out at a disaggregated level, where the level of disaggregation can be decided by the users;
- The disaggregated structure of energy consumption is organized as a "hierarchical tree", where the total or overall activity is presented at the top level and the lowest level reflects the fuels and devices used. An example of such a tree will be: sectors, sub-sectors, end-uses and fuels/ devices.
- The socio-economic drivers of energy demand are identified. The distribution of these activities at the disaggregated level following the "hierarchical tree" is also developed.
- Generally, the product of activity and the energy intensity (i.e. demand per unit of the activity) determines the demand at the disaggregated level. However, the model allows alternative options:
    - at the end-use level, useful energy can be considered to forecast the demand.
    - Stock analysis allows the possibility of capturing the evolution of the stock of appliances/ devices or capital equipment and the device energy intensity.
    - For the transport sector, the fuel efficiency of the vehicle stock and distance traveled can be used to determine the demand.

The demand relationships are indicated below (Heaps, 2002):

1. Final energy analysis: $E = A \times I$

   Where A = activity level, I = final energy intensity
2. Useful energy analysis: $E = A \times (U/\eta)$

   Where U = useful energy intensity,

   η = efficiency
3. Stock analysis: $E = S \times D$

   Where S = stock and

D = device intensity

4. Transport analysis: E = S x (M/Fe)

Where M = vehicle miles and

Fe = fuel economy

The model can be run independently on a stand alone mode and can be used for specific sector analysis or for analyzing the energy system of a given geographic region. The model has been widely used and it is reported that 85 countries have chosen the model for their UNFCCC reporting requirements.

The POLES model

The POLES (Prospective Outlook on Long-term Energy Systems)[36] model is a recursive, disaggregated global model of energy analysis and simulation. It covers both the demand and the supply sides of the energy systems and has been used for long-term energy policy analysis by the European Union and the French government. The demand-side of the model is quite detailed and covers key world regions and major consumers.[37]

The demand is analyzed at a disaggregated level in each country or region following the bottom-up approach. The model is disaggregated into five sectors (industry, transport, residential, service and agriculture) to ensure homogeneous levels of activities. To capture the importance of the industrial sector and the transport sector, industry is further disaggregated in four groups, namely steel, chemical, non-metallic minerals and other industries, while four modes of transport, namely road, rail, air and water are considered.

The total demand is decomposed into two parts: substitutable demand and captive demand (normally for electricity). In each sector, the total demand for each part (captive

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[36] See LEPII-EPE (2006) and LEPII-EPE and Enerdata (2006) for further details.

[37] The regions covered are: North America, South America, Central America, Western Europe, Central Europe, Former Soviet Union, North Africa and the Middle East, Sub-Saharan Africa, South Asia, South East Asia, Continental Asia and Pacific OECD. Individual countries covered are G7 countries, two groups for the rest of the European Union, and five major developing countries, namely China, India, Brazil, Mexico and South Korea.

or substitutable) is determined through calibrated equations containing price elasticity, income (or activity) elasticity, technological trend and a residual element to capture other exogenous changes. The model uses a polynomial lag structure of variable duration to capture stock adjustment process and dissipation of reaction to exogenous shocks (as given in equation 8).

$$\begin{aligned}&\log(FC) = \mathrm{Re}\,s\_FC + \log(FC_{-1} + (-ES) * (\log(\frac{AP}{AP_{-1}}) * 0.67 + og(\frac{AP_{-1}}{AP_{-2}}) * 0.33) + \\ &\sum_{I=-1}^{-DP} f(EL * DI, I) * \log(\frac{AP_{I-1}}{AP_{I-2}}) + EY * \log(\frac{ACT}{ACT_{-1}}) + \log(1 + TR/100)\end{aligned} \tag{8}$$

Where

FC – final energy consumption,

AP – average price of energy,

ES – short-term price elasticity of energy demand,

EL – long-term price elasticity of energy demand,

EY – income elasticity of demand,

ACT – activity variable,

F(EL, DI, I) – function capturing long term price effect, where DI is price asymmetry effect,

DP – duration of long-term price effect,

TR – autonomous technological trend, and

the subscripts indicate the lag periods.

For the substitutable energy demand, the substitution process is simulated using putty-clay model. Here, old capital is assumed to be attached to a source of energy and the substitution takes place only in the case of new demand component. The demand originating from the old capital for each type of energy is estimated using calibrated equations of the sort discussed above. The difference between the total substitutable demand and that coming from old capital corresponds to new demand. The share of each fuel in the new demand is estimated as a function of cost, use efficiency, and maturity of the fuel in the market.

Although the demand model is deeply rooted in the accounting framework and follows the bottom-up approach, unlike other end-use models, the POLES model has a few special features:

- it generates the what on a yearly basis, as opposed to a snapshot picture at the end of a forecasting period;
- incorporates the price variable as a demand driver and thus can analyse the effects price and tax influences on demand;
- uses econometric-style relationships that are quite different from other standard end-use models.

Because of these features, the POLES model can be considered a hybrid model. The model base year is regularly updated and the forecasts for energy demand are prepared for various studies, mainly for research and policy making by the EU. Unlike other general purpose models such as LEAP, MEDEE or MAED, the POLES model, being an integrated global model, is not designed for independent use in a specific country context.

5.2 Comparison of selected energy demand models

Given that each model has its own features, characteristics and limitations, it is important to compare their capabilities using a simple framework. This is attempted in table 8, which is self-explanatory. The following observations can be made from the comparison:

a) Large national or global models are purpose-built and require considerable skills and lack versatility, irrespective of modeling approach used (econometric or hybrid). They also lack transferability or transportability. As a consequence, these models tend to be used by a limited number of dedicated user groups and are not accessible to wider users.

b) Only MAED/ MEDEE and LEAP have the generic capabilities to be used in a wider context. This explains the wider use of the above two models.

c) While econometric models can be used for price-based policy analyses, many such models lack the capability to capture non-price based policies. Moreover, being aggregated demand models, they fail to capture the technological diversity and possibilities adequately.

d) On the contrary, end-use models do not capture price signals and price-based policy analysis cannot be captured. Moreover, the issue of consistency with the macro-economic performance of the country or region is not verified in these models. However, their rich scenario capabilities allow them to consider non-price policies and structural changes in detail.

e) Data requirement is generally a major issue for any demand model. All varieties of models require large data inputs and can pose problems for developing countries. However, simple end-use models can be developed with limited information and LEAP intends to introduce such a limited data version model for developing countries.

f) Rural energy demand tends to be more difficult to capture through econometric models but end-use models can include them if relevant. Hybrid models can also include them if they use geographically differentiated information.

Table 8: Comparison of energy demand forecasting models

Criteria	Kuwait model	DTI	ERASME	NEMS	MAED/ MEDEE	LEAP	POLES
Type	Top-down	Top-Down	Top-down	Hybrid	Bottom-up	Bottom-up	Hybrid
Purpose	Energy demand forecasting	Energy system analysis	Energy demand forecasting	Energy market analysis	Energy demand forecasting	Energy system analysis	Energy market analysis
Approach	Econometric	Econometric	Econometric	Econometric with rich technology representation	Accounting	Accounting	Accounting with econometric-style equations
Geographical coverage	National	National	Regional level but aggregated	National	Flexible	Flexible	Global
Activity coverage	Main end-use sectors	Demand and supply sectors	Main demand and supply sectors	Supply and demand sectors	Demand sectors	Demand and supply sectors	Demand and supply sectors
Level of disaggregation	Industry, residential, transport, commercial and others	Domestic, transport, service and industry	?	Industry, residential, commercial and transport	Industry, transport, household and service	Industry, transport, household and service	Industry, transport, household, service and agriculture
Technology coverage	Conventional	Both renewable and conventional	?	Both conventional and renewable	Both conventional and renewable	Both conventional and renewable	Both conventional and renewable
Data need	Time series data for econometric estimation	Time series data and technology data	Time series data for econometric estimation	Time series data, technology data, survey and census data	Data and survey/ estimates for base year information and estimation parameters	Historical, socio-economic, technological and other information	Time series, socio-economic data, technological data and survey/ estimates for various parameters
Skill	High for	High for	High	High for	Low	Medium	High for

Criteria	Kuwait model	DTI	ERASME	NEMS	MAED/ MEDEE	LEAP	POLES
requirement	econometric estimation	econometric analysis	econometric analysis	running a complex model			running a global model
Versatility	Low – country specific	Low – country specific	Low – region specific	Low – country specific	High – general model	High-general model	Low – specific global model
Portability to another country	Difficult	Difficult	Difficult	Difficult	Easy	Easy	Difficult
Documentation	Limited	Limited	Limited	Excellent	Excellent	Excellent	Poor
Capability to analyse price-induced policies	High	High	High	High	Does not exist	Does not exist	High
Capability to analyse non-price policies	Low	Good	Low	Good	High	High	High
Rural energy	Not covered separately	Not covered separately	Not covered separately	Included through geographical coverage	Can be included	Can be included	Not covered specifically

6. Policy Implications for Developing Countries

Our analysis in the previous sections has established that

a) There are unresolved conceptual issues arising out of the existence of non-monetized transactions and reliance on traditional energies in the developing countries.

b) Most of the existing energy demand models are incapable of reflecting the specific features of energy systems of developing countries.

