Received 12 February 2010
Revised 28 July 2010
Accepted 3 August 2010

A review of energy system models

Subhes C. Bhattacharyya
CEPMLP, Dundee University, Dundee, UK, and
Govinda R. Timilsina
Development Research Group, The World Bank, Washington, DC, USA

Abstract

Purpose – The purpose of this paper is to provide a comparative overview of existing energy system models to see whether they are suitable for analysing energy, environment and climate change policies of developing countries.

Design/methodology/approach – The paper reviews the available literature and follows a systematic comparative approach to achieve its purpose.

Findings – The paper finds that the existing energy system models inadequately capture the developing country features and the problem is more pronounced with econometric and optimisation models than with accounting models.

Originality/value – Inaccurate representation of energy systems in the models can lead to inaccurate decisions and poor policy prescriptions. Thus, the paper helps policy makers and users to be aware of the possible pitfalls of various energy system models.

Keywords Energy supply systems, Energy industry, Developing countries

Paper type Literature review

Abbreviations

AIM	Asian-Pacific Model
BERR	Department for Business, Enterprise and Regulatory Reform
BESOM	Brookhaven Energy System Optimisation Model
CIMS	Canadian Integrated Modelling System
DTI	Department of Trade and Industry (now called Department for Business, Enterprise and Regulatory Reform, BERR)
EFOM	Energy Flow Optimisation Model
EGEAS	Electricity Generation Expansion Analysis System
EMF	Energy Modelling Forum
EU	European Union
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IIASA	International Institute for Applied System Analysis
IPCC	Intergovernmental Panel on Climate Change
LEAP	Long-range Energy Alternative Planning
MAED	Model for Analysis of Energy Demand
MARKAL	Market Allocation Model
MEDEE	Modele d'Evolution de la Demande d'energie
NEMS	National Energy Modelling System

The authors thank the reviewers for their comments on this paper. The views expressed in this paper are those of the authors only and do not necessarily represent the World Bank and its affiliated organizations. The Knowledge for Change Program (KCP) Trust Fund of the World Bank provided financial support to this paper.

International Journal of Energy Sector Management
Vol. 4 No. 4, 2010
pp. 494-518

1750-6220
DOI 10.1108/17506221011092742

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
WASP	Wien Automatic System Planning

1. Introduction

Since the early 1970s, a wide variety of models became available for analysing energy systems or sub-systems (such as the power system) which were concerned with a number of purposes, namely better energy supply system design given a level of demand forecast, better understanding of the present and future demand-supply interactions, energy and environment interactions, energy-economy interactions and energy system planning. As "energy system models are formulated using theoretical and analytical methods from several disciplines including engineering, economics, operations research and management science", these models apply different techniques, including "mathematical programming (especially linear programming), econometrics and related methods of statistical analysis and network analysis" Hoffman and Wood (1976).

Consequently, energy system models vary in terms of data requirements, technology specification, skill requirements and computing demand. Some models are technologically explicit and require a huge database, most of which is not readily available in developing countries. The skill requirement and computing requirement for some models can be too onerous for developing countries where the pool of skilled human resource may be in short supply. Most of these models were developed in the industrialised countries to analyse a specific issue or a problem in a specific context. Some of these models have been applied to the developing country contexts but such a transfer of modelling technologies is fraught with difficulties. A relatively few set of models are found in the literature that are developed in the developing countries but often such models did not cross national boundaries to generate a wider developing country portfolio of modelling tools.

