CHAPTER 3
MITIGATION ASSESSMENT OF THE ENERGY SECTOR: AN OVERVIEW

3.1 INTRODUCTION

The energy sector is comprised of the major energy demand sectors (industry, residential and commercial, transport, and agriculture), and the energy supply sector, which consists of resource extraction, conversion, and delivery of energy products. GHG emissions occur at various points in the sector, from resource extraction to end use, and accordingly, options for mitigation exist at various points.

In most countries, the energy sector will be a major focus of GHG mitigation analysis. Globally, the energy sector is the predominant source of carbon dioxide (CO_2), the most important GHG. The combustion of fossil fuels accounts for about 60% to 90% of current net anthropogenic emissions of CO_2 emissions. The energy sector is also a source of the GHG methane (CH_4) and nitrous oxide (N_2O), and of other gases that may indirectly affect the earth's climate, such as nitrogen oxides (NO_x), carbon monoxide (CO), and non-methane hydrocarbons (NMHC). The production and transmission of coal, oil, and natural gas are estimated to account for about one-fifth of global methane emissions (IPCC, 1992).

The primary focus in Chapters 3-9 of this book is on “bottom-up”, least-cost analysis. This approach involves the development of scenarios based on energy end uses and evaluation of specific technologies that can satisfy demands for energy services. One can compare technologies based on their relative cost to achieve a unit of GHG reduction and other features of interest. This approach gives equal weight to both energy supply and energy demand options. A variety of screening criteria, including indicators of cost-effectiveness as well as non-economic concerns, can be used to identify and assess promising options, which can then be combined to create one or more mitigation scenarios. Mitigation scenarios are evaluated against the backdrop of a baseline scenario, which simulates the events assumed to take place in the absence of mitigation efforts. Mitigation scenarios can be designed to meet specific emission reduction targets or to simulate the effect of specific policy interventions. The results of a "bottom-up" assessment can then be linked to a "top-down" analysis of the impacts of energy sector scenarios on the macro-economy.

3.2 STRUCTURE OF AN ENERGY SECTOR MITIGATION ASSESSMENT

Mitigation analyses require physical and economic data about the energy system, GHG emissions, socio-economic variables, and specific technology options. Using these data, a model or accounting system of the energy sector should be designed to suit local circumstances.

The manner in which a mitigation assessment is performed will reflect each country’s resources, objectives, and decision-making process, and also the type of modeling approach employed. Figure 3-1 depicts the basic steps of a typical mitigation assessment and how they relate to one another. Some of the steps are interlinked, so they are not necessarily sequential, and require iterations.

An initial step is to assemble data for the base year on energy demand by sector, energy supply by type of energy source, and energy imports and exports. The disaggregated energy data should be normalized to match the national energy supply totals for the base year. One should then calibrate base year emissions with the existing GHG inventory, as available. The analyst should also assemble data for the base year on the technologies used in end-use sectors and in energy supply.

The data for the base year is used as a starting point for making projections of future parameters and developing integrated scenarios of energy demand and supply. On both the demand and supply sides, one should identify and screen potential technology options to select those that will be included in the analysis. The screening should be guided by information from an assessment of energy resources, as well as the potential for energy imports and exports.

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Once the list of technologies has been made manageable by the screening process, the analyst must characterize potential technology options in end-use sectors and in energy supply with respect to costs, performance, and other features. On the demand side, this characterization will assist in projecting end-use energy demands in the various sectors. Projecting energy demand also requires one to project activity levels in each subsector for indicators such as tonnes of various industrial products, demand for travel and freight transport, and number of urban and rural households. These projections should be based on the assumptions for growth in key parameters such as GDP and population. Assumptions about sectoral policies with respect to energy pricing and other factors are also important in developing projections of energy demand.

The data from the energy demand and supply analyses is then entered into an energy sector model or accounting framework that allows for integrated analysis of the various options that can meet energy requirements. This analysis should calculate costs and impacts over the time horizon considered, review the results for reasonableness, and account for uncertainty. This step involves combining technology options to meet the objectives of each scenario. The selection of technologies may be made directly by the analyst or performed by the model (as with an optimization model).

The baseline scenario projects energy use and emissions over the time horizon selected, reflecting the development of the national economy and energy system under the assumption that no policies are introduced to reduce emissions. The baseline scenario must include sufficient detail on future energy use patterns, energy production systems, and technology choices to enable the evaluation of specific mitigation options. Alternative baseline scenarios can be developed if desired (for example, to reflect different assumptions about GDP growth).

Mitigation scenarios can be defined to meet particular emission reduction targets, to assess the potential impact of particular policies or technologies, or to meet other objectives. The comparison of mitigation and baseline scenarios should reveal the net costs and impacts of the mitigation options. The results need to be assessed with respect to reasonableness and achievability, given barriers to implementation and the policy instruments that might be used, such as taxes, standards, or incentive programs.

For both baseline and mitigation scenarios, the analyst should assess the impacts on the macro-economy, social goals (such as employment), and the national environment. One approach is to integrate bottom-up assessment with a macroeconomic model. Decision analysis methods that allow for consideration of multiple criteria may also be appropriate.

Once attractive mitigation options have been identified and their impacts characterized, the analyst should assess policy options to encourage their adoption. In practice, some consideration of policy options would likely take place as part of development of mitigation scenarios. A mitigation scenario might assume that particular policies will be implemented in order to bring about certain results. These could range from efficiency standards on end-use equipment to policies regarding power sector investments.

