Integrated energy planning: Part I. The DEFENDUS methodology

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The process of energy planning involves the estimation of future energy demand and the identification of a mix of appropriate sources to meet this demand. This mix must emerge from a rational procedure in which various energy generation and/or saving options are evaluated. A powerful, simple and transparent approach to energy planning – the development-focused end-use-oriented service-directed (DEFENDUS) approach – is discussed here. Demand for a source of energy is based on the services for which it is required – the extent to which such services are spread among the population and the efficiency with which they can be delivered. The energy requirement so estimated is then matched with energy-supply and/or energy-saving options, so as to minimize costs. Starting with the reference energy system (RES) – the energy system as it obtains in the present (or the most recent past for which data is available) – the DEFENDUS approach constructs scenarios of future energy demand, paying deliberate attention to the equity and energy-efficiency considerations of alternative scenarios. The costs per unit of energy supplied/saved are then estimated, including both investment and operating expenses as well as the costs of delivery to the consumer and the losses in distribution. Environmental impacts – and the cost of mitigating them – can be taken into consideration in the methodology. The economic impacts of a chosen scenario can also be included. By ranking the energy supply/saving technologies in increasing order of costs, the least-cost mix is obtained. Whereas with most pre-programmed packages, the planner must accept the format already provided, the DEFENDUS approach suggested here enables one to validate every step of the computation procedure and modify assumptions according to the actual case being considered.

The first part of the paper deals with the methodology proper. It refers to the reasons for developing such an energy-planning method, sketches a conceptual framework and then discusses the actual procedure in detail, including the usage and advantages of spreadsheets for computation. Part II (to be published in the following issue) will elaborate on examples of DEFENDUS scenarios.

1. Introduction

1.1. Energy planning

Energy is required to perform the tasks (such as lighting, cooking, and heating) through which consumers obtain the services (illumination, cooked food, and heat) they want. The amount of energy needed by each consumer varies with the level of services desired and the efficiency with which these services can be achieved. The aggregation of individual requirements in a given region leads to sectoral demand and hence to the total energy demand of the region. This energy demand must then be matched by a supply of energy. Often, this supply is from a mix of various sources.

The fundamental premise underlying this study is that the mix must emerge from a rational procedure in which choices are made from alternative options of energy generation and/or energy saving. The energy-saving options (through improvements in the efficiency of usage) have to be considered because by obviating the need for generation to the extent of the energy saved, they are effectively equivalent to supply. Energy planning consists of estimating future energy requirements and identifying the appropriate ''supply'' technologies to satisfy these requirements.

Since energy plays such a central role in satisfying human needs and advancing development, energy planning is obviously a crucial activity which deserves prime importance. The purpose of this paper is to discuss a simple, transparent and powerful approach to energy planning.

1.2. Existing energy-modelling software

There are a number of software packages that can be run on personal computers (PCs) to make forecasts in the energy sector – LEAP (Long-range Energy Alternatives Planning) [LEAP, 1990], MEDEE-S (Modèle de demande en énergie pour les pays du Sud) [MEDEE-S, 1995], and BEEAM-TEESE (Brookhaven Energy Economy Assessment Model-TERI Energy Economy Simulation and Evaluation) [Pachauri and Srivastava, 1988], and others.

These ‘‘ready-made’’ software packages are based on models of the energy system. They provide scope for relating energy demand directly to the end-uses of energy at the device and service levels. They also include macroeconomic parameters by which the impact of structural changes in the economy can be monitored. The linkages between the various programs of a package ensure that changes in one sector are transmitted to other relevant sectors. Further, very detailed analyses can be carried out. For instance, in the LEAP package, an alteration in the energy consumption of a device can be tracked from the unit-usage of the device in each sub-sector, to the total demand, which in turn is translated to the primary resource requirements and consequently to a relative change in costs. The models also permit various technological options and choices of fuel-mix in end-use activities.

Hence, these energy-planning packages afford a comprehensive analysis of the energy sector, as well as its relationship with the rest of the economy. Obviously, the usual advantages of computers over manual calculations (even with hand-calculators) are obtained – computers perform tasks much faster and more accurately and also eliminate the tedium of repetitive calculation, freeing the analyst for more productive work.

A study of five software packages – Energy Toolbox, ENPEP [Buehring et al., 1991], MESAP [Reuder, 1990], LEAP and MEDEE-S has been carried out [Enerdata S.A., 1993] to choose an energy demand projection model for African countries. The study has highlighted three main issues. Almost all African countries have an energy demand model at their disposal (thanks invariably to a project based on a foreign consultant), but the model is not used in energy planning after the consultant has left. Because of the similarities between the various African countries, there should be a common methodology, but the approach must have the flexibility to cope with the diversities as well. The model must be of the end-use type.

There are, however, disadvantages with pre-programmed packages. Firstly, the formulae employed in the programs are entered at the stage of software programming, so that the user has little or no control over the actual computational procedure. As such, the energy-planner is forced to accept the general-case treatment instead of evolving a method that could be more appropriate for the particular case under consideration.

Secondly, as users are generally not equipped with the source-codes, they remain dependent on the programmers of the package for any alterations. Moreover, in cases where the formulae are not clearly specified in the user-manual, they have first to be derived by the user or else the estimation procedure remains opaque. Because of this, it is also difficult to locate errors.

Thirdly, the form in which data has to be entered may not coincide with that in which information is available, so that a certain amount of exogenous data-processing has to be completed before the package can be used. Fourthly, some packages impose major constraints on the planning process, for example, constant energy efficiencies throughout the planning period.

There are also a number of energy-system models implemented on mainframes, such as MARKAL [Goldstein, 1990][1] (and its regional version MENSA) and BESOM[2] – both linear programming models, the Argonne Energy Model[3] (a network model) and many others that have been used in various countries [Meier, 1985]. These facilitate much more elaborate calculations than the PC-based systems, but they suffer even more from the ‘‘black-box’’ syndrome. Since the models are large and complex, the fundamental relationships between the variables and the data parameters are often taken as ‘‘given’’ and the users are not able to validate these equations in relation to the region being studied, unless there is continuing software support. Large-system packages are also less accessible because of their cost.

1.3. The origin of the DEFENDUS methodology

In the context described above, it is essential to evolve a simple method of computing energy demand and supply in which the planner has complete control over the entire procedure. Also, the steps followed must be ‘‘transparent’’ enough to be easily understood and amenable to easy modification by another planner. Finally, those who wish to replicate computations must be able to use the first computation as a model and ‘‘default case’’ and therefore avoid ‘‘re-inventing the wheel’’. All these objectives were achieved by the **DE**velopment-**F**ocused **END**-**U**se-oriented **S**ervice-directed (DEFENDUS) methodology for estimating the demand and supply of energy in an energy system.