Econometric models have often attempted to analyze the demand at the aggregate level and attempted to identify the statistically significant relationships between demand and explanatory drivers drawn from economic theories. These studies have evolved over the past thirty years by passing through the trans-log wave and more recently through the co-integration revolution. While these methods have been applied to the developing countries, the issues of rural-urban divide, traditional energies, informal economies, technological diversities and inequity have not been adequately captured. Moreover, little attention has been paid to structural changes and the transition to modern energies. Although the end-use models are in principle better placed to capture the developing country features, in practice the situation is not always very encouraging. The informal activities are hardly covered by any model, while the spatial difference (i.e. the rural-urban difference) as well as divergence in consumption behavior by income groups is often inadequately captured.

In the developing country context, data limitations arise an additional limitation,. Both the econometric and end-use approaches require different sets of information and often such detailed data is not available or where available, the quality may not be of high standard. The data gap poses hurdles to build scenarios, evaluate technologies and analyze policy impacts (Worrel et al. 2004). The econometric approach, even at the aggregate level, suffers due to lack of enough time series data. Often pooled time series of state cross-sections, national time series and international cross-sections have been used normally but cross-sectional data within a country is generally undesirable because locational effects overstate elasticities, particularly price elasticities; international cross sections are likewise undesirable because structural differences bias elasticities. Although national time series could avoid the cross-sectional difficulties but it suffers from multi-collinearity and limited degrees of freedom (Hartman, 1979). Moreover, model results often suffer from little parameter robustness and over-estimation of long-run price elasticity. End-use models on the other hand require information on consumption behavior by income class, location and end-use types, technology-related information, information on economic and other drivers of demand, policy and scenario related data. While the nature of information is qualitatively different from that of an econometric approach, the information burden can be substantial.

Generally, the consumption behavior varies widely by income group and by location. This is more evident in larger countries but even in smaller countries this is visible. As the income distribution is generally skewed, the benefits of modern energies reach only a selected few and assuming an average level of consumption for the entire population does not fairly represent the demand behavior. Similarly, the supply is also skewed towards urban centers and accordingly, those who can afford to pay in rural areas may be deprived of modern energies due to inadequate supply facilities and resource availabilities. Thus using the idea of representative consumers or producers in the case of developing countries might produce biased results. More disaggregated analysis using detailed consumer characteristics is required but because such analyses are data intensive, often they are not attempted.

Inappropriate characterization of technologies and transition possibilities also affects the analysis. Although developing countries are characterized by their dependence on inefficient technologies, they can benefit from technological advances and leapfrog the technological ladder by adopting cleaner technologies. However, such technological transitions are not automatic and often require state intervention in the decision-making through appropriate institutional arrangements.

The inaccurate characterization of energy systems in energy demand models can lead to incorrect policy prescriptions having implications for long-term energy system development and for sustainability. Clearly the dynamics of economic growth and consequent energy implications are poorly understood in developing countries, which in turn results to inadequate infrastructure development or poorly adapted development. An example can be provided from the Indian power sector (see Bhattacharyya, 2008). Recently, concerned with the growing capacity shortage in the country studies and plans were undertaken to determine the long-term capacity needs. A comparison of such estimates from the government agencies with those from the World Energy Outlook 2007 (WEO 2007) (where India and China's needs were specifically considered) showed a great divergence in the estimates, essentially originating from the diverging assumptions and modeling approaches. While Indian studies used simple, aggregated forecasting techniques, IEA relied on a bottom-up demand forecasting approach. The demand forecasts by the government agencies are significantly higher than that of the WEO 2007 (IEA, 2007). Bhattacharyya (2008) concludes that "If the lower end of the capacity requirement as suggested by the IEA is really what is required to meet the demand, there would be an excess capacity of above 200 GW by 2030, for which the country would be paying a high cost, as the investment could have been better utilized in other areas." The shortage and excess capacity situations found in the developing countries can often be related to the inaccurate demand estimations that fail to consider the specific features of these economies.

Similar problems arise while considering the issue of energy access in developing countries. Clearly, the top-down approach of demand analysis is inappropriate in dealing with such cases due to the prevalence of informal economic activities, reliance on non-marketed fuels to a large extent, and use of inefficient technologies that do not represent the most efficient production frontier. There can be significant differences in the consumption behavior between urban and rural areas and within rural areas across various geographic zones as well by income class. Inadequate representation of such characteristics hinders any search for policy interventions for addressing the issue of access to clean energies. As widespread reliance on dirty energies has local as well as global consequences, inappropriate demand modeling can lead to biased prescriptions and generate an inaccurate picture of future implications.

Thus, lack of understanding of consumer behavior and supply conditions can led to costly misallocation of resources and choices. In addition, better characterization of rural-urban divide and consumers by income groups and spatial distribution is essential for a clearer picture of energy demand projections. Incorporating these features in energy demand models poses a challenge to energy demand modelers.

7. Concluding Remarks

This study presents a detailed review of the literature on energy demand forecasting models with the objective of identifying their relevance to developing countries. We found that mainly two types of methods, namely, econometric and accounting, are used in the literature to forecast energy demand. While econometric methods are employed mainly in aggregated (i.e., national level) energy demand forecasting, accounting methods are used at more disaggregated (i.e., sectoral and end-use) levels. A large number of models have been developed by academics, research institutions, government agencies and private companies for energy demand forecasting. These models use either econometric or accounting or both techniques.

Our study finds that although the econometric tradition has evolved quite significantly over the past four decades, and despite the fact the academic literature has followed the fashion closely, the quality of the forecasts did not see major improvements. The continued emphasis on price and income elasticities as the main demand drivers and the neglect of rich technical and spatial diversity of demand as well as non-price socio-economic policy influences remain the main concern with this approach. In contrast, the end-use methodology was not subjected to any major fashionable change of style since its inception in the 1970s, although the computing capability and data availability as well as greater emphasis on training and dissemination ensured a wider reach of this methodology. Yet, in terms of academic application or research outputs, a significant decline can be noticed. It is also noticed that due to the inherent limitations of the econometric and end-use approaches, there is now a greater recognition of hybrid approaches to demand forecasting. The interest in the hybrid approach is growing in recent times.

A detailed comparison of various models suggests that the purpose built models of national focus lack general transferability and are not suitable for wider applications. This is especially true for models following the econometric tradition and hybrid modeling approach. On the other hand, end-use accounting models tend to be more versatile in nature and require relatively less skills due to their accounting approach to forecasting.

There is no guarantee that complex models necessarily lead to better results. Moreover, the developing countries have certain specific characteristics which are not adequately captured by models originating from the developed countries. The problem is more pronounced with econometric models than with accounting models. The level of data requirement and the theoretical underpinning of these models as well as their inability to capture specific developing country features such as informal sectors and non-monetary transactions make these models less suitable. The end-use accounting models with focus on scenarios than rather empirical relationships based on long time series data make them more preferable to developing countries. However, these models too are very data intensive.

Developing countries are constrained to implement energy demand models due to several reasons, particularly, lack of data and institutional capacity. Besides, the typical characteristics of their energy systems, such as existence of informal sector, pre-dominant use of traditional energy with non-monetary transactions, shortages of energy supply technologies require careful consideration. Failure to represent these features, energy demand modeling is exposed to additional risks of producing inaccurate results and thereby recommending wrong policy prescriptions. This implies a need to improve energy demand modeling tools and institutional capacities for developing countries. However, the challenge is quite significant.