After scenarios have been analyzed and options have been ranked in terms of their attractiveness (in both quantitative and qualitative terms), it is desirable to conduct a more detailed evaluation of policies that can encourage adoption of selected mitigation options. Such an evaluation can play an important role in the development of a national mitigation strategy. The latter step requires close communication between analysts, policy-makers, and other interested parties.

3.3 MODELS FOR ENERGY SECTOR MITIGATION ASSESSMENT

Assessment of opportunities for GHG mitigation in the energy sector requires an accounting or modeling framework to capture the interactions between technologies and to ensure consistency in the assessment of energy, emission, and cost impacts. Accounting and modeling methods can vary greatly in terms of their sophistication, data intensiveness, and complexity. This section provides an overview of key concepts and capabilities of a number of models that are available for mitigation analysis. These models have already been used in energy/environmental studies in various developing countries.

As discussed in Chapter 2, it is common to divide energy-economy models into two types, so-called "bottom-up" and "top-down," depending upon their representation of technology, markets, and decision-making. In practice, there is a continuum of models, each combining technological and economic elements in different ways. At one extreme are "pure" energy models, which focus upon fuels and energy conversion or end-use technologies and treat the rest of the economy in an aggregated fashion. At the other extreme are "pure" economic models, which treat energy markets and technologies in an aggregated manner and focus instead upon economy-wide supply-demand relations and optimizing behavior. Between these two types are a number of models that combine elements of both extremes with various degrees of emphasis and detail.

The description of the future varies among the models. Some models can only analyze a "snapshot" year, and compare this to another year, without any representation of the transition between them. Dynamic models, on the other hand, allow for time-dependent descriptions of the different elements of the energy system. While the "snapshot" models enable great detail in the representation of the system, dynamic models allow for representation of technology capacity transfer between time periods and thus time-dependent capacity expansion, time-dependent depletion of resources, and abatement costs as they vary over time.

In dynamic modeling, information about future costs and prices of energy is available through two diametrically different foresight assumptions. With “myopic foresight”, the decisions in the model are made on a year-by-year basis, reflecting the assumption that actors expect current prices to prevail indefinitely. Assuming "perfect foresight", the decisions at any year are based on the data for the entire time horizon. The model thus reflects the activities of market participants as if they use the model itself to predict prices.

The key design features of the models described in this book are summarized in Table 3-1. Most of the models listed in Table 3-1 can be used to integrate data on energy demand and supply. This information can be used by the models for determining an optimal or equilibrium mix of energy supply and demand options. The various models use cost information to different degrees and provide for different levels of integration between the energy sector and the overall economy.

In addition to the models listed in Table 3-1, we briefly describe a decision analysis methodology known as the "Analytical Hierarchy Process." It can be used to evaluate and rank options according to a combination of quantitative and qualitative criteria.

3.3.1 Energy Accounting Models

Energy accounting models such as LEAP and STAIR reflect an engineering or "input-output" conception of the relations among energy, technology, and the services they combine to produce. This view is based on the concept of energy services that are demanded by end users. Schematically, this can be represented as:

Energy inputs _ Technology _ Energy services _

For policy purposes, the significance of this approach is that a given type and level of energy service can be obtained through various combinations of energy inputs and technologies. In particular,

Table 3-1 here (full page)

holding the service constant while increasing the energy efficiency of the technology allows decrease in the required level of energy input. In a range of cases, when other factors are held equal, this lowers the overall cost of the energy service. In addition, the lower energy input requirement in general means lower levels of GHG emissions. With accounting models, the evaluation and comparison of policies are performed by the analyst external to the model itself.

These models are essentially elaborations upon the following accounting identity describing the energy required for satisfying a given level of a specific energy service:

$$E = AI$$

where E indicates energy, A activity, and I intensity. With multiple end uses, aggregate energy demand is

$$E = \sum_i A_i \quad I_i$$

simply the sum:

Accounting models are basically spreadsheet programs in which energy flows and related information such as carbon emissions are tracked through such identities. The interpretation of the results, and the ranking of different policies quantified in this manner, is external to the model and relies primarily on the judgment of the analyst.

Using such a model, a stylized typical analysis might proceed as follows. Using the notation above, suppose that I_i and I_i^* represent the energy intensities of current and more energy-efficient technologies, respectively. If the incremental capital and maintenance cost of shifting to the efficient technology is C for each I and the (levelized) price of energy is q, then the energy savings available from switching to the efficient technology is estimated as

$$\Delta E = \sum_i A_i \left(I_i - I_i^* \right)$$

$$\Delta C = \sum_i A_i \left[q \left(I_i - I_i^* \right) - C_i \right]$$

and the associated cost saving is

Note that these calculations assume that a number of factors are held constant, including energy service level and equipment saturations. Also, these expressions represent a "quasi-static" view; in actual practice, such calculations would be performed over time paths of costs, activities, intensities, and prices developed in scenario construction. Finally, it is easy to see that factors for carbon savings from the shift to efficient technologies could be easily included in such calculations.

In energy accounting models, macroeconomic factors enter only as inputs in deriving demand-side projections; that is, there is no explicit representation of feedback from the energy sector to the overall economy. While different models contain different levels of detail in representing the supply sector, supply-demand balancing in this type of model is accomplished by back calculation of supply from demand projections.