The DEFENDUS methodology was evolved for a number of immediate reasons. When analysing the projections of Karnataka’s[4] electricity demand obtained from various planning exercises [Pachauri et al., 1980; PPD-GOK, 1981; WG-GOK, 1982; GOK, 1982; PWED-GOK, 1983; CEA, 1985; CPRI, 1987; LRPPP, 1987; CEA, 1987; PD-GOK, 1989], it was found that the estimation of future requirements of electrical energy is conventionally carried out via projections of demand, that is, via extrapolation of current demand at the rate of growth characteristic of the immediate past. These *business-as-usual* projections generally exclude the possibilities of improvements of energy efficiencies and alterations of growth rates, so that the future is viewed as an amplified version of the recent past. However, an alternative *scenario*[5] approach could be adopted where one would assume that, just as present trends in electricity consumption are the outcome of past policies, new outcomes can be chosen and a specification made of what policies can bring them about.

Secondly, the DEFENDUS team had undertaken a project[6] that required the evaluation of an energy-planning software package in the context of developing countries. It was decided to apply the software to the state of Karnataka and construct energy demand and supply projections for the electricity system. Since the results could not be audited step-by-step with a calculator, it was considered important to *verify* the results obtained from the software package. It was also felt that the best verification would consist of developing an alternative methodology and using it for the same problem of electricity in Karnataka.

Thirdly, the perspective in the book *Energy for a Sustainable World* [Goldemberg et al., 1988] included energy conservation measures (the use of more energy-efficient processes and devices) and the use of new renewable sources of energy. But such technologies can be brought into actual usage only if the *magnitude* of energy conservation/generation and the *cost* involved warrant them. This necessitated the quantification of energy saving and generation possibilities and the calculation of the cost per unit in each case, in order to formulate economically viable plans. Once again a simple model that evaluates alternative scenarios was required.

All these considerations led to the formulation of a DEFENDUS approach to energy planning that was used initially for electricity [Reddy et al., 1991] in the state of Karnataka but had the potential for replicability, i.e., it could be used for other energy sources/carriers and other geographical regions.

1.4. Application has received more attention than methodology

Since the DEFENDUS electricity scenario was developed in response to a projection for Karnataka made by a Government-appointed Committee for the Long Range Planning of Power Projects (LRPPP), the focus in the DEFENDUS publication [Reddy et al., 1991] was on the *application* of the methodology to the electricity system of Karnataka. There were a number of reactions [Parikh, 1991; Shah, 1991; Banerjee, 1991] to the work, but these also focused on the Karnataka electricity scenario and its ‘‘implementability’’ rather than on the *methodology* that had been used. For instance, doubts were expressed regarding the practicality of reducing electricity demand through efficiency improvement. Questions were also raised about the validity of using the Karnataka assumptions for other states in India.

Discussion then shifted to the possibility of using the DEFENDUS methodology for energy planning in other developing countries.[7] Questions such as the following have been asked.

- Can the methodology initially developed for electricity be used for other energy sources/carriers?
- Can one go from electricity planning to energy planning involving the integration of a number of energy sources/carriers?
- Can the macroeconomic implications of the DEFENDUS scenarios be spelt out?
- Does the methodology permit an estimate of the environmental impacts of the scenarios?

Though the answers to many of these questions are implicit in the original Karnataka Electricity Scenario paper, it is clear, in retrospect, that *the original presentation buried the methodology in the application*. This paper is addressed therefore to an *ab initio* exposition of the DEFENDUS methodology *per se*.

2. A conceptual framework for energy planning

2.1. A systems view of energy planning

A system can be defined as the portion of the universe that is chosen for consideration. Every system is a subsystem of a larger system that constitutes its environment and with which it is in interaction. At the same time, every system has a structure, i.e., it is itself an organization of parts (sub-sub-systems) in interaction.

The energy system is a sub-system of the economy, which, depending upon the level of analysis, may be the economy of the world, a country, a state within the country, a city or village, or even a firm or farm.

In order to take a systems view of energy planning, it is necessary to treat the energy sub-system, the economic system (of which the energy sub-system is a part) and the activity of planning. Systems involving human beings are goal-oriented, and the purpose of energy planning is to make the energy sub-system drive the goal-oriented system towards its goal(s). Every goal implies choices, values and preferences, and therefore a goal-oriented approach is a *normative* approach that defines what is desirable.

Whenever questions of planning are raised (whether at the level of the country, state, corporate entity or firm), the words: goals, strategies, policies, policy agents and policy instruments are invoked. Hence, it is worthwhile adopting clear-cut definitions of these terms. A *goal* is an objective that the system should attain. A *strategy* is a broad plan to reach that goal. A *policy* is a specific course of action to implement the strategy. A *policy instrument* is an instrument with which policy is initiated and maintained. A *policy agent* is one who wields a policy instrument.

It may be noted that goals, strategies and policies constitute different levels of hierarchy in the scheme of concepts, the degree of specificity, the flow of interconnections and the set of actions.

For goals to be attained, strategies must be implemented, for strategies to be implemented, policies must be given effect to and operated, for policies to be given effect to and operated, policy instruments must be initiated and maintained, and in addition, policy agents must employ policy instruments.[8] Thus, goals, strategies, policies, policy instruments, and policy agents are all interrelated. This interrelationship can be brought out through a systems diagram (Figure 1) which reveals two important features:

1. the feedback loop that emphasises the iterative character of the process, whereby energy planning and implementation make the energy sub-system drive the goal-seeking system towards its goal(s); and
2. the components of energy planning, which include goals, strategies, policies, policy instruments and policy agents, implementation, monitoring, and analysis.

This model can be considered to be applicable at all system levels – the world, a country, a state within a country, a city or village, a farm or firm.

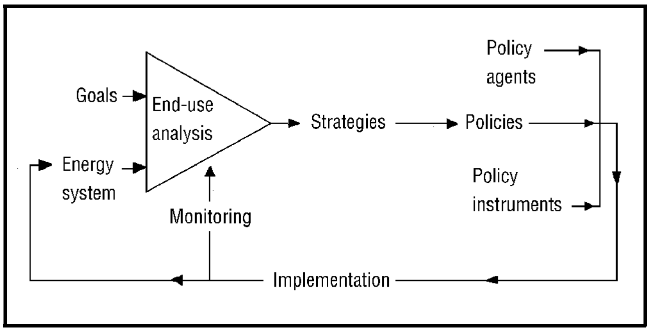

Fig. 1. From goals to policy implementation – the feedback.