Given the diversity of the models in terms of their purpose, philosophy, features, capabilities, possible overlaps and data demand, it is important to develop a comparative picture of the models keeping the specific features of the developing countries in mind. Although reviews have appeared in the past, including, *inter alia*, Hoffman and Wood (1976), Wirl and Szirucsek (1990), Markandya (1990), Pandey (2002), Nakata (2004) and Urban *et al.* (2007), a systematic comparative study is rarely found in the literature. For example, the first two studies have provided a review of the evolution and developments in energy modelling. Markandya (1990) focused on electricity system planning models to assess whether and how they captured environmental concerns, and whether they are appropriate for developing countries. Nakata (2004) focused on energy-environment models. Although Pandey (2002) and Urban *et al.* (2007) have attempted some comparative analysis, their preoccupation was somewhat different from ours. Pandey (2002) considered the special features of developing countries and emphasised on the need to incorporate such features in energy models while Urban *et al.* (2007) analysed how a set of models performed in dealing with developing country features. While all these studies are useful, there is a clear gap in the knowledge here. This paper aims to bridge this knowledge gap by presenting a systematic comparative overview of well-known energy models.

Accordingly, the objective of the paper is to provide a systematic review of a set of energy models to analyse whether they have sufficient characteristics to capture the features of the energy sector of developing countries.

The scope of an energy system model can vary, based on its purpose and focus: engineering models covering the processes of a specific component or sub-components come at one extreme, while comprehensive models covering energy-economy interactions at the national and international levels come at the other extreme. In this review, we exclude both these types that either go beyond the energy sector and include energy-economy interactions or analyse one specific component or sub-component exclusively. Our focus is on integrated models that cover the energy sector and sub-sector levels and those consider both supply- and demand-sides.

However, given the diversity of the technologies used and the complexity of the energy sector, some models specifically focus on a specific aspect of a sub-sector, such as electricity or coal or gas. These may or may not cover both the supply- and demand-sides of the sub-sector. Similarly, many models, while covering multiple fuels, focus only on the supply-side while others focus on the demand-side alone. Strictly speaking, such models do not qualify for inclusion in the energy system models. However, given their importance in the literature, we have included both sector-level and integrated models in this review.

Similarly, following Hoffman and Wood (1976), we have made no distinction between normative and positive models[1] as most models tend to combine both types of features. We cover both purpose-built and generic models and models covering a specific geographical area and multiple regions/areas.

The paper is organised as follows: Section 2 presents alternative categorisation of energy system models, Section 3 introduces the developing country features and the methodology used in the paper. Section 4 compares a number of commonly used models and Section 5 identifies the policy implications of model choices for developing countries. Finally, a concluding section presents an agenda for developing energy system models for developing countries.

2. Evolution of energy system models

2.1. 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) suggest that this consistent and comprehensive approach has been used since 1950s in the USA. This framework is very popular even today and models such as Long-range Energy Alternative Planning (LEAP) or Modele d'Evolution de la Demande d'energie (MEDEE)/Model for Analysis of Energy Demand employ this framework.

A natural extension of the energy balance framework was to use a network description of the energy system – known as the reference energy system (RES) – that captures all the activities involved in the entire supply chain 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, developed by Hoffman (Hoffman and Wood, 1976), has set a new tradition in energy system modelling.

Although the pictorial presentation becomes complex with addition of more technologies and resources, 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 formed an integral part of such models. The Brookhaven Energy System Optimisation (BESOM) model, developed for efficient resource allocation in the USA, 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 the TERI Energy Economy Environment Simulation Evaluation model for India and ENERGETICOS for Mexico. More generic models for wider applications, such as Energy Flow Optimisation Model (EFOM) and Market Allocation Model (MARKAL) models, came into existence. For developing countries, Regional energy scenario generator (RESGEN) was widely used (Munasinghe and Meier, 1993).

In the USA, 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 it 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 support for the report, this initiated a new trend of global modelling. At a collective level, the efforts of the Workshop on Alternative Energy Sources (1977), of US Energy Information Administration (EIA, 1978) and of International Institute for Applied System Analysis (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 and 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 Wien Automatic System Planning (WASP) for the electricity sector planning in 1978. This model has been extensively used 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:

- an objective function where often cost minimisation is considered but financial and environmental goals can also be used;
- a set of decision variables that the modeller aims to decide through the model; and
- 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 USA. 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 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 system 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; and
- 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:

(1) models that includes environmental costs as part of energy supply costs and to minimise the total costs;

(2) models that include environmental costs in the supply-side but minimises costs subject to environmental constraints;

(3) models that aim for cost minimisation but also include an impact calculation module that is run iteratively to evaluate alternative scenarios; and

(4) 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 Asian-Pacific Model (AIM), second-generation model (SGM), Regional Air Pollution Information and Simulation (RAINS)-Asia model, Global 2100, Dynamic Integrated Model of Climate and the Economy, 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 worldwide. Similarly, LEAP model became the *de facto* standard for use in national communications for the United Nations Framework Convention on Climate Change 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. Very Long-term Energy Environment Model initiative of the EU).