The energy accounting models STAIR (Sathaye *et al.* 1989), developed at the Lawrence Berkeley Laboratory, and LEAP (SEI-B, 1993), developed at the Tellus Institute, have both been widely used in developing countries to conduct energy planning, investigate carbon mitigation strategies, and study other environmental policy problems. Associated with LEAP is the Environmental Database, which contains extensive information on energy/environmental linkages.

The STAIR and LEAP models can simulate the effect of selected mitigation options on overall costs and emissions. In contrast to optimization models, they cannot easily generate a least-cost mitigation solution. They can be used to represent cost-minimizing behavior estimated by the analyst, however. They tend to require less data and expertise, and are simpler and easier to use than optimization models. See Appendices A and B for further discussion.

3.3.2 Engineering Optimization Models

In engineering optimization models, such as ETO and MARKAL, the model itself provides a numerical assessment and comparison of different policies. These models are linear programs in which the most basic criterion is total cost of providing economy-wide energy services under different scenarios; when this criterion is used, the structure of this type of model as used in mitigation analysis can be represented schematically as:

Minimize total cost of providing energy and satisfying end-use demand subject to:

- energy supplied $\geq$ energy demanded
- end-use demands satisfied
- available resource limits not exceeded

In addition to the overall optimization structure of these models, the key distinction between these and the accounting models is that, within the model structure itself, trade-offs are made among different means of satisfying given end-use demands for energy services.

There is variation in the intertemporal structure of these linear programming models. Some are constructed to perform a "target year" analysis: the model is first parameterized and run for the base year, then the procedure is repeated for a single designated future year (typically 2005 or 2010). Others perform a more elaborate dynamic optimization in which time paths of the parameters are incorporated and the model generates time paths of solutions.

In engineering optimization models, macroeconomic factors enter in two ways. First, they are used to construct forecasts of useful energy demands. Second, they can be introduced as constraints. For example, the overall cost-minimization can be constrained by limits on foreign exchange or capital resources. In both cases, the models do not provide for the representation of feedbacks from the energy sector to the overall economy.

Supply and demand are balanced in engineering optimization models by the presence of constraints, as indicated above. The engineering detail and level of disaggregation used in both the supply and demand side are at the discretion of the user, and in practice these vary widely among models.

This type of model allows several means of analyzing GHG emissions and the effects thereupon of various policy options. For example, as an alternative to minimizing energy costs, criteria such as minimizing carbon output subject to the constraints can be employed. In addition, an overall cap on carbon emissions can be entered as a constraint in the model, and the cost-minimization performed with this restriction. Each such approach allows the comparison of different policy intervention.

ETO was developed in India and at the Lawrence Berkeley Laboratory, while MARKAL was developed at Brookhaven National Laboratory. ETO has been applied to analyses of energy efficiency and carbon reduction scenarios in India, Brazil, and China (Mongia *et al.* 1991, La Rovere *et al.* 1994). MARKAL has been applied to energy and environmental analysis by over thirty users in twenty countries, with new countries currently undertaking its development (Manne *et al*. 1992).

3.3.3 An Iterative Equilibrium Model

The Energy and Power Evaluation Program (ENPEP) model, developed at Argonne National Laboratory, incorporates the dynamics of market processes related to energy via an explicit representation of market equilibrium, that is, the balancing of supply and demand (Buehring *et al.* 1994). ENPEP is used to model a country's total energy system and does not explicitly include an economy model integrated with the energy system model. Thus, macroeconomic factors enter the model exogenously, as in the previous model types discussed. (That is, demands for energy services are derived from macroeconomic drivers rather than being obtained endogenously.) ENPEP thus occupies an intermediate position between engineering, energy-focused models, and pure equilibrium models.

ENPEP has been used to do total energy system analysis and electric sector studies in a wide range of developing countries. It is organized in modular form for flexibility and ease-of-use. Among the modules are a library of technical data on electricity generation technologies, a detailed representation of a specified electric power sector, and module for separating electricity demand from overall energy demand. Thus, depending on the application, ENPEP's representation (particularly as regards the electric generation sector) can be quite detailed. The methodology employed to solve the model is a "process network" wherein individual energy processes are represented with standard model forms, but application-specific data, and linked together as appropriate. Prices and quantities are then adjusted iteratively until equilibrium is achieved. This iterative approach makes it much easier to include non-competitive-market factors in the system than in the optimization approach.

3.3.4 Hybrid Models

In hybrid models, such as MARKAL-MACRO and ETA-MACRO, the basic policy measure is the maximization of the present value of the utility of a representative consumer through the model planning horizon. Constraints are of two types: macroeconomic relations among capital, labor, and forms of energy, and energy system constraints. The model generates different time paths of energy use and costs and macroeconomic investment and output. The energy sub-model contains representations of end-use technologies, with different models containing different levels of detail. Schematically, this type of model can be represented as:

Maximize (discounted) utility of consumption subject to:

- macroeconomic relations among output, investment, capital, labor, and energy;
- energy system and resource constraints (as in engineering optimization models).

The constraints in this case are also dynamic: they represent time paths for the model variables.

In this type of model, energy demands are endogenous to the model rather than imposed exogenously by the analyst. In addition, this optimization structure indicates the difference we noted above in the way the different models incorporate macroeconomic data. Specifically, in accounting and engineering optimization models, these data—on GDP, population growth, capital resources, etc.—enter essentially in the underlying constructions of the baseline and policy scenarios, as discussed in previous chapters. In the hybrid model, however, such data enter in the "macroeconomic relations" (technically, the aggregate production function) as elasticities and other parameters. Within this model framework, changes in energy demand and supply can feed back to affect macroeconomic factors. It should be noted that, despite their inclusion of engineering optimization sub-components, these models typically do not contain as much detail on specific end-use technologies as many purely engineering models.