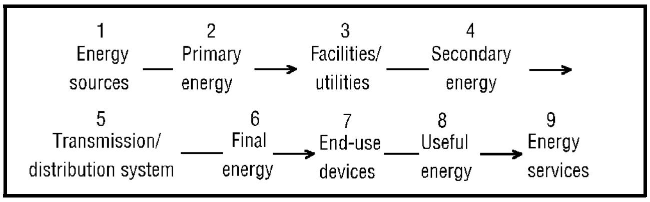

Fig. 2. The reference energy system.

2.2. Reference energy system (RES)

The starting point of energy planning activity at any system level has to be the *structure* of the energy system. This structure involving the parts of the energy system and their interactions is best represented by the *reference energy system* (RES), i.e., the energy system as it obtains at present or as it obtained in an immediate past for which data is available. The RES must include all the energy *sources* of nature that are exploited, all the intermediate forms or *carriers* into which these sources are transformed to enhance the convenience with which they are utilized, the sub-systems for *transmission/transportation* and distribution of these energy carriers, and the end-use devices that are used to obtain the *services* that energy provides – cooking, lighting, water, process and space heating, mobility, shaft power, and information flow. Further, the RES must span both the qualitative and quantitative descriptions of the energy system.

The RES can have several possible structures in the sense that there are many equally valid ways in which the RES can be displayed. One possible structure results from the *fuel-cycle* approach – the RES can be structured to follow *the flow of energy from sources to services.* Such an approach would start from the *primary energy* provided by the sources as found in nature, then consider in sequence the *secondary energy* at the output of the facilities which convert the primary energy into carriers that are readily and conveniently usable by consumers, the *final energy* as received (after transmission/ transport and distribution) by the consumers, and the *useful energy* at the output of the consumer's end-use device, i.e., energy conversion system, which provides the energy service sought by the consumer.

Power plants, oil refineries and coal gasification plants are examples of facilities/utilities that convert primary into secondary energy. The high-voltage grid, gas pipelines, and petroleum transport, storage and distribution facilities are examples of the energy transmission/transport and distribution sub-system. Stoves, furnaces, kilns, lightbulbs, engines and motors are examples of end-use devices.

Further, at every one of these stages of energy conversion, there inevitably are energy losses. In the transformation from primary energy into secondary-energy carriers, there are conversion losses at the facilities/utilities. Similarly, in delivering the energy carriers as final energy to the ultimate consumers, there are transmission/transport, storage, and distribution losses. Finally, when the consumers convert the final into useful energy, there are losses in the end-use devices.

It appears that a simple and logical way of representing the RES is in terms of a nine-column structure (Figure 2).

Unfortunately, it is extremely difficult, if not virtually impossible, to find energy data in a form which can be incorporated directly into this structure.

In the first place, it is much easier to get information on primary and secondary energy, particularly for the conventional commercial sources of energy, than on final and useful energy. That is, *there is far more data on the supply aspects of the energy system than on the demand aspects.*

Secondly, the available demand data is usually in a highly aggregated form. For example, energy consumption data invariably pertains to a few important sectors – industry, agriculture, transport, domestic, and commercial – rather than to types of services, consumers, and end-use devices. (Incidentally, this biased character of the database for energy represents the rapidly vanishing era when the bridging of the energy supply-demand gap could be achieved exclusively by augmenting energy supplies and without exploring the possibilities of demand management.)

To develop an RES structure that would be appropriate for the available energy data, it may be necessary to alter the specified columns. The resulting RES structure would permit the use of sectoral energy consumption data which cannot be further sub-divided at this stage of the study into consumption by consumers and by end-use devices. Where the data is available in a less aggregative form, it can be collated into sector-wise categories. The structure would also allow the energy carrier data to be seen alongside the sectoral consumption for conventional discussions.

2.3. Energy futures

2.3.1. Prediction, forecast, projection, scenario, target and goal

Energy planning necessarily involves goals, and goals require discussion about the future. This involves various words related to the certainty, freedom of choice, degree of detail and the sharpness of focus of that future. In particular, six words are commonly used: *prediction, forecast, projection, scenario, target* and *goal*. Appendix 1 provides working definitions for these words so that there is no ambiguity.

2.3.2. Reference energy system to energy planning

The first step in energy planning is to choose a time horizon for the planning exercise. The energy plan must then describe the evolution of the reference energy system from the base year up to the horizon year. That is, the dynamic changes in the energy system must be considered. For the horizon year, therefore, both the demand side of the energy system and the supply side must be elaborated.

Thus, an energy future consists of two parts – future energy demand and future energy supply to meet that demand.

Two crucial questions arise.

1. How is future demand to be arrived at, given the present energy demand from the reference energy system?
2. How are future supplies to be ensured over and above the supplies described by the reference energy system?

On the demand side, the focus should ideally be on the useful energy that decides the energy services enjoyed by consumers, but in practice, attention is usually restricted to final energy. On the supply side, attention is restricted either to the primary energy or, in the case of electricity and petroleum derivatives, to secondary energy.

3. Basic components of the DEFENDUS methodology

The DEFENDUS methodology has two main components:

1. a methodology for the construction of DEFENDUS (development-focused end-use-oriented service-directed) *demand scenarios* for an energy carrier/source, in which deliberate attention can be paid both to the equity (distributional) and the energy-efficiency dimensions of energy scenarios; and
2. a methodology for the determination of a *least-cost supply mix* (of saving, decentralized generation and centralized generation options) to meet future energy requirements.

3.1. Construction of DEFENDUS demand scenarios

With regard to the prediction/forecast/projection/scenario of future demand, there are at least five conventional approaches:

1. the *trend* method,
2. the *growth rate* method,
3. the *econometric*[9] method,
4. the *techno-economic* method, and
5. the *input-output* method.

However, these approaches are well-known and are therefore not elaborated upon here.

In contrast, the DEFENDUS methodology makes use of the scenario approach which – as pointed out above – is based on a set of energy measures that would transform the present into the future. Thus, scenarios are quite different from projections that relate the future to the present with the aid of mathematical relations. Scenarios are actually exercises that answer the question: ‘‘If measures M_1, M_2, M_3, ..., are implemented, what will the result be?’’

The particular measures that provide the basis for the scenarios have to be derived from the goals and strategies for the energy system prescribed by the scenario-builder as part of a normative exercise (Figure 3). Hence, scenarios cannot be constructed without specification of measures; measures must follow from strategies; and strategies have to be derived from goals.