2.2. 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, input-output approach, econometric method, process models, system dynamics and game theory. Pandey (2002) on the other hand has used a set of attributes to classify energy models (Table I).

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, 2008), Ashina and Nakata (2008) and Wang and Nakata (2009).

For our purpose, we shall consider the modelling approach (or paradigm), sectoral coverage, time horizon and spatial focus. This would enable us to compare similar models.

3. Model comparison methodology

As the purpose of this review is to see whether they are suitable for developing country applications, first we present a set of features generally found in the energy systems of developing countries. We then identify how we use such features for model comparison.

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)

Table I. Classification of energy-economy models

3.1. Specific features of energy sectors of developing countries

Although there is a wide variation amongst developing countries in terms of socio-economic structure, a few features are found in common in the energy sector of many developing countries[2]. These characteristics include: reliance on traditional energies, the existence of large informal sectors which are sometimes as large as the formal sector, urban-rural divide and prevalence of inequity and poverty, structural changes of the economy and accompanying transition from traditional to modern lifestyles, inefficient energy sector characterised by supply shortages and poor performance of energy utilities, and existence of multiple social and economic barriers to capital flow and slow technology diffusion make developing countries' energy systems significantly different from that of developed countries (Urban *et al.*, 2007; Pandey, 2002; Bhattacharyya, 1995, 1996; Shukla, 1995).

Birol (2007) suggested that about 40 per cent of the global population relies on traditional energies for their energy needs and this trend is likely to continue even in future. In addition, the informal sector plays an important role in rural and semi-urban areas where the degree of in-kind payments and barter as opposed to monetised transactions remains high. 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, 1996) further highlighted these issues and suggested that exclusion of these features results in inaccurate results. Models which assume optimal allocation of resources based on perfect information and completeness of markets are clearly in contradiction with the developing country realities. The co-existence of market and non-market-based energy supplies introduces a complex decision making which requires considering monetary and non-monetary transactions. Pandey (2002) further highlights the need to capture the existence of widespread inequity and poverty as well as co-existence of modern and traditional lifestyles in the analysis. 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.

At the same time, developing economies have the possibility of leapfrogging and avoiding the mistakes by learning from others' experiences. Moreover, some supply-side options such as renewable energies are being adopted by some developing countries almost at the same time and rate as in industrialised countries. In fact, promoting such changes can be a strategy for a sustainable energy future for developing countries. Yet, many developing economies are plagued by supply shortages, especially for commercial energies in general and electricity in particular, which arise due mainly to inappropriate policies and investment decisions and limited access to finances. Therefore, any model dealing with the energy sector of developing countries should be capable of capturing such features.

3.2. Methodology

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 developing countries. We consider the following alternative types of energy system models:

- bottom-up, optimisation-based models (such as EFOM, MARKAL, etc.);
- bottom-up, accounting models (such as LEAP);
- top-down, econometric models (such as Department of Trade and Industry energy model);
- hybrid models (such as POLES, world energy model (WEM); and
- electricity system models (such as WASP, Electricity Generation Expansion Analysis System (EGEAS)).

A brief description of the models is presented in Appendix for interested readers. More details are available in Bhattacharyya and Timilsina (2009).

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

(1) 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.

(2) 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.

4. Results and discussion

Table II 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. Econometric models use price-driver which play a limited role in developing countries and cannot capture informal sector or traditional energies adequately. These models also have difficulties in capturing the technological diversity. Both econometric and optimisation models require high skill levels.