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Appendix 1: Review of Energy System Models

A1.1 Evolution

As an energy balance provides a simple representation of an energy system, the energy accounting approach is one of the frameworks used in energy system analysis. Hoffman and Wood (1976) describe the initial efforts in this area and suggest that this consistent and comprehensive approach has been used since 1950s in the US. The accounting framework of analysis is very popular even today and models such as LEAP or MEDEE/ MAED essentially employ this framework.

A natural extension of the energy balance framework was to use a network description of the energy system to represent energy flows. This development took place in the early 1970s and has found extensive use until now. The reference energy system (RES) captures all the activities involved in the production, conversion and utilisation of energy in detail by taking the technological characteristics of the system into account. This approach allows incorporation of existing as well as future technologies in the system and facilitates analysis of economic, resource and environmental impacts of alternative development paths. This approach was developed by Hoffman [Hoffman and Wood, 1976] and has set a new tradition in energy system modelling.

Although the pictorial presentation becomes complex with addition of more technologies and resources, the advantage of this approach derives from the ease of developing an optimisation or a simulation model based on the RES to analyse complex problems. The fundamental advantage of this approach was the ability to apply optimisation techniques to analyse alternative forms of system configuration using alternative technologies and energy sources, given a set of end-use demand. Thus from the early stage of RES development, the linear programming models were used. One of the well-known applications of the early days was the BESOM model [Brookhaven Energy System Optimisation Model] that was developed for efficient resource allocation in the US. The first version of the model was implemented at the national level for a snap-shot analysis of a future point in time. A number of other versions were developed subsequently, that extended the capabilities of the model, including a macro-economic linkage through an input-output table [Hoffman and Jorgenson, 1977]. Similarly, multi-period or dynamic models have emerged and in fact, one of today's best known energy system models, MARKAL, is indeed a derivative of the BESOM model.

Munasinghe and Meier (1993) indicate that many countries followed the BESOM example and developed their own model or adapted the BESOM model. Examples include TEESE model for India, ENERGETICOS for Mexico, etc. In addition to country specific models, more generic models for wider applications also came into existence. EFOM and MARKAL models come under this category. For developing countries, RESGEN was widely used [Munasinghe and Meier, 1993].

In the US, Hudson and Jorgenson (1974) pioneered the tradition of linking an econometric macroeconomic growth model with an inter-industry energy model. The input-output coefficients of the inter-industry model is endogenously determined, and the macro-model allowed a consistent estimates of demand and output.

While most of the above initiatives were at the national level, the pioneering works of large-scale global modelling started with the efforts of Jay Forrester for his World Dynamics and its application in Limits to Growth by Meadows et al (1972). As is well known now, the doomsday prediction of this report fuelled a fierce debate about resource dependence for economic growth and the issue of sustainability. Despite its limited representation of the energy sector and the limited following of the report, this initiated a new trend of global modelling. At a collective level, the efforts of the Workshop on Alternative Energy Sources (WAES, 1977), of US Energy Information Administration

(EIA, 1978) and of International Institute for Applied System Analysis (IIASA) [in Haefele et al (1981)] stand out.

One of the major developments during 1973-1985 was the investigation and debate about the interaction and interdependence between energy and the economy. In a simple aggregated conceptual framework, Hogan and Manne (1979) explained the relationship through elasticity of substitution between capital and energy, which consequently affects energy demand. Berndt and Wood (1979) is another classical work in this area which suggested that capital and energy may be complimentary in the short-run but substitutable in the long-run. In contrast, Hudson-Jorgenson (1974) used a disaggregated study using the general-equilibrium framework to analyse the effects of oil price increases on the economy.

The other major development of this period is the divergence of opinion between top-down and bottom-up modellers. While the traditional top-down approach followed an aggregated view and believes in the influence of price and markets, the bottom-up models stressed on the technical characteristics of the energy sector. Despite attempts of rapprochement the difference continues until now.

The high prices of oil in the 1970s emphasised the need for co-ordinated developments of the energy systems and led to a number of modelling efforts for strategic planning. IAEA developed WASP for the electricity sector planning in 1978. This model has been used extensively and modified over the past three decades to add various features. Electricity related models often tend to rely on optimisation as the basic approach. Hobbs (1995) identifies the following as the main elements of their structure:

a) an objective function where often cost minimisation is considered but financial and environmental goals can also be used;

b) a set of decision variables that the modeller aims to decide through the model;

c) a set of constraints that ensure the feasible range of the decision variables.

The concept of integrated planning received attention at this time and efforts for integrated modelling either by linking different modules or by developing a stand-alone model multiplied.

At the country level, we have already indicated the developments in the US. A set of alternative models was developed in France, including two widely used models, namely MEDEE and EFOM. India relied on an input-output model for its planning purposes and included energy within this framework. Parikh (1981) reports an integrated model for energy system analysis. This was a sort of hybrid model that had a macro-economic element connected with a detailed end-use oriented energy sector description. The focus shifted to energy-environment interactions in the mid-1980s. This is the time when deregulation of the energy sector also started. The energy models incorporated environmental concerns more elaborately and the practice of long-term modelling started at this stage. Later, TEEESE (Teri Energy Economy Environment Simulation Evaluation model) was used in India for evaluating energy environment interactions and in producing a plan for greening the Indian development (Pachauri and Srivastava, 1988).

In the 1990s, the focus shifted towards energy-environment interactions and climate change related issues. Most of the energy systems models attempted to capture environmental issues. For energy models this was a natural extension:

- the accounting models could include the environmental effects related to energy production, conversion and use by incorporating appropriate environmental co-efficients;
- the network-based models could similarly identify the environmental burdens using environmental pollution coefficients and analyse the economic impacts by considering costs of mitigation;
- energy models with macro linkage could analyse the allocation issues considering the overall economic implications.

Markandya (1990) identified four approaches that were used for the treatment of environmental issues in electricity planning models as follows:

a) Models that includes environmental costs as part of energy supply costs and to minimise the total costs;
b) Models that include environmental costs in the supply side but minimises costs subject to environmental constraints;
c) Models that aim for cost minimisation but also include an impact calculation module that is run iteratively to evaluate alternative scenarios;
d) Models not based on optimisation but analyses the impacts of alternative power development scenarios.

During this period, the effort for regional and global models increased significantly and a number of new models came into existence. These include AIM (Asian-Pacific Model), SGM (Second Generation Model), RAINS-Asia model, Global 2100, DICE, POLES, etc. At the same time, existing models were expanded and updated to include new features. MARKAL model saw a phenomenal growth in its application world wide. Similarly, LEAP model became the de-facto standard for use in national communications for the UNFCCC reporting. As the climate change issue required an understanding of very long terms (100 years or more), modellers started to look beyond the normal 20-30 years and started to consider 100 or 200 years. However, the uncertainty and risks of such extensions are also large and the validity of behavioural assumptions, technological specifications and resource allocations becomes complex. This has led to incorporation of probabilistic risk analysis into the analysis on one hand and new model development initiatives on the other (e.g. VLEEM initiative of the EU).

A1.2 Categorisation

Energy system models can be grouped using a number of alternative criteria. Hoffman and Wood (1976) have used the modelling techniques to categorise models and identified the following approaches:

- Linear Programming based method (used for its interesting and useful economic interpretations through dual problem and thus providing “a natural link between process and economic analysis”).
- Input –output approach (used for its ability to capture the sectoral interdependence but faces difficulties in terms of restrictive assumptions relating to fixed technology, zero price elasticity, long time delays in data availability).
- Econometric method (for its ability to represent and validate economic theories and laws).
- Process models
- System dynamics and
- Game theory.

Pandey (2002) has used a set of attributes to classify energy models. Table A1.1 captures his classification.

Table A1.1: Classification of energy-economy models

Paradigm	Space	Sector	Time	Examples
Top-down/ simulation	Global; national	Macro-economy, energy	Long-term	AIM, SGM2, I/O models
Bottom-up optimisation/ accounting	National, regional	Energy	Long-term	MARKAL, LEAP
Bottom-up optimisation/ accounting	National, regional, local	Energy	Medium term, short term	Sector models (power, coal,

Source: Pandey (2002)

Nakata (2004) has considered the modelling approach (top-down and bottom-up), methodology (partial equilibrium, general equilibrium or hybrid), modelling technology (optimisation, econometric, or accounting) and the spatial dimension (national, regional and global). This leads to another classification of models. He uses a Meta-Net approach for energy system modelling and demand analysis, further information on which is available in Kanagawa and Nakata (2006, 2007 and 2008), Ashina and Nakata (2008) and Wang and Nakata (2009).