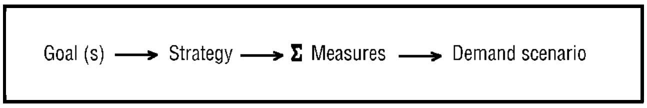

Fig. 3. Construction of scenarios.

Initially, the emphasis has to be on scenarios for specific energy sources/carriers – electricity, coal, petroleum derivatives, biomass, etc. These source/carrier-specific scenarios can then be linked together, as described later.

As the term DEFENDUS suggests, there are two important aspects to be considered when constructing a scenario for the future demand of an energy source/carrier – the *development focus* and the *end-use orientation.*

The development focus presumes a view on development, but the methodology does not in any way constrain this view. If, for instance, development is considered to be a process of economic growth directed towards (1) the satisfaction of basic needs, starting from the needs of the neediest, (2) a strengthening of self-reliance, and (3) harmony with the environment, then the development focus must reflect a determination to reduce poverty and inequality, and to increase self-reliance in an environmentally sound way. Such a focus would determine the *rates of growth* of particular sectors (or categories of consumers) in an economy; for instance, one of the requirements for need-oriented development of a region could be the provision of electric lighting in every home, which would necessitate an enhanced rate of growth of electricity connections in the domestic category.

If, however, development is simply equated with economic growth measured by the GDP, irrespective of the distribution of its benefits, then current growth rates of various categories of consumers can be made to persist throughout the scenario.

The end-use orientation concentrates on the end-uses of energy and the *services* to be derived from energy, rather than the quantity of energy used. What is pertinent is the attainment of a certain amount of heating, lighting or motive power, and not necessarily an increased energy usage, because technological improvements can lower the need for energy while retaining the same level of energy-derived services. Thus, the end-use orientation is based on an understanding of the technological opportunities in the utilization of energy. In this case too, the DEFENDUS methodology does not constrain the planner to pursue an efficient future – present (in)efficiencies can be made to prevail.

The *development focus* and *end-use* factors imply that in order to estimate the requirement of a particular source/carrier of energy, one must take into account:

- the number of energy users (or energy-using entities, such as pieces of equipment or devices) of that source of energy; and
- the average amount of energy required per user per period, i.e., the existing energy consumption ‘‘norm’’

of that user.

The total energy demand is then equal to the aggregate demand of all the categories of users (or types of energy-using devices) for every end-use. The mathematical representation of this approach to energy demand is given in Appendix 2.

The estimation of demand for a particular energy source/carrier in a particular year is therefore dependent on two variables – the number of users and their actual energy requirement in any base year, as well as the expected (or policy-driven) changes in these two variables in subsequent years. On the basis of this relationship, one can calculate any variant of the general case.

For instance, by maintaining the *status quo* in the average energy usage and the current trend of growth of users, one can develop a *business-as-usual* scenario.

Another alternative would be to alter only the growth rates of the number of users, keeping the energy usage constant. This *frozen-efficiency* scenario would assume that although the number of users changes, the level of energy usage per user remains constant as the technical efficiencies of energy-using processes/devices are ''frozen'' at the base-year level and no substitution between energy carriers takes place.[10]

The other type of scenario would involve changes in both the category-wise growth rates of users (for development or equity reasons) as well as the energy usage of these consumers (possibly with efficiency improvements and carrier substitution).

3.2. Comparative costing

Once the total energy demand has been estimated, the question of how this demand should be met must be addressed.

The sources of energy available to a region may be of different types – whether from large-scale centralized plants (such as petroleum refineries, coal-mines, and thermal and hydro-electricity generating plants, etc.) or small-scale decentralized (local) plants. Further, conservation of energy (through the improved efficiency of processes and devices) can also be considered as an option for meeting the energy needs, in so far as the demand for a certain amount of energy is reduced and supply can therefore be avoided or diverted to other uses.

A choice between different options -- generation and conservation – must depend, in the first instance, on their comparative costs. However, while computing the costs per unit of energy from various technologies, it has been found [Reddy et al., 1990] that great care must be taken to ensure that the comparison occurs on equal terms. In particular, the following requirements must be ensured.

- All the costs – fixed or variable – should be expressed with respect to *a particular (reference) year,* so that a dollar of one year is not equated with that of another.
- *Discounted cash flow techniques* must be used to take into account the time value of money. Thus, although the cash flows of the plants would differ, the comparison would be made between the present value (PV)[11] at the same reference date of each stream of flows.
- The *same discount factor* must be used for all the calculations; further, either nominal or real discount rates should be used, but not both.
- The *gestation period* (the time-lag between the commencement of construction of the plant and its commissioning) varies greatly between technologies. This must be taken into account in one of two ways. Either the value of the physical output (energy generated/saved) must be *discounted* from the different commissioning dates to the commencement date at which point comparison can be made. Or, the costs must be appropriately *inflated* to compensate for the time lags between the commencement of construction and the commissioning of each plant. This is economically justifiable, as the longer the gestation period, the greater will be the imputed cost per unit of energy; conversely, the sooner the returns can be obtained, the lower the imputed cost.
- When comparing centralised technologies (which have to transmit energy over long distances to the end-use devices of consumers) with decentralised (local) technologies, the *storage, transmission, and distribution losses* should be taken into account so that the actual *energy delivered* is quantified. Then, the comparison can be made at the consumption end – but it is not permissible to take one technology at the generation end and the other at the consumption end. Further, the additional costs of delivering energy via the grid (setting up transmission and distribution facilities) should be added to the costs of generation.

Once the cost per unit of energy generated/saved from each technology has been calculated with the above precautions, a comparison of technologies on equal terms is possible and available. One can even rank technological options on purely economic terms. All this is essential to facilitate the task of determining a *least-cost mix* of generation/saving technologies.

3.3. Least-cost supply mix

The purpose of selecting a ''least-cost'' mix of energy-supply options is to attain the energy-demand goal at the minimum cost. In terms of a *linear programming (LP) problem,* the objective function would be the total cost of the supply of energy and one would have to minimize this, subject to the constraints that the total energy obtainable would be at least as much as the forecast requirement and that the contribution that each technology can make towards meeting the demand does not exceed its viable potential. The LP formulation would be:

$$\text{Minimize } Z = \Sigma\, C_i.E_i \text{ , subject to:}$$

$$\Sigma\, E_i \geq E_t$$

and

$$E_1 \leq P_1$$

$$E_2 \leq P_2$$

$$. . . .$$

$$. . . .$$

$$E_m \leq P_m$$

where each C_i represents the cost per unit of the source of energy E_i ($i = 1, 2, . ., m$), E_t is the total requirement of energy in the year t for which plans are being made, and P_i is the limit of the potential of the source pertaining to that region. This implies that the total cost of energy supply (equivalent to the sum of the costs of the various sources) must be minimised, while meeting the total energy demand and simultaneously not exceeding the available potential of each source in the region.