The ETA-MACRO model has been used for energy-environmental planning in a number of different countries and provides the core of the regional energy-economy modules included in the Manne-Richels Global 2100 carbon emission analysis model (Manne and Richels 1992). This model combines an aggregate process analysis model of electric and non-electric energy production with a aggregate economy-wide production function with labor, capital, electric, and non-electric energy inputs. The strength of this model is its ability to represent a number of fundamental energy-economy relationships with a minimal set of input data. In addition to cost data on electric and non-electric generation, the model only requires a few macroeconomic inputs (e.g., labor force participation and productivity growth rates), resource inputs (e.g., oil and gas resources), and macroeconomic behavioral parameters (e.g., the rate of substitution between energy and other inputs into the economy).

MARKAL-MACRO, developed at Stanford University and the Brookhaven National Laboratory, also provides an integrated representation of macroeconomic relations and energy technology processes (Manne *et al.* 1992). This model, however, contains much greater detail in the end-use or process analysis component. It can address conservation and energy-efficiency changes in end-use devices directly. The model-wide objective function combines with the cost-minimization in the linear programming sub-model, which ensures that energy demands are satisfied at least cost (both on the supply and the demand sides). This model represents the most complete effort to-date to combine the "top-down" and "bottom-up" approaches. MARKAL-MACRO has been applied in the United States and is currently being used in ten countries participating in the International Energy Agency's Energy Technology Systems Assessment Programme.

3.3.5 "Top-down" Models

Top-down models focus on economic equilibria, with less emphasis upon details of energy technology and end-use analysis. They are built upon the assumptions of competitive equilibrium and optimizing behavior on the part of consumers and firms. They differ from hybrid models in being based upon general equilibrium rather than neoclassical growth theory, and in eschewing detailed engineering sub-components for energy system representation. While theoretically capable of including deviations from these assumptions in the form of representations of "imperfect competition," such developments have not been pursued in the context of energy analysis.

The MIMEC model has been used to study development, energy, and environmental policy in Egypt and India (Eckhaus and Lahiri 1994). A distinctive feature of this model is the use of a process analysis form of input-output analysis to summarize the production possibilities of the economy. In the two applications, ten sector (Egypt) and eighteen sector (India) input-output tables were constructed using historical data; various substitution elasticity estimates were used to develop alternative input vectors for producing the output of the sector in question; and input vectors for alternative technologies (those that have been introduced, but are not yet in widespread use) were included directly. The selection of technology for the production of the output of each sector depends on the relative costs of the inputs to it. The MIMEC model is capable of addressing information on costs and energy savings by technology type for selected industries. Thus, in-depth analysis of selected industries can be linked through this model to overall economic activity. The analysis of other sectors cannot be explicitly represented in this model. The model chooses a mix of products that maximizes the discounted utility of consumption of a representative consumer with a linear expenditure system underlying the model of consumer behavior.

The LBL-CGE model is a multi-sector computable general equilibrium model designed for analyzing energy and environment policies. It focuses on macroeconomic effects of investment in the energy sector and also on effects of energy price increases on energy consumption in different sectors of the economy. The above are contrasted with effects of investment in improving energy efficiency. The energy/economy interaction is modeled by dividing the economy into materials and energy sectors. The materials sector is subdivided into agriculture, basic industry, other industry, construction, transport, and the services sector. The energy sector is divided into crude extraction, natural gas, electricity and petroleum products. The model allows for interfuel substitution both in production activities as well as in household consumption. Overall energy consumption is assumed to be sensitive with respect to prices and investment in energy efficiency. The effects of policies are analyzed on different points of time in a comparative static framework. Unlike MIMEC, continuous functions rather than process analysis are used to represent production possibilities. It is proposed to experiment with alternative functional forms and nesting schemes for modeling production technology.

3.3.6 Decision Analysis Methodology

The Analytical Hierarchy Process, or AHP, is a decision analysis tool that allows the explicit application of both quantitative and qualitative policy criteria. It includes a technique for weighing different criteria in combinations according to the judgment of the analyst. Possible criteria include cost (life-cycle and capital), resource availability, social acceptance, state-of-development, environmental impact, and infrastructure requirements. The AHP has been applied by the U.S. National Renewable Energy Laboratory to the study of renewable energy technologies in Mexico.

3.4 KEY STEPS IN THE MODELING PROCESS

The modeling process typically consists of a number of interrelated steps. Seven key steps in the process are briefly discussed here: (1) determining model objectives, (2) model formulation, (3) data collection, (4) data analysis, (5) model calibration, (6) model implementation, and (7) sensitivity analysis.

The first step in the model building process is typically the selection of one or more objectives for the analysis. For example, if carbon emissions are to be addressed in a model, are costs and benefits of carbon emissions to be balanced? Are emissions to be reduced a specified amount at minimum cost? Are the impacts of various policies on carbon emissions to be traced? If benefits, costs, or impacts are to be considered, how are they to be measured?

The choice of objective(s) places some restrictions on the model formulation, but a number of alternatives are still generally feasible. Should the model be formulated to optimize some objective, to compute an energy, or economy-wide equilibrium, or simply to simulate the evolution of the market as various external forces and policies evolve? Crucial decisions made here include the amount of geographic, and sectoral aggregation, the time horizon, the disaggregation of time into time periods, the amount of foresight to attribute to various economic actors, and the decision rules used by those actors.