For the purposes of comparison of models in this review, we shall consider the approach, sectoral coverage and spatial focus. This would enable us to compare similar models.

A1.3 Model comparison

A number of models, found in the literature, are systematically used to analyse the energy system. In this section, we present a comparative view of model capabilities with an objective of assessing their suitability for African developing countries. We start with a brief description of the models considered in this review (Section 6.1), which is followed by a systematic comparison using a set of common criteria. (Section 6.2)

A1.3.1 Model description

We consider the following models:

A1.3.1.1 Bottom-up, optimisation-based models

RESGEN (Regional Energy Scenario Generator)

RESGEN, a model developed by the Resource Management Associates, was a widely used model in the 1990s for energy planning in developing countries. This is a software package rather than model per se which allows the modellers to specify the energy system configuration of a country. It relies on the RES approach and uses linear programming as the solution technique. It allows three different types of demand structures: econometric specifications, industry/ project specific demands and process models. For the electricity sector, plant specific dispatching is permitted using a linearised load duration curve.

The model is flexible and has been used in many developing countries (Munasinghe and Meier, 1993, Munasinghe and Meier 1988). More recently, this was used in RAINS-ASIA model for generating energy scenarios for a large number of Asian countries.

EFOM [Energy Flow Optimisation model]

EFOM was initially developed in the 1970s by Finon (1974) at the then “Institut Economique et Juridique de l’Energie” at Grenoble, France [Sadeghi and Hosseini (2008)] and was then widely used in the European Union and other countries in Asia (Pilavachi et al, 2008). It is a multi-period system optimisation tool based on linear programming that minimises the total discounted costs to meet the exogenously specified demand of a country. The model can be used to analyse a specific sector (single sector mode of analysis) or for the overall energy system planning exercise (multi-sector mode). The electricity industry is extensively covered by the model. To increase the environmental capability of the model, the model was modified and a new version called EFOM-ENV came into existence. This is normally considered a sister model of the MARKAL family of models.

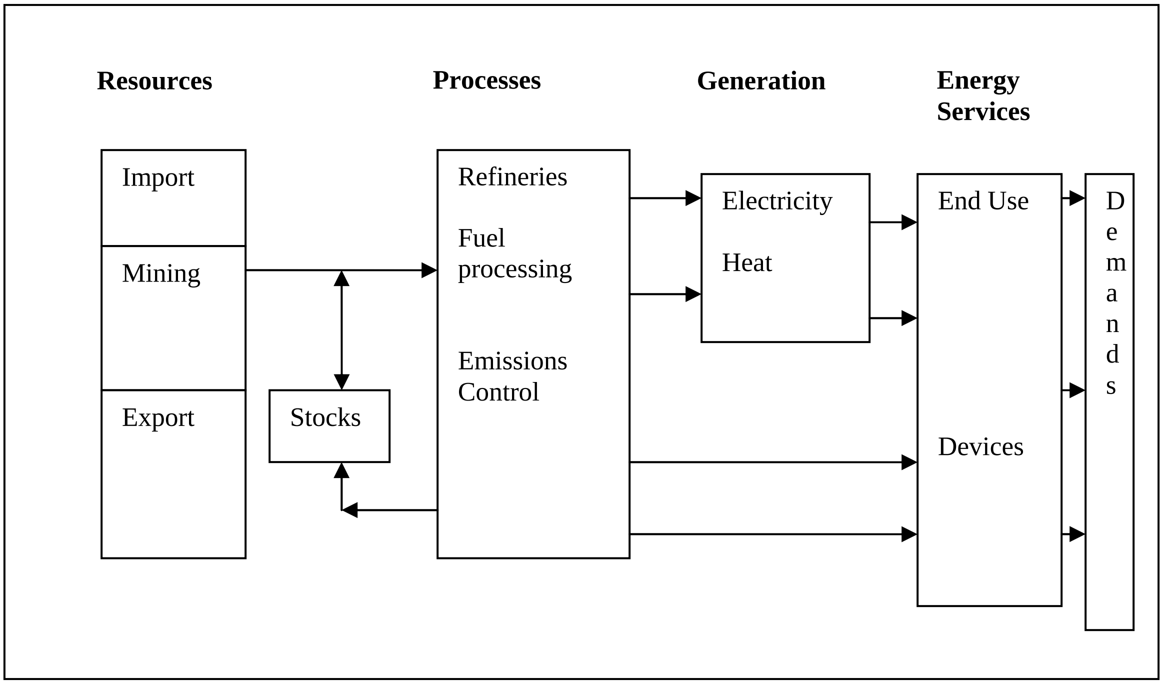
EFOM employs the network representation of the activities in the form of a RES. Being an end—use driven model, it is also technologically rich and covers both supply and end-use technologies. Its optimisation approach allows identification of marginal costs, and accordingly, the results have intuitive and economic appeal.

MARKAL model [Market allocation model]

The MARKAL model is the most widely used and best known in this family of optimisation models (Seebregts et al, 2001). The model uses the linear optimisation technique to generate the least cost supply system to meet a given demand given the energy system configuration (technical aspects including the efficiency), energy resource availability specified by the users. The model identifies the optimal feasible configuration that would ensure least-cost supply of energy to satisfy the demand.

The model covers the entire energy system – from energy resources to end-uses through energy conversion processes. Like other bottom-up models, the model provides a detailed technological representation of the energy system and can be used to analyse the environmental effects as well. The building blocks of the standard model are indicated in Fig. A1.1 below.

Fig. A1.1: MARKAL building blocks



Source: Seebregts et al (2001)

The original model has been extended in various ways and now a family of MARKAL models exists. Table A1.2 indicates some such MARKAL extension efforts. The model is the outcome of an international collaborative effort under the International Energy Agency’s Energy Technology Systems Analysis Programme. Although the model was designed initially for the mainframe computers, the PC version of the model is now available. A database of technological choices is now available with the model.

Table A1.2: MARKAL family

Model name	Modelling method	Description
MARKAL	Linear Programming (LP)	Standard version
MARKAL-MACRO	Non-linear programming (NLP)	Integrated macro and energy system model, with energy demand endogenously determined.
MARKAL-MICRO	NLP	Integrated micro and energy system model, with endogenous energy demand.
Multiple regions MARKAL	NLP	Multiple country-specific models linked together
MARKAL with uncertainties	Stochastic programming	Standard MARKAL with stochastic programming

Source: Seebregts et al (2001).

As table A1.2 indicates, the assumption of exogenous demand specification of the standard model has been overcome in some extensions to make demand price-responsive. This produces a more realistic solution than the standard model under the tax policies or emission constraints.

TIMES [The Integrated MARKAL-EFOM System]

The TIMES model is the new avatar of the MARKAL and EFOM models where the features of the two widely used models have been integrated to produce a powerful analytical tool using the optimisation technique (Loulou et al, 2005, Vaillancourt et al, 2008). The model produces the least-cost solution as MARKAL or EFOM but also considers the investment and operating decisions and can be applied for the entire system or a specific sector.

The demand-side of the model uses exogenous assumptions about demand drivers and the elasticities of demand with respect to these drivers and prices. Through these elasticities, the model can capture the effects of policy changes (price or tax or environmental constraints) on demand. This is an enhanced capability of the model compared to standard MARKAL model.

The supply-side consists of a set of supply curves representing the potential available resources. The model accepts multi-stepped supply curves, with each step representing the potential corresponding to a given cost. The model seeks to optimise the total surplus (consumers and producers surplus) and leads to partial equilibrium solutions.

The model is a multi-period model that can be applied to a large number of regions and can capture trading options. This is another additional feature of this model that was not available in the MARKAL model.

TIMES model can be divided into four generic elements: topology and time dimension, numerical data, mathematical structure and scenarios. The model relies on the RES-type description of the energy system but multi-regional and multi-period capabilities are included. Thus it can be run for a single year to over a long period. Similarly, it can be used for local, regional, national or international studies. The model is data-intensive and accordingly, databases are linked and used to manage the information system. The model uses linear optimisation but allows the user to specify non-standard constraints as well as technology specific discount rates and other flexibilities. The model also uses scenarios to explore uncertainties of future energy system development paths.