An alternative to such an LP calculation is to construct a *least-cost supply curve* showing the cheapest mix of energy generation/saving options that will meet the energy requirement. In fact, it can be shown that *this least-cost mix is automatically the mix that would be obtained from a solution to the LP cost-minimization problem.* To construct a least-cost supply curve, the technologies must be ranked in increasing order of the costs per unit of energy (or unit energy cost). Options must then be chosen in this order,[12] adding the contribution of each towards the fulfilment of energy requirements. This procedure could be diagrammatically represented in the form of a staircase, on a grid where energy is measured on the horizontal axis and cost per unit of energy on the vertical axis (Figure 4). Then the width of each stair indicates the energy potential of a particular option and the height refers to its cost per unit of energy, so that the rectangle representing each step of the stairway corresponds to the total cost incurred on that option. One must consider the least expensive technology as the first element of the supply mix and, after the potential of that option is exhausted, the next costlier option (corresponding to the next higher step), and so on, up the *cost-supply staircase* until the energy goal is reached.

It must be observed that the same energy-efficiency improvement measures cannot be considered on both the demand and the supply sides; they can be counted only once. Hence, if efficiency measures are to be included as candidates among the supply options (in terms of supply avoided), then the estimation of the demand goal should obviously not include efficiency improvement, that is, a *frozen-efficiency* scenario must be used for the corresponding demand forecast.

The approach thus described does not favour any particular type of technology; *an option will be chosen if and only if its unit cost and energy contribution find a place on the cost-supply staircase before the frozen-efficiency demand goal is reached.*

A DEFENDUS scenario for an energy carrier/source is unaware of the spatial domain under its consideration – whether it is a village, city, state, or country. On the demand side, it only considers the categories of consumers and their energy usage; on the supply side, it has the flexibility of considering imports. Thus, the validity of the DEFENDUS methodology is invariant with respect to the size and nature of the domain; it is either valid for all domains or for none.

3.4. Environmental impacts

The DEFENDUS methodology can capture the environmental impacts of the supply mix at two stages.

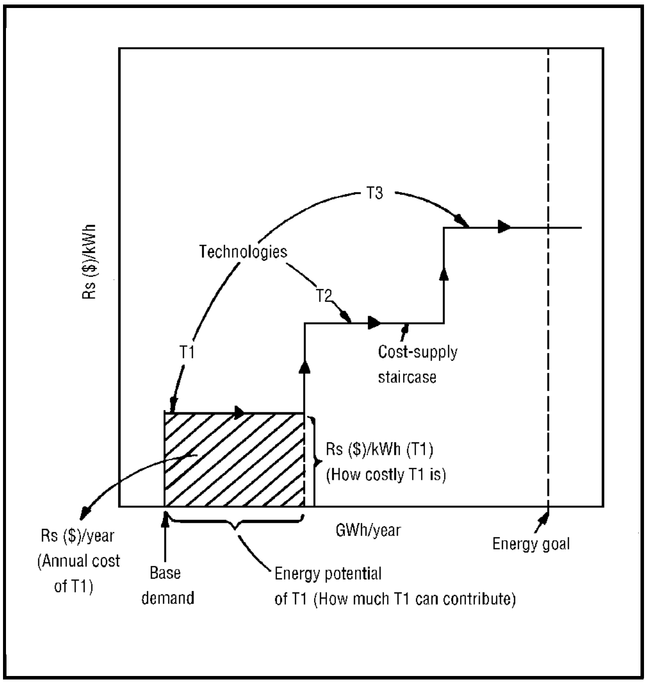

Fig. 4. Least-cost planning – construction of a cost-supply staircase.

During the determination of the least-cost supply mix: This requires a consideration of the costs of the option with and without the costs of environmental protection. For instance, the cost of hydroelectric energy (or power) can be estimated with and without the costs of compensatory afforestation and rehabilitation of displaced persons; the DEFENDUS Electricity Scenario for Karnataka has done this for the costing of hydroelectricity. Like the costs of an energy technology, the costs of the environmental impact of that technology and the mitigation costs have to be analysed separately from the energy planning exercise, but once these costs are determined, they can be incorporated into the procedure for determining supply mixes.

After determining the least-cost supply mix: The environmental impacts per unit of energy saved/generated, for each option in the least-cost supply mix, can be estimated separately (for example, carbon emissions per kWh) and compared with other supply mixes; this has also been done in the paper on the DEFENDUS Electricity Scenario for Karnataka.

Thus, the DEFENDUS methodology has the capacity to handle environmental impacts and their mitigation costs once these are determined.

3.5. Economic implications

The area under the least-cost supply curve represents the annualized financial cost of that particular mix, and this cost can be compared with the corresponding cost for any other mix. (The DEFENDUS electricity scenario for Karnataka was compared with the costs of the LRPPP projection for Karnataka in this manner.) If the cost-supply curve were to be constructed with economic costs,[13] then a comparison of economic costs would also be possible. Thus, financial and economic impacts are within the scope of the DEFENDUS methodology.

Though DEFENDUS scenarios have not hitherto elaborated on their *macro-economic* implications, there are simple approaches to assessing these impacts.

The empirical relationship between the production and the energy usage of a sector can be easily obtained. The regression of sectoral energy usage (for example, industrial electricity usage in a state) on the sectoral production (say, industrial contribution to state domestic product) yields an estimate of the energy-product coefficient.[14] Substituting this coefficient and the estimated energy requirement in a DEFENDUS scenario for a particular year, in the same equation, one can obtain an estimate for sectoral output in that year. However, this will be a *lower bound estimate of the sectoral product* because it uses a constant product-energy coefficient obtained from past data along with an efficiency-induced (i.e., relatively low) future energy requirement.