Tables III and IV compare specific bottom-up and hybrid models using the criteria indicated for the second stage of the analysis. Table III 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

Table II.
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 and 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 III. 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 multiple countries	Local, regional, national or multiple countries	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 IV.
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

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 III, 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. As most of the existing models are designed and developed in the developed world, they fail to capture the specific needs of the developing countries. Although some models have the flexibility for capturing some features (such as traditional energies), the specific national or local applications often do not try to capture the developing country features. These routine applications of such models 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.

5. Policy issues related to energy system models for developing countries

Our analysis in the previous sections has established that most of the existing energy system models are incapable of reflecting the specific features of energy systems of developing countries. Econometric models have often attempted to analyse the effects at the aggregate level by identifying statistically significant relationships taking support of economic theories. These studies have evolved over the past 30 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 behaviour by income groups is often inadequately captured.

In the developing country context, data limitations arise as an additional limitation. Both the econometric and the 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 analyse 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, it suffers from multi-collinearity and limited degrees of freedom (Hartman, 1979). Moreover, model results often suffer from little parameter robustness and overestimation of long-run price elasticity.

- End-use models on the other hand require information on consumption behaviour 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 behaviour 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 behaviour. Similarly, the supply is also skewed towards urban centres 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 characterisation of technologies and transition possibilities also affects the analysis. Although developing countries are characterised 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 characterisation of energy systems 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 (Bhattacharyya, 2008). Recently, concerns 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* (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 modelling approaches. While Indian studies used simple, aggregated forecasting techniques, International Energy Agency (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 utilised 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 behaviour 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 modelling can lead to biased prescriptions and generate an inaccurate picture of future implications.

Thus, lack of understanding of consumer behaviour and supply conditions can lead to costly misallocation of resources and choices. In addition, better characterisation of rural-urban divide and consumers by income groups and spatial distribution is essential for a clearer picture of energy system development needs in the future.

This also brings the issue of inefficient institutional arrangements in these countries, which goes beyond the traditional optimal theories. Given that institutional issues are less amenable to standard modelling methods, they are left out, making analyses inaccurate. Clearly, as Urban *et al.* (2007) suggest, there is need for further improvement in energy system models taking developing country features into account. Incorporating the above in the energy system modelling remains a challenge.

Inappropriate characterisation of technologies and transition possibilities also affects the analysis. Although developing countries are characterised by their dependence on inefficient technologies, they can benefit from technological advances and leapfrog the technological ladder by adopting cleaner technologies and avoiding the mistakes made by the developed countries in their development process. However, such technological transitions are not automatic and often require state intervention in the decision making through appropriate institutional arrangements. Inadequate identification of such possibilities and analysis of options and requirements make policymaking more difficult.

In policy terms, inaccurate characterisation of energy problems and issues leads to incorrect policy prescriptions. The dynamics of economic growth and consequent energy implications are poorly understood, which in turn leads to inadequate infrastructure development or poorly adapted development. Lack of understanding of consumer behaviour and supply conditions have led to costly misallocation of resources and choices. The analyses of climate change issues based on such models are unable to depict a correct picture and introduce wrong interactions and implications.

6. Conclusion

In this paper, we present a comparative study of existing energy system models with an objective of finding whether they are suitable for developing countries. For this purpose, we have reviewed a number of models covering energy systems but excluding energy-economy models. We have considered models from various modelling traditions, such as top-down and bottom-up, employing alternative approaches such as optimisation, accounting, econometric and hybrid techniques. The review was performed using a set of specified criteria covering the needs of developing country characteristics.

The review suggests that most of the existing models inadequately capture the developing country characteristics and that the problem is more pronounced with econometric and optimisation 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 accounting-type end-use models with their flexible data requirements and focus on scenarios rather than optimal solutions make them more relevant for developing countries. The global models also suffer from the same problems – as the developing countries are given limited focus in such models and the modelling approach is not varied for developing countries.