MESAP [Modular Energy System Analysis and Planning]

As the name indicates, this is a modular toolbox developed at IER[38] in University of Stuttgart and uses a number of sub-component models energy and environmental planning. The model has three parts: calculation modules, data and information modules and additional tools.

The calculation part includes the following: INCA – investment calculation, PlaNet – Energy system simulation, TIMES – energy system optimisation, PROFAKO – Operational planning for electricity and district heat, Xtractor – GAMS model interface and CalQlator – general equation editor.

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[38] Institute of Energy Economics and Rational Use of Energy

The MESAP data and information system caters to the data needs and data management issues. Finally, additional tools are available for special purposes – RES Editor, Case Manager, etc. to improve user friendliness of the model.

The model is a Windows based software package that starts with a RES based representation of the energy system.

A1.3.1.2 Bottom-up, accounting models

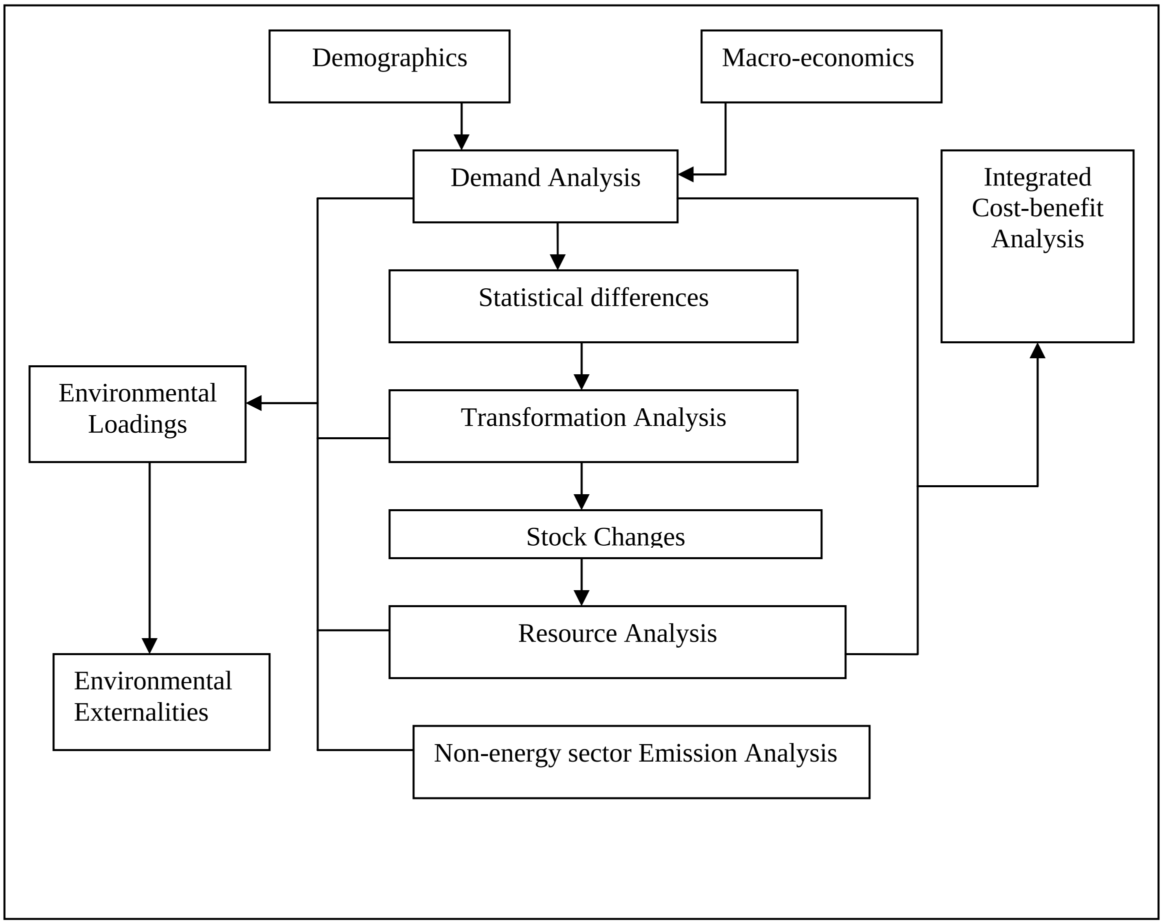
LEAP [Long-range Energy Alternatives Planning model]

The Long-range Energy Alternatives Planning (LEAP) is a flexible modelling environment that allows building specific applications suited to particular problems at various geographical levels (cities, state, country, region or global). As an integrated energy planning model LEAP covers both the demand and supply sides of the energy system. However, we briefly outline the demand forecasting features of the LEAP model here.

The model follows the accounting framework approach to generate a consistent view of energy demand (and supply) based on the physical description of the energy system. It also relies on the scenario approach to develop a consistent storyline of the possible paths of energy system evolution. Thus for the demand forecasting, the model does not optimise or simulate the market shares but analyses the implications of possible alternative market shares on the demand.

The supply-side of the model does not try to find the least cost solution or system configuration as in the optimisation model but uses accounting and simulation approaches to provide answers to “what-if” type of analysis under alternative possible development scenarios. This spreadsheet like tool is flexible enough to consider various data requirements and supports some econometric and simulation features in addition to basic energy accounting framework. The framework is presented in Fig. A1.2.

Fig. A1.2: LEAP framework



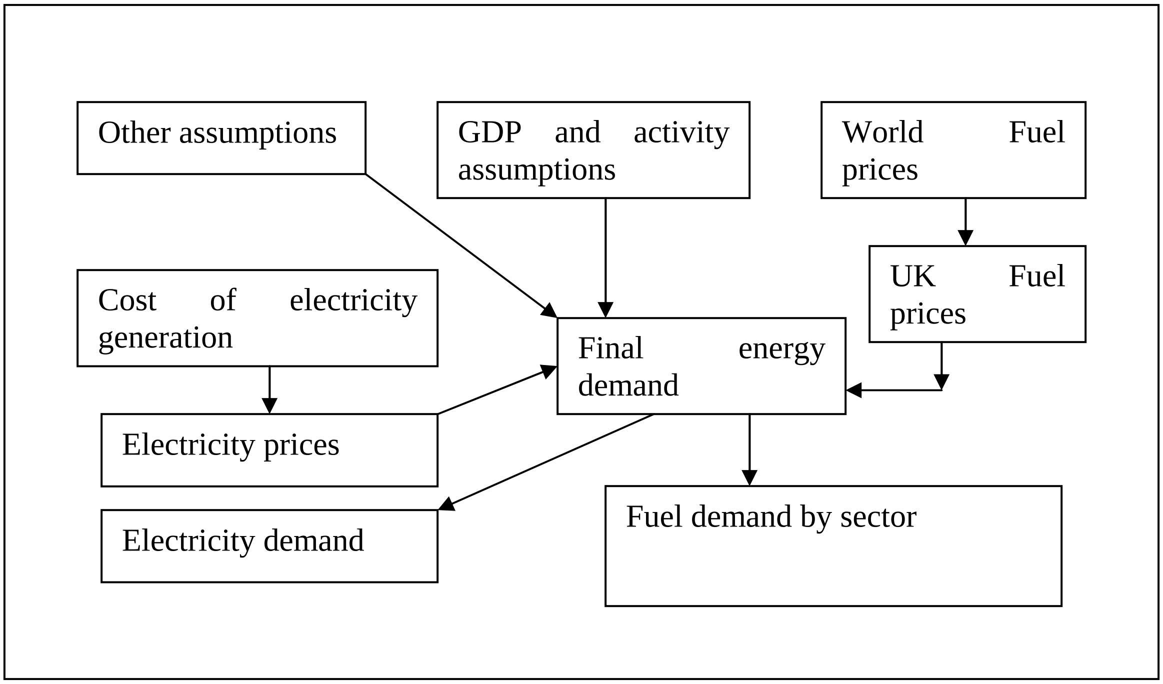
Source: Heaps (2002)

A1.3.1.3 Top-down, econometric models

DTI energy model

For its energy forecasts and future carbon emission estimations, the Department of Business, Enterprise and Reform of the United Kingdom relies on an econometric model. The model covers both supply and demand sides but the demand is fairly elaborate. The demand model contains 150 econometric relationships to determine the demand in various sectors of the economy. The model follows the Error Correction Modelling approach and uses price and economic activity as main variables although time trends are used in some sectors. The model has 13 final users who are then grouped into four major sectors, namely industry, transport, services and domestic. Each final user sector is further disaggregated by fuels. The model structure of the model is shown in Fig. A1.3.