If, instead of the DEFENDUS scenario energy estimate, the frozen-efficiency scenario estimate of energy requirement is used, along with the same energy-product coefficient, then the result will be an *upper bound estimate of sectoral product.* Efficiency improvements will put the estimate of sectoral production somewhere between these lower and upper bounds. However, as the energy-service levels achieved in both the DEFENDUS scenario (with efficiency improvement) and the frozen-efficiency scenario (without efficiency improvement) are the same, the sectoral product estimate corresponding to the latter can be considered for the former as well. Taking this estimate of production and the corresponding DEFENDUS scenario energy demand, one can calculate a new energy-product coefficient. The difference between the two coefficients indicates the effect of efficiency improvement. Appendix 3 deals with this in greater detail.

3.6. Spreadsheets for DEFENDUS scenarios

Spreadsheets have been found to be very useful for the construction of DEFENDUS energy scenarios as they have certain inherent advantages for the computational procedure described above.

In actual practice, the spreadsheet is arranged so that the columns denote the various consumer or end-use device categories which comprise the usage of the particular energy source/carrier. With regard to the rows, an initial block is assigned to specify the characteristics of the energy usage in the base year. Thereafter, one block of rows is assigned for each year of the plan until the horizon year. Each of these blocks is used to carry out the estimation of the number of consumers/end-use devices in that category and their corresponding energy usage. The computation requires the growth in the total number of consumers or end-use devices, the fractions of old consumers/end-use devices that retain the previous year’s average energy usage and those that have a different average energy usage. Thus, *the spreadsheet is based on a year-by-year estimation advancing from the base year to the horizon year.*

The advantages of constructing DEFENDUS scenarios using spreadsheets are many. Firstly, the energy planner has the freedom to specify the parameters and the formulae on the basis of which the values of the variables are calculated. Depending on the scenario envisaged, these can be easily modified. Thus, the energy planner has complete freedom to change at will (or not to change at all!) the growth rates of consumers/end-use devices and their average energy usage throughout the planning period. The structure also enables one to determine the pattern of implementation of efficiency improvements and new devices, for example, according to a logistic curve.

Secondly, within a spreadsheet, a formula applied to a particular cell can be easily replicated for the remaining cells of the row or column, so that the calculation for any category of consumers/suppliers can be used for other categories of consumers/suppliers. Further, formulae can be entered in terms of the cell addresses, instead of the absolute values of the variable – this links various sections of the spreadsheet, enabling one to estimate the sensitivity of results to changes in any particular value. Results of iterative calculation are obtained almost instantaneously.

Thirdly, it is convenient to utilise the framework already constructed for any new but analogous calculation. For instance, similar spreadsheets were used for the estimation of electricity demand in Karnataka and various other states, the requirement of biomass and of petroleum products in Karnataka and of petroleum products in India. Obviously, the actual sectors, categories of users, and other such parameters would determine the final framework of the spreadsheet. However, the method of analysing demand by type of consumer (or uses or devices) and quantifying each category of demand through the product of the number of consumers/uses/devices and their average energy requirement is applicable to different analyses.

Separate spreadsheets can also be linked to each other – a facility particularly necessary for any study of more than one sector and for linking the energy sector with the rest of the economy. ■

Appendix 1. Definitions of prediction, forecast, projection, scenario, target and goal

A **prediction** is a prophesy that describes what *will* happen, a **forecast** states what is *likely* to happen, and a **projection** is an *estimate* of future trends. Thus, these three words constitute a hierarchy in which the degree of certainty increases as one goes from projection (estimate) to forecast (likelihood) to prediction (prophesy). When the question of how certain we are of the future arises, then one of these three words must be invoked.

There are two categories of projections, forecasts and predictions: the *reference level* or *base-line* versions that assume that there will be no interventions to alter present trends, i.e., the *business-as-usual* (BAU) category, and the *intervention-based* (IB) variety. The business-as-usual and intervention-based projections, forecasts and predictions involve starting from the present and working forwards to the future. But it is also possible to assume a future and work backwards – this is what is done in a *scenario* or imagined sequence of events that would transform the present into the future. Scenarios, business-as-usual extrapolations and intervention-based versions of the future all concern the question of how the future is chosen or designed.

The *degree of choice and activeness of role* increases as we ascend the hierarchy from business-as-usual extrapolations through intervention-based projections, forecasts and predictions to scenarios. On the other hand, the *extent of destiny and passiveness of our roles* increases as we descend from scenarios to business-as-usual extrapolations.

Finally, there is the question of the *degree of detail and the sharpness of focus* with which we see the future. When the image is sharp and there is a wealth of detail, we refer to a **target** or minimum result to be aimed at. In contrast, when there is only a broad picture without much detail and the focus is blurred and diffuse, we speak of a **goal** or broad objective.

Thus, the words prediction, forecast, projection, scenario, target and goal arise from attempts to answer the following three questions regarding the future.

1. How *certain* is the future?
2. How much *choice* is there with respect to the future?
3. How *clear* is the future? ■

Appendix 2. Derivation of the mathematical expression for the estimation of future energy demand

Consider the annual energy demand of a region in the year t.[15] Let this total energy requirement be E_t. Then E_t is the aggregate requirement of all i energy sources or carriers in use (such as electricity, diesel, firewood, etc.). That is,

$$E_t = \sum_{i=1}^{m} E_{it} = E_{1t} + E_{2t} + \dots + E_{mt} \qquad (1)$$

where E_{it} is the requirement of the ith energy source or carrier in the tth year considered.

However, the total energy demand for the ith source E_{it} must be equivalent to the aggregate requirements of all the diverse consumer categories/sectors (such as homes, industrial units, passenger transport, freight haulage, etc.), so that

$$E_{it} = \sum_{j=1}^{n} E_{ijt} \qquad (2)$$

where E_{ijt} is the energy requirement of the ith source or carrier for the jth sector in the tth year.

Again, the energy demand of the jth sector E_{ijt} is the sum of the energy requirements for all the p end-uses of that sector, hence,

$$E_{ijt} = \sum_{k=1}^{p} E_{ijkt} \qquad (3)$$

where E_{ijkt} is the energy requirement from the ith source or carrier used by the jth category of users for the kth end-use, in the tth year.

Therefore, the total energy demand E_t in the year t is the aggregate requirement of all m sources or carriers, in all the n sectors, for all the p end-uses:

$$E_t = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{p} E_{ijkt} \qquad (4)$$

For each of the p end-uses in the jth category of users of the ith energy source, let there be N_{ijkt} users in the year t. Let the average annual energy usage per end-use or (E_{ijkt}/N_{ijkt}) be e_{ijkt}. Then

$$E_{ijkt} = N_{ijkt} \times e_{ijkt} \qquad (5)$$

In DEFENDUS scenarios, the two parameters – the number of users N_{ijkt} and the average energy-usage e_{ijkt} – are used to introduce development objectives and efficiency improvements, respectively.