These considerations influence the decision among energy accounting, engineering optimization, and economic optimization models. In the accounting models, the comparison among policies, including cost-benefit calculations, is carried out externally by the analyst. In the engineering optimization models, minimum costs associated with different energy sector configurations are computed by the model, but these are not explicitly integrated with the larger economy. The hybrid models provide integrated optimization within the model itself, thereby enabling the analyst to rank policies directly.

Steps three and four address data collection and analysis. Model formulation is often constrained by the amount and quality of the data available. Two types of data may be employed: (1) historical economic data regarding economic activity, amounts of labor, capital, materials, and energy consumed, and (2) engineering data concerning the costs of existing and likely future technologies. Once data has been collected it may be analyzed in a number of ways. It may simply be checked for quality, or statistical methods may be used to estimate relationships between key economic parameters.

Data considerations also differ among different types of models. In the more engineering-focussed models, input-output data on energy use and efficiency can be the primary need, with only aggregate macroeconomic data required to derive forecasts. In models that employ more detailed economic elements, estimates of parameters such as elasticities of substitution are also required. The latter can dictate more sophisticated statistical methods for model implementation.

When the necessary data have been introduced into the model, it is then usually necessary to calibrate it to base year conditions. Of course, if credible independent estimates of enough of these parameters are available, care must be taken to calibrate by varying the least reliable parameter values.

Once the model has been calibrated, it is usually embedded in a user-friendly computer environment to allow inputs to be changed and outputs observed easily, and the model to be solved efficiently. Once the model has been implemented, extensive sensitivity analyses are usually run to determine to which inputs the model outputs of interest are most sensitive. This yields information of use to policy-developers and gives the user more or less confidence in the model, depending on how the results square with intuition. Sensitivity analyses, thus, form an important part of the model assessment process, which also includes third-party review of the data and formulation of the model and comparisons of the results it produces with those produced by other models with the same objectives.

3.5 KEY CHALLENGES IN THE MODELING PROCESS

A number of key challenges must be met in order to proceed through the model-building process successfully. Each modeling project confronts its own unique set of challenges, but some appear to be common to almost any effort. These include (1) incorporating efficiency versus equity; (2) aggregation over time, regions, sectors, and consumers; (3) representing decision rules used by consumers; (4) incorporating technical change; (5) capturing facility retirement dynamics; (6) avoiding extreme solutions; and (7) accounting for carbon flows.

None of the models we have discussed provides explicitly for making trade-offs between efficiency and equity. Different models, however, have different implications for the analyst's consideration of this important issue. Non-optimization models do not themselves choose among different policies in an explicit way, but can allow for the ranking of policies according to criteria specified by the analyst, including considerations of equity. Engineering optimization models, since they focus on least-cost solutions to the provision of energy services, leave to the analyst the judgment of how to trade off the importance of energy with that of other economic and social priorities. The models which optimize the utility of a representative consumer, in a sense, constrain consideration of the issue the most. Embedded in this modeling structure is a view of the economic system that equates social optima with competitive economic equilibria; the appropriateness of this perspective in the application at hand must be weighed in selecting a model.

Perhaps the most fundamental formulation issues faced by the model-builder involve the level of aggregation at which costs and benefits are calculated. Economic efficiency is generally insured if discounted benefits less costs are maximized in the aggregate and any desired income re-distribution is handled subsequently. The models described here do not explicitly examine equity considerations; these would have to be examined outside the model. Decision-makers, however, are fundamentally interested in how the costs and benefits fall on various income, industry, and regional groups. Coupled with the relative emphasis of the analysis on equity versus efficiency is the desired level of disaggregation of the model by region, time periods, industry, and income group. Obviously, the level of disaggregation must be sufficient to allow reporting of results at the desired level. If possible, it is important to capture the heterogeneity in decision-making on the part of the different groups. Decision rules are critical elements of the models and range from minimizing discounted future costs (or maximizing benefits) over a 40- or 50-year time horizon to picking investments that come close to minimizing costs based on conditions for a single year only (which is more typical of the LBL-CGE model).

Accounting models contain no explicit representation of consumer decision-making. In practice, however, their use often reflects the view that certain "market barriers" constrain consumers from making optimal decisions with respect to energy efficiency. At the other extreme, the use of the "representative consumer" in the optimization models rests upon very strong assumptions regarding consumer behavior. Key among these is the assumption of perfect foresight. It is also important to note that this method of representing the aggregate outcome of individual decision-making serves primarily to ensure mathematical and empirical tractability, and has only weak theoretical justification as a model of market processes.

Another set of key assumptions about inputs are those made about the costs and efficiencies of current and future technologies**,** both for energy supply and energy use. Most analysts use a combination of statistical analysis of historical data on the demand for individual fuels and a process analysis of individual technologies in use or under development to represent trends in energy technologies. At some point these two approaches tend to look similar, as the end-use process analysis usually runs out of new technology concepts after several decades, and it is then assumed that the efficiency of the most efficient technologies will continue to improve as time goes on. Particularly important, but difficult, here is projecting technological progress. Attempts to empirically estimate the dependence of future trends in productivity on factor prices, including energy, are rare.