Fig. A1.3: DTI energy model overview



Source: DTI[39]

The supply side of the model considers the electricity supply system in detail. It captures the diversity of the capacity mix, technological differences and characteristics, and determines the cost of generation and operation of the system to meet the demand. The supply and conversion of other fossil fuels are taken into consideration as well.

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[39] See (http://www.berr.gov.uk/files/file26611.ppt).

A1.3.1.4 Hybrid models

NEMS [National Energy Modelling System]

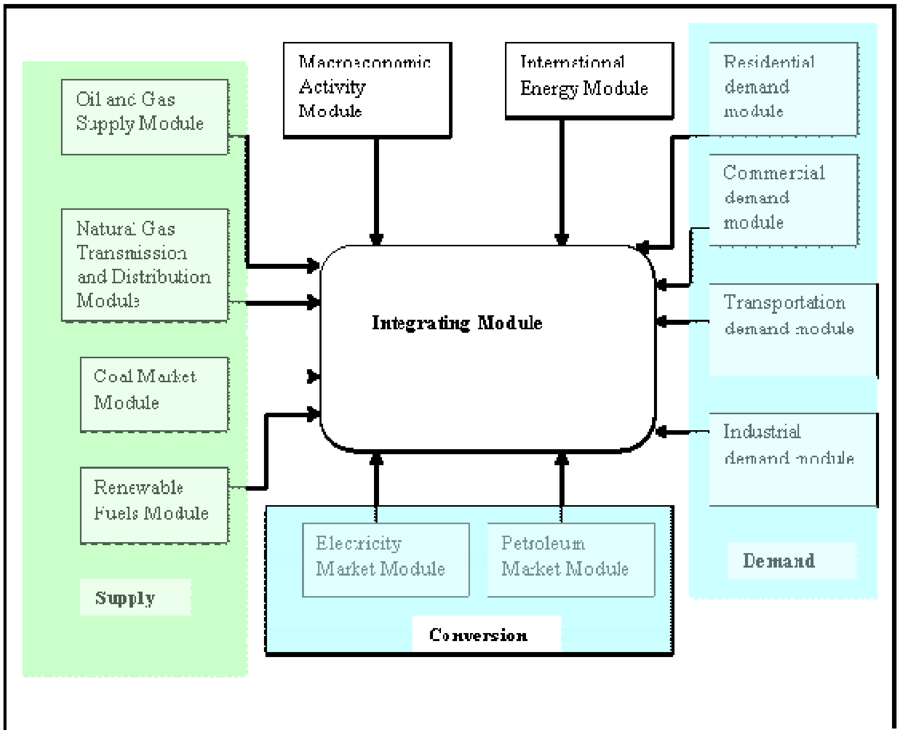
NEMS was designed and primarily used by the US Department of Energy for preparing the Annual Energy Outlook. It is a model of energy-economy interaction that is used to analyse the functioning of the energy market under alternative growth and policy scenarios. The model uses a time horizon of about 25 years (up to 2030 for the present version).

The model employs a technologically rich representation of the energy sector and covers the spatial differences in energy use in the US. The demand-side is disaggregated into four sectors, namely industry, transport, residential and commercial but both industry and transport are further disaggregated to capture the specific features of energy intensive users and alternative modes of transport. This is a hybrid model because it uses the details found in engineering-economic models but retains the behavioural analysis found in top-down models.

The supply-side of the model contains four modules – one each for oil and gas supply, gas transportation and distribution, coal supply and renewable fuels. The oil and gas supply module captures the onshore, offshore and non-conventional oil and gas supply and generates oil and gas production functions. The gas transportation module tracks the supply of natural gas across regions and allows an analysis of the pipeline and storage capacity constraints and capacity needs as well as pricing of natural gas. The coal supply module considers the mining of coal, its transportation and pricing in various regions of the country and generates the coal production functions.

There are two conversion modules, namely for electricity and petroleum product markets. These modules consider the technological characteristics of electricity supply and refining. The basic structure of the NEMS model is shown in Fig. A1.4.

Fig. A1.4: NEMS model structure



Source: EIA (2000)

POLES [Prospective Outlook on Long-term Energy Systems]

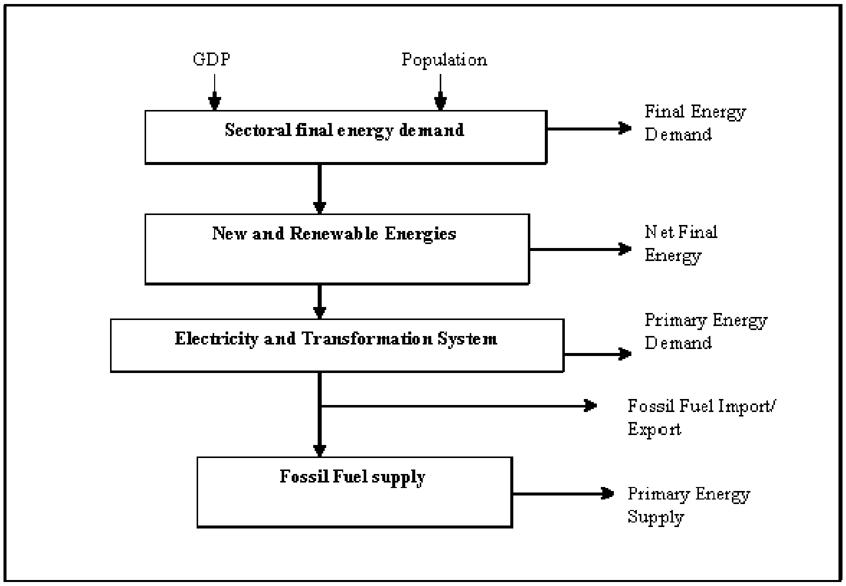
POLES is a recursive, disaggregated global model of energy analysis and simulation. It covers both the demand and the supply sides of the energy systems and has been used for long-term energy policy analysis by the European Union and the French government. The model has four main modules: final energy demand, new and renewable energy technologies, conventional energy transformation system and fossil fuel supply. Accordingly, the model captures the entire energy system.

The demand is analysed using a disaggregated end-use approach in which demand is broken down into homogeneous groups to allow for separate treatment of energy intensive and non-intensive uses. The global demand is generated from country and regional demands where all large consumers are separately considered.

The model considers twelve renewable and new technologies and simulates the role they are likely to play using the concepts of learning curves and niche markets. The conversion fossil fuel is analysed at an aggregated level using losses and conversion efficiencies. The electricity system is captured in more detail and uses the screening curve approach to identify the role of different electricity technologies. The supply of oil and gas is analysed using a detailed production model of main producers using the resource, cumulative production and depletion information.

While the regional and country level analyses generate the respective energy balances, they are horizontally linked through an energy market module which is used to clear the market. For oil, a single global market is considered while for coal three regional markets have been used. For gas, bilateral trade flows are considered. This price-driven formulation of the model makes it different from others of its kind (i.e. accounting, end-use models). Figure A1.5 presents the general structure of the POLES model.

Fig. A1.5: POLES model structure



Source: Criqui (2001).