It is obvious that *the number of users*, N_{ijkt}, can change over time, but it is also possible that *the average energy consumption per user*, e_{ijkt}, for each category can also change (even if only a few users alter their consumption patterns).

Let the change in the number of users be represented by an annual growth rate, so that

$$N_{ijkt} = N_{ijk(t-1)} \times (1 + g_{ijkt}) \qquad (6)$$

where N_{ijkt} and $N_{ijk(t-1)}$ are the number of users in the years t and (t-1), respectively, and g_{ijkt} is the average growth rate (in the form of a fraction = percentage/100). The growth rates (positive or negative) would depend on a combination of factors – the natural trend rates (for example, population growth) and, more importantly, those that are selected by the planner according to the scenario envisaged. *In a DEFENDUS scenario, the development focus would determine the growth rates assigned to particular sectors.*

Similarly, let there be a change in the average annual energy requirement per end-use, so that

$$e_{ijkt} = e_{ijk(t-1)} \times (1 + c_{ijkt}) \qquad (7)$$

where e_{ijkt} and $e_{ijk(t-1)}$ refer to the average energy usage per category-j consumer in the years t and (t-1), respectively, and c_{ijkt} is the change in this usage between the years t-1 and t. This rate of change could be negative or positive as the use of more efficient devices (via technological improvements) and/or substitution of the particular energy source/carrier under consideration with another energy source/carrier would lower e_{ijkt}, while increases in energy-based activities (for instance, increase in the number of appliances per consumer) without compensating efficiency improvements would raise e_{ijkt}.[16]

Relating the total energy consumption in the year t with that in the previous year via annual rates of change, i.e., from equations 5, 6, and 7, one would get

$$(N_{ijkt} \times e_{ijkt}) = \{N_{ijk(t-1)} \times (1 + g_{ijkt})\} \times \{e_{ijk(t-1)} \times (1 + c_{ijkt})\} \qquad (8)$$

so that the energy requirement for each category of users would be:

$$E_{ijt} = \sum_{k=1}^{p} \{N_{ijk(t-1)} \times (1 + g_{ijkt})\} \times \{e_{ijk(t-1)} \times (1 + c_{ijkt})\} \qquad (9)$$

In the special cases where the annual growth rate in the number of users remains constant from year to year (i.e., $g_{ijk1} = g_{ijk2} = . . . = g_{ijkt} = g_{ijk}$) and where the annual changes in the average energy usage are constant (i.e., $c_{ijk1} = c_{ijk2} = . . . = c_{ijkt} = c_{ijk}$), the category-wise energy requirement in the tth year will be

$$E_{ijt} = \sum_{k=1}^{p} \{N_{ijk1} \times (1 + g_{ijk})^{t-1}\} \times \{e_{ijk1} \times (1 + c_{ijk})^{t-1}\} \qquad (10)$$

However, it may be difficult to prescribe annual rates of change in the average energy usage. Instead one can consider two types of devices for each end-use -- more efficient (new or retrofitted) devices and less efficient (existing) devices. The users, N_{ijkt}, can then be distinguished on the basis of the type of equipment/devices they use.

Let us refer to the ith source being used in the jth sector for the kth end-use. There are two options for the type of devices being used for this end-use – one option being those devices existing at the beginning of the scenario with the average energy usage e_{ijk} and the other option being the new (or improved) devices with the energy use e'_{ijk}. The difference between e_{ijk} and e'_{ijk} depends on the fraction of energy, s_{ijk}, that is saved by switching to the new (or improved) devices, i.e.,

$$e_{ijk} - (s_{ijk} \times e_{ijk}) = e'_{ijk}$$

$$\text{or } e'_{ijk} = e_{ijk} \times (1 - s_{ijk}) \qquad (11)$$

Let the ‘‘new users’’ be defined as all those who join the consumer population after the start (first year) of the efficiency improvement plan. These can then be treated as distinct from those counted at the start of the plan period,

$$\text{i.e., } N_{ijkt} = [\{N_{ijk1}\} + \{N_{ijkt} - N_{ijk1}\}] \qquad (12)$$

or total users = {base-year users} + {new users}

But the end-use orientation might require that even the existing users acquire efficiency-improved (or retrofitted) devices. The population of users in the year t would then comprise three categories, namely:

- those still with the less efficient devices prevailing at the beginning of the scenario;
- those who acquired the improved/retrofitted devices after the start of the scenario; and
- new users who start with the new improved devices.

Using the above categories, if p_{ijkt} is the proportion of the base-year kth end-use devices used in the jth sector (with the ith source of energy) retrofitted in the year t, it follows that

Total users = [{those with unchanged devices}
+ {those with retrofitted devices}]
+ [new users]

$$\text{or } N_{ijkt} = [\{N_{ijk1} \times (1 - p_{ikjt})\} + \{N_{ijk1} \times p_{ijkt}\}] + [N_{ijkt} - N_{ijk1}] \qquad (13)$$

In this context, it may be pertinent to note that the recent DEFENDUS scenarios have, in general (as will be seen in Part II of this article, Sections 3, 5, and 6, to appear in the next issue of *Energy for Sustainable Development)* considered the rate of adoption of more efficient devices to approximate a logistic curve, so that

$$p_{ijkt} = K / [1 + \{(K - N(0))/N(0)\} \times e^{-rt}] \qquad (14)$$

where K is the saturation limit of the replacement, N(0), the starting percentage taken as a negligible finite quantity, to avoid division by zero, and r, the constant that determines the slope of the logistic curve.

To compute the energy usage E_{ijkt} (with the same scheme of three categories of users), Equation 13 can be substituted in Equation 5 to yield the equation

$$\begin{aligned} E_{ijkt} = {} & [\{N_{ijk1} \times (1 - p_{ikjt})\} \times e_{ijk}] \\ & + [\{N_{ijk1} \times p_{ijkt}\} \times e'_{ijk}] \\ & + [\{N_{ijkt} - N_{ijk1}\} \times e'_{ijk}] \end{aligned} \qquad (15)$$

Further, by substituting from Equation 11, the result is

$$\begin{aligned} Eijkt = {} & [\{Nijk1 \times (1-pikjt)\} \times eijk] \\ & + [\{N_{ijk1} \times p_{ijkt}\} \times e_{ijk} \times (1 - s_{ijk})] \\ & + [\{N_{ijkt} - N_{ijk1}\} \times e_{ijk} \times (1 - s_{ijk})] \end{aligned} \qquad (16)$$

Equation 16 can be used to compute the requirement of energy from the ith source/carrier by the jth sector for the kth end-use in any year t.