Most current modeling approaches focus on investments in new energy-producing and -consuming equipment, which is typically assumed to have a fixed useful lifetime. In scenarios where conditions change significantly (either through external factors or explicit policy initiatives), it may be economical to retire facilities earlier or later than dictated purely by physical depreciation rates. This endogenous calculation of facility retirement dates can be handled analytically in most models, but represents a major increase in data and computational requirements.

Another typical problem, particularly with models that assume optimizing behavior on the part of individual economic agents, such as MARKAL-MACRO and MIMEC, is the danger of "knife edge" results, where a few cents difference in the cost of two competing technologies can lead to picking the cheaper one. This is generally handled by disaggregating consumers into different groups who see somewhat different prices for the same technology (e.g., coal is cheaper in the coal fields than a thousand miles away), modeling the decision process as somewhat less than perfect, and/or building appropriate time lags into the modeling structure.

Finally, estimating carbon flows for a given energy system configuration can be complicated. It is more accurate to measure emissions as close to the point of combustion as possible so types of coal and oil products can be distinguished and feedstocks (which do not necessarily produce carbon emissions) can be netted out. However, a point of use model requires far more data and computation than the models described here which aggregate several fuel types and use average carbon emissions factors for each fossil fuel.

3.6 SELECTION AND USABILITY OF MODELS FOR MITIGATION ASSESSMENT

The selection of an appropriate model depends on the purpose for which the model will be used and the data and human resources available to make proper use of it. It is important to list the questions that the model will be used to address, in order of priority, prior to selecting a model.

The models described in this chapter differ in their application for mitigation studies among countries. Several usability criteria appear to be critical, but how critical each criterion is depends on the analytic environment in the country under consideration, e.g., Ph.D. economists may be plentiful in some countries but scarce in others. Table 3-2 shows how the models considered in this chapter can be scored on several usability criteria, which are further discussed below.

Data requirements**.** The selection of a model for mitigation assessment needs to be guided by the data that are already available and those that might be collectable within the time period of the assessment. A mitigation assessment requires that data be collected for various energy forms and on the technical characteristics of mitigation measures. Switching to less-carbon-intensive fuels and more efficient supply and use of energy are two basic types of mitigation opportunities. Switching includes the use of renewables. The availability of data for both renewables and energy-efficiency opportunities is inadequate in most developing and transitional countries, as official data collection is primarily focused on conventional fuels.

An energy accounting model (STAIR or LEAP) has the simplest framework which can be used for mitigation assessment with the minimum of non-energy data. But even in this case, if a mitigation assessment requires the evaluation of costs, then data on cost of individual options is needed. Most countries have energy balances, but a mitigation assessment will need data well beyond these, and an analyst needs to bear this fact in mind before attempting a detailed mitigation assessment.

The other bottom-up models (ETO, MARKAL and ENPEP) require increasingly more sophisticated data sets. Since the optimization models rank options on the basis of their costs of providing energy services, reliable estimates of costs become crucial to the least-cost selection of technology options. The ENPEP model complicates this further by requiring both supply and demand curves for each type of fuel. Gathering data for these curves can be difficult when future resources are not known with much certainty.

The hardware and software requirements for each model can be crucial in the early stages of model development, but these may be the easiest constraints to surmount as computer costs fall and the requisite computer infrastructure (particularly as regards technical support services) develops in each country.

The ease of modifying the source code of the models varies considerably. LEAP and ENPEP use a proprietary software code and a user cannot access the model code and make changes to it. STAIR and ETO, on the other hand, use an open structure whereby the user can make changes to the code. STAIR uses either Lotus 123 or Symphony and ETO uses the GAMS software. MARKAL and MARKAL-MACRO are also programmed using GAMS, and the user can in principal access the source code and make changes to it.

The advantage of being able to change the code is that the user can change the type of output desired from the model. For instance, if the user wishes to focus on capital investment and foreign exchange in addition to estimating the costs of providing energy services, he/she can make the changes to the ETO code to serve this purpose. Changing the source code requires a detailed understanding of the structure of the software and should only be done by a skilled modeler.

Table 3-2 here

A disadvantage of changing the software is that the software will not be identical across all users, which complicates comparison of results. Modifications of the source code without guidance from the software provider/developer will also make support and maintenance difficult. Some of the models also have a high degree of "built-in" flexibility; for example, in MARKAL an option of providing user-defined equations is included. The modular design of ENPEP also allows the user a high degree of flexibility.

Ease of modification of input data and processing of results. Both ENPEP and MARKAL/MARKAL-MACRO are provided with menu-driven user interfaces that simplify modification of input data and structuring of the model. For both systems, demonstration cases with default data are provided. These interfaces also organize file handling and execution of runs and include result processing menus for both tabular and graphical display. A similar menu-driven data entry system is provided with LEAP, which also includes a flexible graphics reporting system.

ETO and LBL-CGE do not have any specialized user interface. In both cases, modification of data is done directly in the GAMS input file. The results are checked and processed through investigation of the output file produced by GAMS. For presentation and analysis of the results, the GAMS output file can be modified and imported to spreadsheet software like Excel.

Incorporation of non-market factors. For some countries, a significant issue can be incorporating factors other than those that lead to competitive market equilibrium solutions. Typically, optimization models can compute a competitive equilibrium market solution quite efficiently, but they must be modified, sometimes substantially, to include factors that depart from the competitive equilibrium paradigm. Models which search iteratively for an equilibrium solution are generally less efficient in finding competitive equilibria, but easier to modify to take into account non-competitive market factors. One prime example of an important non-competitive market factor is average cost pricing for electricity. The optimization models must be modified to convert the marginal cost prices they produce automatically into average cost prices, while the iterative equilibrium models can accommodate any desired pricing rule directly. The accounting models, since they are not based upon the equilibrium concept, do not run into these problems directly.