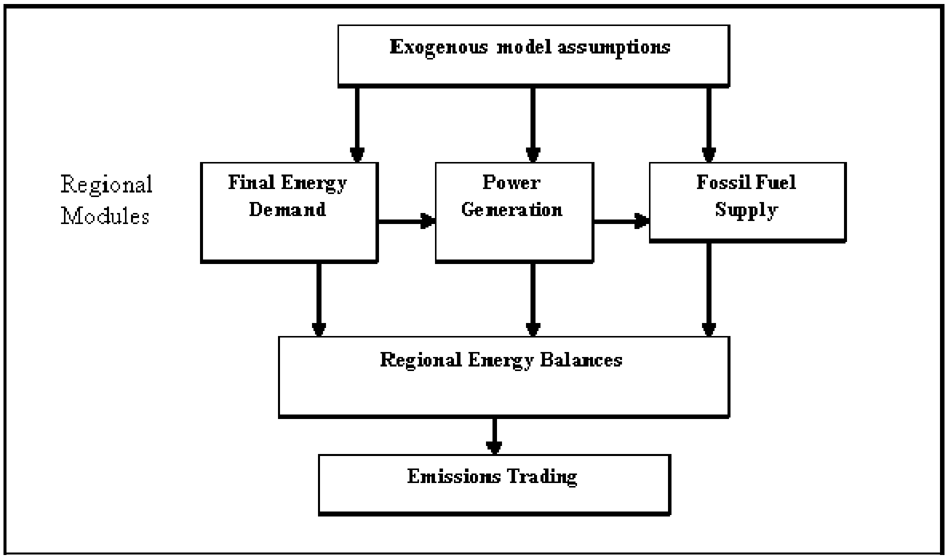
WEM (World Energy Model)

The World Energy Model used in the World Energy Outlook (WEO) publication of the IEA is a global energy market model. The model has evolved over time as the issues explored in the WEO change. The basic model has four main components: a final demand module, power generation module, fossil fuel supply and emissions trading. Figure A1.6 indicates the general model structure.

The final energy demand module follows the disaggregated end-use approach of forecasting by considering industry, transport, residential, commercial and agricultural activities. Both industry and transport are further disaggregated to take care of the specific features of demand. While the standard model considers a disaggregated level of analysis, due to data problems in developing countries, sometime a more aggregated representation is used. The economic activity, energy prices and other variables are considered as the main drivers of energy demand.

The power generation module considers the electricity demand and determines the new capacity addition need by taking into account a load curve, existing capacities, retirement schedule and reserve margin. A number of alternative technologies are considered for power generation and the levelised cost of generation is estimated. From the generation mix the fuel requirement is determined using the efficiency of plants.

Fig. A1.6: WEM models structure



Source: IEA (2007)

The fossil fuel supply module considers oil and gas separately and differently. Oil supply is determined by taking OPEC, non-OPEC and non-conventional oil production. OPEC supply is determined as the balancing figure while non-OPEC and non-conventional production is determined as a function of international oil price. For gas supply, net importers and exporters are considered separately and the regional nature of the gas market is taken into account. Coal supply is not explicitly modelled but is included in the supply system.

The last module analyses the CO2 emissions for each region and determines the marginal abatement cost curves. The trading possibility is then considered to determine a market clearing price for permits.

Despite retaining its general structure, the model has undergone significant changes over time. In recent times, the access issue has been considered and the residential sector has been modified considerably. Similarly, the industry and transport sectors details have been improved and in its latest version, the model was linked to a macro model to ensure macro-economic consistency of model assumptions.

SAGE [System for the Analysis of Global Energy Markets]

This is the new tool developed and used by the US Department of Energy for analysing global energy situations. The analysis is reported in the International Energy Outlook. This is an integrated regional energy model that captures the technological richness of the energy sector to determine the energy consumption. In its standard version, it considers 42 end-use demands and the regional demand forecasts are made based on the demand trends, economic and demographic drivers, energy equipment stock and technological changes. The demand model considers 15 regions or countries of the world with special emphasis on large consumers.

The supply-side of the model considers the world oil market, gas market and other energy resources. Given the regional demand, the model determines the least-cost supply options to meet the demand taking end-use equipment and supply options into consideration. The analysis is done on a period-by-period basis (each period of 5 years) for 25/30 years.

A1.3.1.5 Electricity system models

WASP [Wien Automatic System Planning]

The WASP model developed by the International Atomic Energy Agency (IAEA) is a widely used tool that has become the standard approach to electricity investment planning around the world (Hertzmark, 2007). The current version, WASP-IV, finds the optimal expansion plan for a power generating system subject to constraints specified by the user. The programme minimises the discounted costs of electricity generation, which fundamentally comprise capital investment, fuel cost, operation and maintenance cost, and cost of energy-not-served (ENS)[40] (International Atomic Energy Agency (IAEA), 1998a). The demand for electricity is exogenously given and using a detailed information

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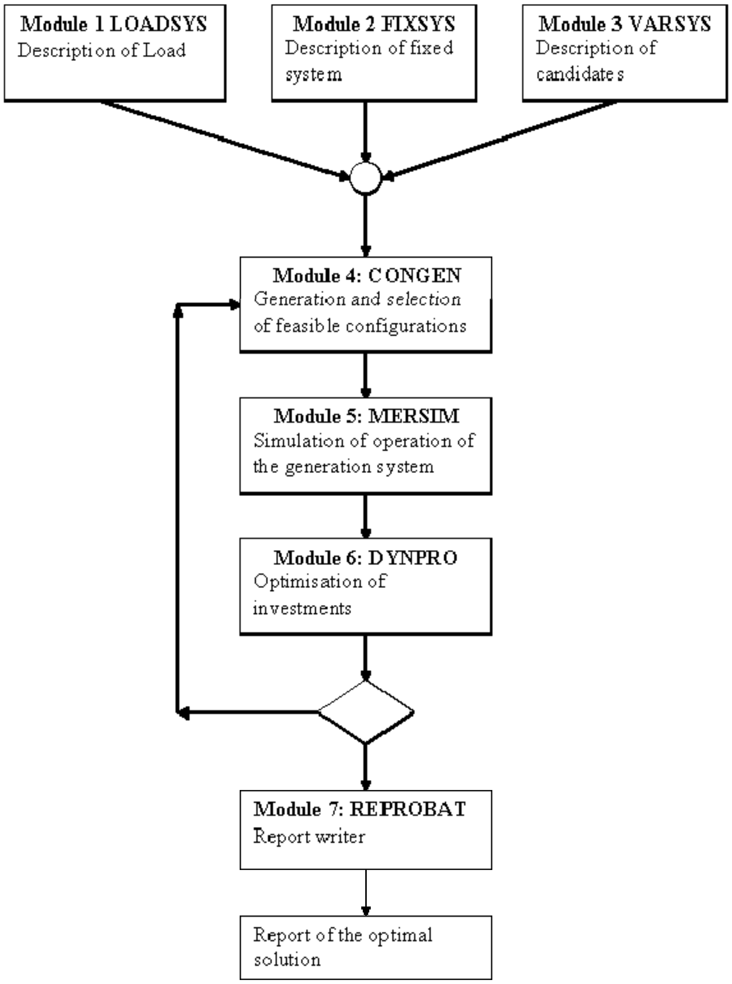
[40] Energy-not-served (ENS) or expected un-served energy is “the expected amount of energy not supplied per year owing to deficiencies in generating capacities and/or shortage in energy supplies” (International Atomic Energy Agency (IAEA), 1984).

of available resources, technological options (candidate plants and committed plants) and the constraints on the environment, operation and other practical considerations (such as implementation issues), the model provides the capacity to be added in the future and the cost of achieving such a capacity addition.

Fig. A1.7: Overall structure of WASP -IV



To find optimal plan for electricity capacity expansion, WASP-IV programme evaluates all possible sets of power plants to be added during the planning horizon while fulfilling all constraints. Basically, the evaluation for optimal plan is based on the minimisation of cost function (IAEA, 1994), which comprises of: depreciable capital investment costs (covering equipment, site installation costs, salvage value of investment costs), non-depreciable capital investment costs (covering fuel inventory, initial stock of spare parts etc), fuel costs, non-fuel operation and maintenance costs and cost of the energy-not-served. Overall, the structure of WASP-IV programme can be presented in Fig. A1.7.

The model works well for an integrated, traditional system but the reform process in the electricity industry has brought a disintegrated system in many countries. The model is less suitable for such reformed markets.

EGEAS [Electricity Generation Expansion Analysis System]

EGEAS was developed under the sponsorship of Electric Power Research Institute (EPRI) to facilitate integrated resource planning of electricity systems. This was developed in the 1980s for generation planning but has been adapted to take care of new issues such as demand-side management and economic dispatch under deregulated environment. EGEAS considers the system operation, plant retirement needs, demand-side management options and decides whether new capacity is required or not. Capacity can be made available through new building or by purchasing capacity if extra capacity is available.

The model uses dynamic programming to decide the generation plants from the candidates to meet the demand. It has a screening curve based preliminary selection tool and a sophisticated plant selection tool. It can also perform probabilistic production cost and reliability analysis. The model however does not cover the transmission and distribution system. The programme has been widely used in the US and the results are well accepted by the regulators.