However, if the growth rate of the number of users has been constant during the period 1 to t, i.e., $g_{ijk1} = g_{ijk2} = . . = g_{ijk(t-1)} = g_{ijk}$, then one can compute the energy requirement for any year directly from the base-year energy requirement ($N_{ijk1} \times e_{ijk}$) and the parameters entered (p_{ijkt}, s_{ijk}), i.e.,

$$\begin{aligned} E_{ijkt} = {} & [\{N_{ijk1} \times e_{ijk}\} \times (1 - p_{ikjt})] \\ & + [\{N_{ijk1} \times e_{ijk}\} \times p_{ijkt} \times (1 - s_{ijk})] \\ & + [\{N_{ijkt} \times e_{ijk}\} \times (1 - s_{ijk})] \end{aligned}$$

$$
\begin{aligned}
&- [\{N_{ijk1} \times e_{ijk}\} \times (1 - s_{ijk})] \\
&= [\{E_{ijk1}\} \times (1 - p_{ikjt})] \\
&+ [\{E_{ijk1}\} \times p_{ijkt} \times (1 - s_{ijk})] \\
&+ [\{E_{ijk1} \times (1 + g_{ijk})^{t-1}\} \times (1 - s_{ijk})] \\
&- [\{E_{ijk1}\} \times (1 - s_{ijk})] \qquad (17)
\end{aligned}
$$

Simplifying,

$$
\begin{aligned}
E_{ijkt} = E_{ijk1} \times [&\{s_{ijk} \times (1 - p_{ikjt})\} \\
&+ \{(1 - s_{ijk}) \times (1 + g_{ijk})t-1\}] \qquad (18)
\end{aligned}
$$

Eventually, aggregating the energy requirements over all the end-uses, sectors and sources or carriers, the total energy demand (in Equation 4) would be obtained, i.e.,

$$E_t = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{p} E_{ijkt}$$

■

Appendix 3. Macro-economic implications of the DEFENDUS approach

The requirement of energy in any sector of the economy is related to such factors as the production of that sector, the average energy prices, etc.,

i.e. $E = f(X_1, X_2, X_3, X_4, ..)$

where E is the requirement of energy, and the X_i are the determinants of demand.

Regarding the type of function, a multiplicative power function (analogous to a Cobb-Douglas production function) could be considered:

$$E = a\, X_1^b .\, X_2^c .\, X_3^d .\, X_4^e$$

so that $\ln E = a + b.\ln X_1 + c.\ln X_2 + . .$

It follows that from the coefficients b, c, etc., one can gauge the effect on the dependent variable of a change in the value of the corresponding independent variable, when the other independent variables are held constant. So, if X_1 is the gross domestic product from the relevant sector, then b denotes the *response* or *elasticity* of the quantity of energy required to a *stimulus* from sectoral production, *ceteris paribus.*

As an example of the regression analysis discussed in the text, consider the industrial sector of the state of Karnataka. The industrial electricity usage (both low tension and high tension) from 1969-70 to 1992-93 (E) was regressed on the industrial contribution to the state domestic product (G). The resulting equation obtained was

$$\ln E = 2.4177 + 0.5938 \ln G$$
$$R^2 = 0.77$$

Thus the elasticity of industrial electricity consumption with respect to industrial output was found to be 0.5938.

Using the above regression equation and the level of electricity demand according to the frozen efficiency scenario (which assumes no efficiency improvement), the corresponding estimate of industrial product was Rs.109.119 billion. This estimate can be considered the upper limit because the actual elasticity will turn out to be less when efficiency improvements are incorporated.

Since the energy end-use service levels are the same for both the DEFENDUS (efficiency improvement) scenario and the frozen efficiency DEFENDUS scenario (without efficiency improvement), the industrial output estimate corresponding to the frozen efficiency scenario, i.e., Rs.109.119 billion, can also be applicable for the DEFENDUS scenario with efficiency improvement. Taking this level of output and the electricity demand of the DEFENDUS scenario with efficiency improvement, the implied elasticity coefficient was found to be 0.5706. This reduction of the elasticity coefficient reflects the decrease in the energy requirement for the corresponding output level. ■

Notes

1. MARKAL was developed by the Brookhaven National Laboratory (USA) and Kernforschungsanlage Jülich (Germany) originally for IEA countries, but later used for Indonesia, Brazil and Mexico.
2. BESOM (Brookhaven Energy Systems Optimization Model) was developed by the Brookhaven National Laboratory for the USA, but also applied to Yugoslavia, South Korea and Greece.
3. Developed by the DFI (USA), the Argonne Energy Model was used initially in the USA and later applied to Portugal, South Korea and Argentina.
4. Karnataka is a state in south-western India.
5. A "scenario" is an intended or imagined sequence of events.
6. This project at the Department of Management Studies of the Indian Institute of Science (January 1988-July 1991) was funded by the Swedish International Development Agency (SIDA).
7. Personal communication (1994) – Arshad Khan, K.V. Ramani and Peter Hills.
8. At the national and state levels, typical policy instruments include the market (with its price mechanism) as a resource allocator or technology selector, administrative allocation (including rationing) of energy, capital and technology, subsidies, taxes, regulations and standards, information, research and development, and institution-building. At the firm level, the policy instruments may include awareness-creation as well as monetary and other incentives. Policy agents at the national, state and local levels would include governments, autonomous bodies and agencies, energy suppliers, and energy consumers.
9. Econometrics involves the application of mathematical and statistical techniques to economic problems.
10. This implies that the "utility" derived by each user from energy usage is fixed at the base-year level, but the total number of users increases.
11. Spreadsheet-based software (LOTUS 1-2-3, Supercalc, Quattro Pro, Excel, etc.) and financial calculators give instantaneous results for PVs and amortization; even iterative calculations for rates of return are accomplished quickly, eliminating the need for specifying algorithms.
12. The *order* in which the various technologies appear in the mix does not imply a chronological sequence. In fact, all the options that are needed to reach the energy requirement should be started *simultaneously.*
13. These are calculated to reflect the actual economic value of the inputs, rather than the administered prices (which could include additional subsidies or duties).
14. This is equivalent to the elasticity of energy requirement with respect to production.
15. If the energy consumption in this year is abnormal either due to some policy-imposed constraint (such as rationing) or natural causes (such as floods, earthquakes, etc.), this deviation from the normal should be adjusted suitably to obtain the "true" requirement.

16. Shifts from one energy source to another would also change the demand for the relevant energy sources.

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