Clearly, as Urban *et al.* (2007) suggest, there is need for further improvement in energy system models taking developing country features into account. Following Pandey (2002) and Urban *et al.* (2007), we propose the following agenda for energy system modelling for developing countries:

- incorporation of traditional energies and informal sector activities;
- incorporation of transition from traditional to modern sector due to modernisation and urbanisation which manifests in the form of migration, increased demand for employment in the modern sector, increased consumption pattern and rising energy intensity;
- better characterisation of rural-urban divide and consumers by income groups and spatial distribution for a clearer understanding of energy sector developments;
- integrated evaluation of decentralised supply options along with centralised options;
- taking care of structural changes and competition in the emerging markets and the uncertain and changing patterns of business environment; and
- better representation of technological changes and technology diffusion and capturing uncertainties about long-term economic growth in the future.

Incorporating the above in the energy system modelling remains a challenge.

Notes

1. Positive models are based on verifiable descriptions or statements, while normative models use value-based judgements.
2. See Bhattacharyya and Timilsina (2009) and Bhattacharyya and Timilsina (2010) for further details on this issue.
3. Institute of Energy Economics and Rational Use of Energy.
4. 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" (IAEA, 1984).

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Appendix. Model description

This appendix provides additional information on a selected set of models.

Bottom-up, optimisation-based models

Regional energy scenario generator. This model, shortly RESGEN, 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.

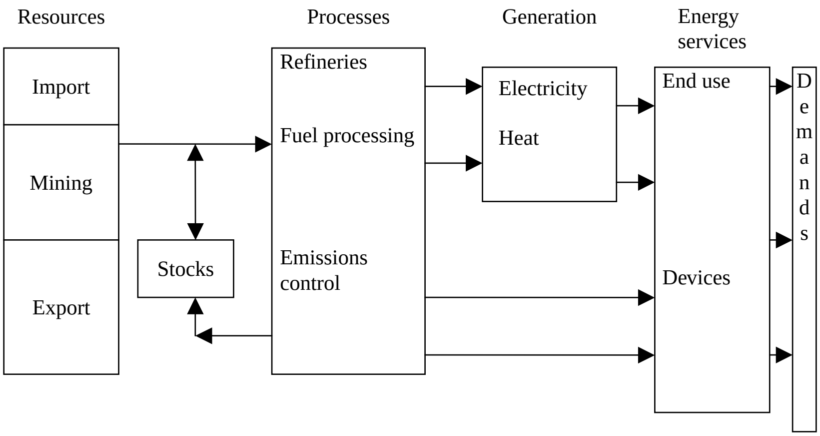
The model is flexible and has been used in many developing countries (Munasinghe and Meier, 1993, 1988). More recently, this was used in RAINS-ASIA model for generating energy scenarios for a large number of Asian countries.

Energy flow optimisation model. This model, shortly 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 world (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 a sister model of the MARKAL family of models.

Market allocation model. This model, shortly MARKAL, 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. 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 Figure A1.

The original model has been extended in various ways and now a family of MARKAL models exists (Table AI). One major development is to make energy demand price-responsive that better analyses tax policies or emission constraints. The PC version of the model is now available and a database of technological choices is now available with the model.

The integrated MARKAL-EFOM system. The integrated MARKAL-EFOM system, shortly TIMES, is the new avatar of the MARKAL and EFOM models where the features both the models have been integrated (Loulou *et al.*, 2005; Vaillancourt *et al.*, 2008). The model produces the least-cost solution for the entire system or a specific sector and can consider the investment and operating decisions.



Source: Seebregts *et al.* (2001)

Figure A1.
MARKAL building blocks

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)

Table AI.
MARKAL family

The demand-side of the model uses exogenous assumptions about demand drivers and the elasticities of demand with respect to these drivers and prices. 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.

The model has multi-regional and multi-period capabilities. 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.

Modular energy system analysis and planning. Modular energy system analysis and planning, shortly MESAP, is a modular toolbox developed at IER[3] in the University of Stuttgart and uses a number of sub-component models for energy and environmental planning. The model has three parts: calculation modules, data and information modules and additional tools.