3.6.1 The Types of Questions That Each Model Can Best Address

Following are some key questions that an analyst would seek to answer in a mitigation assessment:

1. What is the economic cost of providing energy services in a baseline or mitigation scenario? What is the incremental cost between scenarios?

1a. What are the capital and foreign exchange implications of pursuing alternative scenarios?

2. What is the economic cost of pursuing particular mitigation options, such as high-efficiency lighting or a renewable technology, and what are its carbon implications?

3. What are the costs of reducing carbon emissions to a predetermined target level? (Target may be annual or cumulative.)

4. What is the shape of the marginal cost curve for reducing carbon emissions?

4a. How do alternative technologies rank in terms of their carbon abatement potential?

Any one of the three types of models discussed above can address questions 1 and 2.[1] However, only the ETO model is currently set up to address the foreign exchange component of question 1a, which is important for developing country planners.

Question 3 is easiest to address using an optimization model. The other models may require several runs to come up with an answer. Of the two optimization models, MARKAL is a dynamic model, while ETO focuses on a target year. MARKAL can evaluate the impacts of a cumulative carbon constraint, as well as annual constraints changing over time. Both models can evaluate target-year constraints.

Question 4 requires that energy supply and demand be evaluated in an integrated manner. A demand-side mitigation measure may change the energy supply configuration measure, which will affect the GHG emissions of the energy system. The optimization and iterative models are capable of capturing the integrated effect and deriving the changes in carbon emissions. The accounting models may not capture the changes in the energy supply mix and the consequent GHG emissions, and thus may show higher emissions reduction for a mitigation measure. Only the optimization models can calculate marginal costs directly. In the other models, an approximation of the marginal cost curve can be constructed by performing a large number of carefully selected runs (see discussion of cost curves in Chapter 2).

3.7 DESIGNING AND SETTING UP A BOTTOM-UP ANALYSIS

The first step in conducting a mitigation analysis is to begin the collection of relevant data. The analyst must also define several key parameters that will guide data collection and analysis, such as the base year and the time horizon of the study. Data are then assembled in a modeling or accounting framework, which should be designed to reflect local conditions and priorities. In order to ensure consistency, the detailed data should be calibrated to match official aggregate energy supply totals and any existing GHG inventory.

The exact data requirements for a given study will depend on the nature of the energy demand and supply model that the analyst develops. Development of the model structure and relationships, in turn, depends upon the availability of disaggregated data, local circumstances and priorities, the relative importance of sectors and end uses in terms of current and projected GHG emissions, and the specific mitigation options that will be considered. As a consequence, data collection, the specification of model structure, and the screening of mitigation options are interdependent and thus iterative tasks.

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[1] Each of the models described above currently ranks or selects technological options, or can do so, on the basis of their net present value or annualized energy cost. The models thus assume that energy costs determine the choice among demand- and supply-side technologies and processes. In the optimization models ETO and MARKAL, technologies can also be selected on the basis of total cost of industrial production, which assumes that industries make their technology choices on the basis of total production cost rather than energy cost alone.

Two key considerations are the choice of discount rates and the definition of which costs and benefits to include in the analysis. Direct economic costs include the costs for equipment, operations and maintenance, and energy resources. The analyst might want to estimate the administrative and program costs associated with measures to encourage adoption of mitigation technologies and practices.[2] The analyst must also decide whether less tangible social and environmental costs will be included.

3.7.1 Data Collection

Regardless of the approach taken and analysis tool used, the collection of reliable data is a major and relatively time-consuming aspect of mitigation analysis. In order to keep data constraints from becoming a serious obstacle to the analysis, two points are essential. First, modeling tools should be sufficiently flexible to adapt to local data constraints. Second, the data collection process should be as efficient as possible. Efficiency can be maximized by focusing the detailed analysis on sectors and end uses where the potential for GHG mitigation is most significant and avoiding detailed data collection and analysis in other sectors.

Data collection generally begins with the aggregate annual energy use and production figures typically found on a national energy balance sheet. The remaining data requirements will depend largely on (a) the disaggregated structure of the analysis; (b) the specific mitigation options considered; and (c) local conditions and priorities.

The typical types of data needed for a bottom-up approach to mitigation analysis are shown in Table 3-3. They tend to fall within five general categories: macroeconomic and socioeconomic data; energy demand data; energy supply data; technology data; and emission factor data. The full listing of potential data requirements may appear rather daunting. In practice, however, much of the data needed may already be available in the form of national statistics, existing analytical tools, and data developed for previous energy sector studies. The development and agreement on baseline projections of key variables, the characterization of mitigation options relevant to local conditions, and, if not already available, the compilation of disaggregated energy demand data are typically the most challenging data collection tasks facing the analyst.

In general, emphasis should be placed on locally derived data. The primary data sources for most mitigation assessments that are carried out over a period of around one year will be existing energy balances, industry-specific studies, household energy surveys, electric utility company data on customer load profiles, oil company data on fuel supply, historical fuel price series maintained by government departments, vehicle statistics kept by the transportation department, etc. The main thrust of the data collection effort is not so much on collecting new primary data but on collating secondary data and establishing a consistent data set suitable for analysis using the model of choice.