A1.4 Model comparison

As a large number of energy system models have been presented before, it is now appropriate to compare them to see whether they are suitable for developing country applications. Shukla (1995) raised the need for incorporating specific features of developing countries in energy-environment modelling and highlighted the need for considering the informal sector and traditional energy use in the analysis. Bhattacharyya (1995) and Bhattacharyya (1996) further highlighted these issues and suggested the biases introduced as a result of exclusion of these features. Pandey (2002) suggests specific features of developing countries as follows:

> "existence of large scale inequity and poverty, dominance of traditional life styles and markets in rural areas, transitions of populations from traditional to modern markets, existence of multiple social and economic barriers to capital flow and technology diffusion, and radical nature of policy changes being witnessed in energy industries".

Urban et al (2007) indicated three specific features of developing countries requiring special attention: poor performance of the power sector and traditional fuels, transition from traditional to modern economies, and structural deficiency in society, economy, and energy systems. They have compared the model capabilities considering the following characteristics of developing countries: performance of the power sector, supply shortage, electrification, traditional bio-fuels, urban-rural divide, informal economy, structural economic change, investment decisions, and subsidies.

As the purpose of this comparison is to verify usefulness of models for developing countries, we shall follow a two-step procedure.

a) First, we consider the alternative modelling approaches in general and consider how they perform based on the following features:

> modelling approaches, incorporation of supply and demand modules, input data requirement; flexibility to incorporate new end-use, fuel and technology including those used in developing countries, rural energy specificities, informal sectors; data and skill concerns, and the possibility of capturing transition.

b) Subsequently, we focus on specific bottom-up and hybrid models and compare them based on the following: modelling approach, geographical, technical and activity coverage, data and skill needs, portability, disaggregation, price and non-price policy capabilities, rural energy capabilities, energy shortage, informal sector, subsidies, rural-urban divide, and economic transition.

Table A1.2: Comparison of models by modelling approaches

Criteria	Bottom-up, Optimisation	Bottom-Up accounting	Top-Down, econometric	Hybrid	Electricity planning
Geographical coverage	Local to global, but mostly national	National but can be regional	National	National or global	National
Activity coverage	Energy system, environment, trading	Energy System and environment	Energy System, environment	Energy System, environment and energy trading	Electricity system and environment
Level of disaggregation	High	High	varied	High	Not applicable
Technology coverage	Extensive	Extensive but usually pre-defined	Variable but normally limited	Extensive but usually pre-defined	Extensive
Data need	Extensive	Extensive but can work with limited data	High	High to Extensive	Extensive
Skill requirement	Very high	High	Very high	Very high	Very high
Capability to analyse price-induced policies	High	Does not exist	High	Normally available	Available
Capability to analyse non-price policies	Good	Very good	Very good	Very good	Good
Rural energy	Possible but normally limited	Possible	Possible but normally limited	Possible but normally limited	Difficult
New technology addition	Possible	Possible	Difficult	Possible but often limited	Possible
Informal sector	Difficult	Possible	Difficult	Possible	Difficult
Time horizon	Medium to long-term	Medium to long-term	Short, medium or long term	Medium to long-term	Medium to long term
Computing requirement	High end, requires commercial LP solvers	Not demanding	Econometric software required	Could required commercial software	Requires commercial or licensed software

Table A1.2 presents a comparison of features of different types of energy system models considered above. The bottom-up accounting type of framework appears to be more appropriate for developing country contexts because of their flexibility and limited skill requirement. These models can capture rural-urban differences, traditional and modern energies and can account for non-monetary transactions. Their suitability for a developing country context is enhanced by the fact that these models do not look for an optimal solution and can take non-price policies prevailing in developing countries. However, their inability to analyse price-induced effects is the main weakness but given the regulated nature of prices in many developed countries and incompleteness of markets, this weakness is not a major concern for modelling.

The hybrid models come next and the optimisation and econometric models appear to be less suitable for the developing country contexts.

Tables A1.3 and A1.4 compare specific bottom-up and hybrid models using the criteria indicated for the second stage of the analysis. Table 10 indicates that while the optimisation models contain a good description of technological features, they have difficulties in capturing non-monetary policies and informal sector activities. These models can incorporate rural-urban divide but often to avoid complexities, this aspect is not included explicitly. The problems of subsidies and shortages are also not adequately captured as the demand is not explicitly covered in these models. The accounting type models like LEAP being scenario-based are usually better placed to take rural-urban divide, economic transition, informal sector and energy shortage features into account.

Table A1.3, which essentially covers global models, shows that most of the models are not suitable for developing country contexts as they do not explicitly cover the essential features of developing countries. These models are developed from the developed country perspectives and apply those features common to developed countries to the entire model. This makes such models inappropriate for developing countries.

From the comparative overview, it appears that most of the standard models are perhaps not suitable for developing country applications. However, many routine applications of such models are found in the developing countries, which raise concerns about the policy implications of such analyses. The last section briefly touches on the policy concerns related to application of energy systems models in developing country contexts.

Table A1.3: Comparison of bottom-up models

Criteria	RESGEN	EFOM	MARKAL	TIMES	MESAP	LEAP
Approach	Optimisation	Linear Optimisation	Linear Optimisation	Optimisation	Optimisation	Accounting
Geographical coverage	Country	regional and national	Country or multi-country	Local, regional, national or multi-country	National	Local to national to global
Activity coverage	Energy system	Energy System	Energy System	Energy System and energy trading	Energy System	Energy system and environment
Level of disaggregation	Pre-defined	User defined	User defined	User defined	Pre-defined sector structure	Sector structure pre-defined
Technology coverage	Good	Extensive	Extensive	Extensive	Extensive	Menu of options
Data need	Variable, Limited to extensive	Extensive	Extensive	Extensive	Extensive	Extensive but can work with limited data
Skill requirement	Limited	High	High to very high	Very high	High to very high	Limited
Portability to another country	Difficult	Difficult	Difficult	Difficult	Difficult	Difficult
Documentation	Limited	Good	Extensive	Good	Good	Extensive
Capability to analyse price-induced policies	Exists	Exists	Exists	Exists	Exists	Does not exist
Capability to analyse non-price policies	Good	Very good	Very good	Very good	Good	Very Good
Rural energy	Possible	Possible	Possible	Possible	Not known	Possible
Informal sector	Not possible	Not possible	Not possible	Not possible	Not possible	Possible
New technology addition	Difficult	Possible	Possible	Possible	Possible	Possible
Energy shortage	Not explicitly	Not explicitly	Not explicitly	Not explicitly	Not known	Possible explicitly
Subsidies	Difficult	Possible but often ignored	Possible but normally ignored	Possible but normally ignored	Not known	Not considered explicitly
Rural –urban divide	Possible but not covered usually	Possible but not covered usually	Possible and covered	Possible and covered	Not known	Possible and covered usually
Economic transition	Not covered	Not covered	Not covered	Can be covered	Not known	Usually covered through scenarios

Table A1.4: Comparison of hybrid models

Criteria	NEMS	POLES	WEM	SAGE
Approach	Optimisation	Accounting	Accounting	Optimisation
Geographical coverage	Country	Global but regional and country specific studies possible	Global but regional or country specific studies possible	Global but regional or country specific study possible
Activity coverage	Energy system	Energy System	Energy System	Energy System and energy trading
Level of disaggregation	Pre-defined	Pre-defined	Pre-defined	Pre-defined
Technology coverage	Extensive but pre-defined	Extensive but pre-defined	Extensive but pre-defined	Extensive and pre-defined
Data need	Extensive	Extensive	Extensive	Extensive
Skill requirement	Very high	High to very high	High to very high	Very high
Portability to another country	Difficult	Difficult	Difficult	Difficult
Documentation	Extensive	Limited	Good	Extensive
Capability to analyse price-induced policies	Good	Good		Good
Capability to analyse non-price policies	Good	Very good	Very good	Good
Rural energy	Possible and covered in a limited way	Possible but not included	Possible and included in a limited way in recent version	Possible but not included
Informal sector	Difficult and not included	Possible but not included	Possible but not included	Not included
New technology addition	Possible but difficult	Possible but difficult	Possible but difficult	Possible but difficult
Subsidies	Yes	Yes	Yes	Yes
Rural-urban divide	Possible and considered	Possible but not considered	Possible and included in the recent version	Possible but not considered
Economic transition	Not applicable	Considered implicitly	Considered implicitly	Considered implicitly