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.

Bottom-up, accounting models

Long-range energy alternatives planning model. This model, shortly 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). The model follows the accounting framework 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 analyses the implications of possible alternative market shares on the demand.

The supply-side of the model 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 shown in Figure A2.

Hybrid models

National energy modelling system. This model, shortly NEMS, was designed and primarily used by the US Department of Energy for preparing the Annual Energy Outlook. It is a hybrid 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 USA. 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.

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. 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 Figure A3.

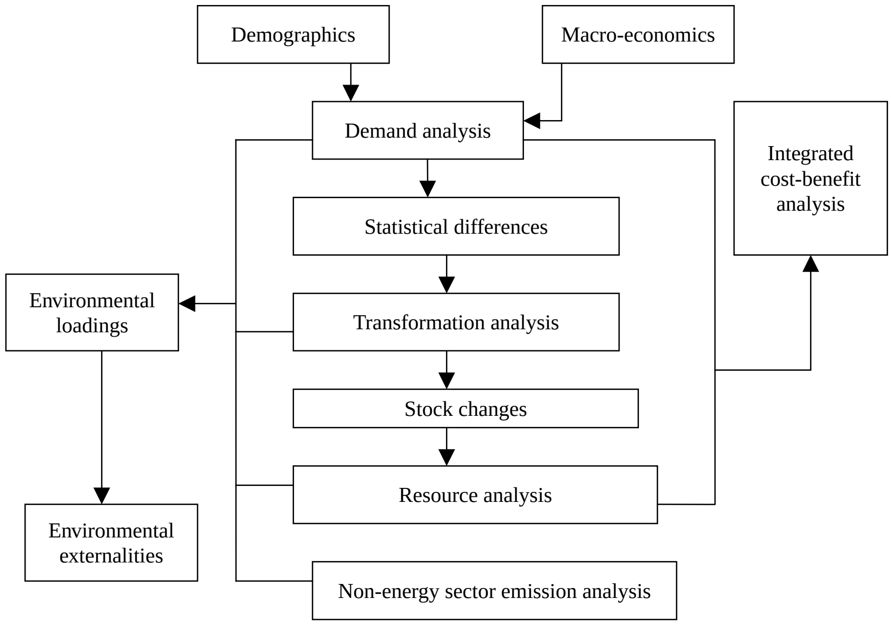


Figure A2.
LEAP framework

Source: Heaps (2002)

Prospective outlook on long-term energy systems. Prospective outlook on long-term energy systems, shortly POLES, is a recursive, disaggregated global model of energy analysis and simulation that 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.

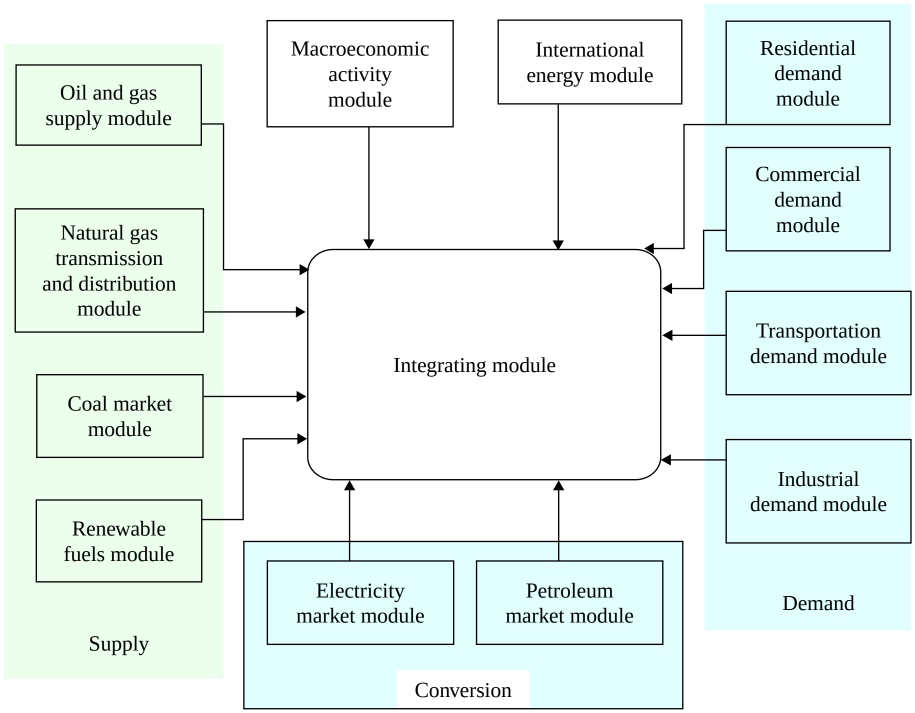
The demand is analysed using a disaggregated end-use approach with separate treatments of energy intensive and non-intensive uses. The global demand is generated from country and regional demands where all large consumers are separately considered.

The model considers 12 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. Figure A4 shows the general structure of the POLES model.

World energy model. The WEM used in the 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 A5 shows the general model structure.

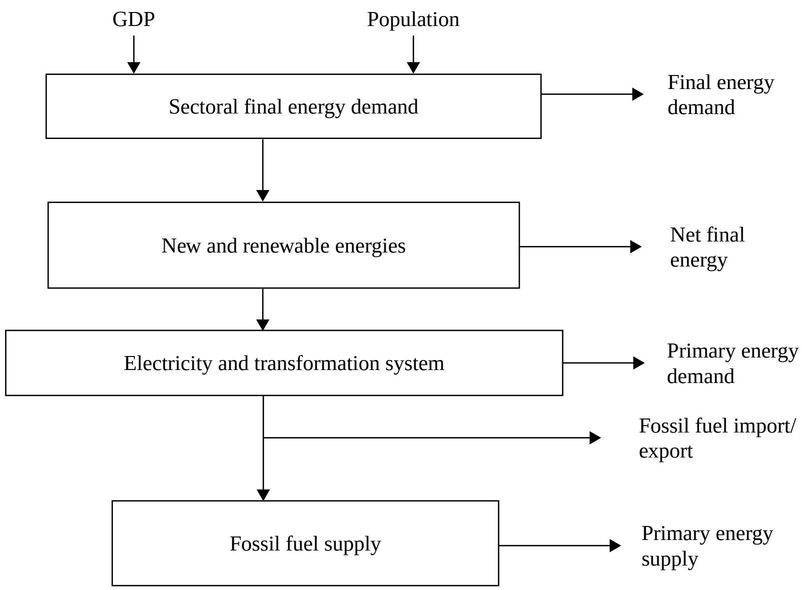
The final energy demand module follows the disaggregated end-use approach of forecasting and uses the economic activity, energy prices and other variables as the main drivers of energy demand. The power generation module considers the electricity demand and determines the new capacity addition need considering alternative technologies.

The fossil fuel supply module considers oil and gas separately and differently. Oil supply is determined by taking Organisation of Petroleum Exporting Countries (OPEC), non-OPEC and non-conventional oil production. OPEC supply is determined as the balancing figure while



Source: EIA (2000)

Figure A3.
NEMS model structure



Source: Criqui (2001)

Figure A4.
POLES model structure

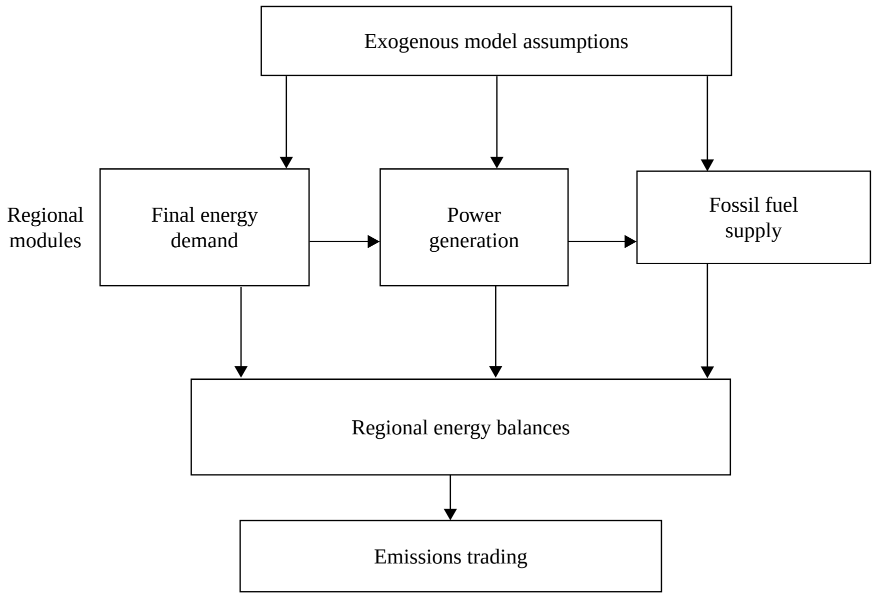


Figure A5.
WEM models structure

Source: IEA (2007)

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 CO_2 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 sector 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.

System for the analysis of global energy markets. System for the analysis of global energy markets (SAGE) is the new tool developed and used by the US Department of Energy for analysing global energy situations. This is an integrated regional energy model and the standard version considers 42 end-use demands. 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 five years) for 25/30 years.

Electricity system models

Wien automatic system planning. This model, shortly WASP, 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)[4] (IAEA, 1998). The demand for electricity is exogenously given and using a detailed information 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.

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, 1998), 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 shown in Figure A6.

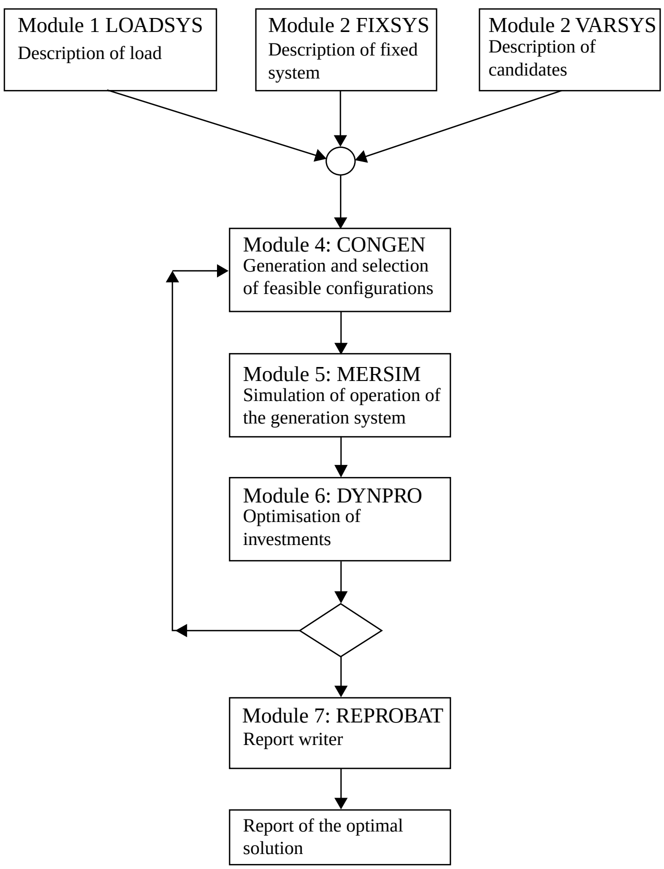


Figure A6.
Overall structure of WASP-IV

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.

Electricity Generation Expansion Analysis System. Electricity generation expansion analysis system, shortly EGEAS, was developed under the sponsorship of Electric Power Research Institute 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 USA and the results are well accepted by the regulators.

Corresponding author
Subhes C. Bhattacharyya can be contacted at: s.c.bhattacharyya@dundee.ac.uk