Where unavailable, local data can be supplemented with judiciously selected data from other countries. For example, current and projected cost and performance data for some mitigation technologies (e.g., high-efficiency motors or combined-cycle gas units) may be unavailable locally, particularly if the

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[2] To specify these costs more precisely would generally require that the exact mechanism or program for efficiency improvement be identified. For the purpose of an initial mitigation analysis, simple assumptions will generally suffice and can be modified once specific programs are evaluated.

technologies are not presently in wide use. For this purpose, technology data from other countries can provide indicative figures and a reasonable starting point. For data on energy use patterns, such as the fraction of electricity used for motor drive in the textile industry, the use of external data can be somewhat more problematic. In general, it may be possible to use estimates and general rules of thumb suggested by other country studies, particularly data from other countries with similar characteristics.

Table 3-3 here (full page)

3.7.2 Selecting and Characterizing Technology Options to Include in the Analysis

The criteria for judging whether a specific option should be included in a mitigation analysis must encompass social, political, and cultural factors in addition to standard economic concerns. GHG mitigation must be integrated with other key national objectives, such as improving the balance of payments or promoting rural development. Some of the potential criteria that could be used for evaluating mitigation options are listed in Chapter 2. The final specification of screening criteria—and weighing the relative importance of those criteria—will depend on local conditions and priorities.

Using a broad set of screening criteria to weed out unpromising, undesirable, or infeasible options requires considerable judgment. Many criteria will likely be qualitative and difficult to measure in an objective fashion. An obvious reason for screening out an option might be the infeasibility of its wide-scale application. Location of options—e.g., fuel resource options or power plants—in environmentally or otherwise sensitive areas may rule them out. There might also be overriding concerns about political acceptability. In addition, there may be options, such as reducing traffic congestion, which may be difficult to analyze since quantifying the impact on GHG emissions may be difficult to do.

Mitigation technology options can be identified from a variety of sources: country case studies, literature review, and international data bases such as those prepared by the IPCC and the International Institute for Applied Systems Analysis (IIASA) (see Box 3-1). If derived from studies in other countries, the cost, performance, and emission characteristics of specific options should be reviewed for their relevance in the local situation.

Box 3-1. Data Sources on Technologies for Reducing GHG Emissions

Two sources of information that may be useful in a mitigation assessment are the *IIASA* CO_2 *Technology Data Bank (CO2DB)*, developed by the International Institute for Applied Systems Analysis in Austria, and the *Inventory of Technologies, Methods, and Practices for Reducing Emissions of GHG*, prepared for the IPCC by the U.S. Department of Energy and the Environmental Protection Agency. Both of these sources contain a consistent set of information on many energy supply and end-use technologies. They each describe technical, economic, and environmental characteristics of the various technologies. The IPCC *Inventory* also describes implementation requirements (labor and infrastructure).

The *CO2DB* presently contains data on about 350 technologies, including conventional as well as more advanced technologies. The IPCC *Inventory* currently contains 43 energy supply and 44 end-use technologies, and is focused more on advanced technologies. The source country for most of the information in the IPCC *Inventory* is the U.S., while the *CO2DB* is more oriented toward European sources. To enhance the usability of the technology data bank, IIASA has developed a fully interactive software package that simplifies retrieval of information.

The key data required for each technology are life-cycle costs (including capital, fuel, and operation and maintenance), energy consumption or production features, lifetime, and environmental characteristics. For end-use technologies, costs can be entered in terms of costs of conserved energy (CCE) for efficiency improvements or the costs of specific equipment. For energy supply technologies, cost data can be entered in different formats depending on how the model is structured. These options include specifying combined costs per unit of energy produced (e.g., cost per kWh) or specific capital, fixed and variable operating and maintenance (O&M), and financing costs by plant type. It may not always be possible to enter all of the relevant data in a particular model, but it is important to have a convenient means of storing such information so it may be used in a multi-criteria assessment.

One approach for characterizing mitigation options is to employ individual experts with detailed knowledge of specific sectors. For example, a mitigation scenario analysis conducted for the U.S. involved teams of sector specialists who conducted separate analyses of technical and policy options for the buildings, transport, industrial, and energy supply sectors, using a common screening approach (UCS *et al.*, 1991). These sectoral analyses generated the cost and penetration rate estimates for selected options that were then entered into the LEAP model as data for the integrated scenario analysis.

3.7.3 Design of Model Structures

The development of demand and supply modeling (or accounting) structures is generally performed in parallel with the data collection process. The principal objectives in developing a model structure are: (a) to represent the national energy system and the major factors that influence its development, and (b) to include a sufficient level of detail to permit the analysis of selected mitigation options. For instance, where irrigated agriculture accounts for a significant share of electricity consumption and related GHG emissions, the model structure might include greater end-use detail in the agricultural sector to enable the evaluation of options such as improved pumpsets or more effective water delivery. In other countries, such model structure and data requirements might be irrelevant. In general, modeling (or accounting) structures should be tailored to local circumstances.

High levels of disaggregation and detailed data structure are characteristic of end-use approaches. While disaggregated data can help in evaluating specific technological options, excessive data disaggregation can be an analytical burden. Where local data are scarce or unreliable and are augmented by the use of secondary data or assumptions, the better resolution otherwise provided by disaggregation is lost in the fuzziness caused by the data. An efficient solution can be to use higher resolution disaggregated approaches in key sectors or subsectors where the potential for cost-effective GHG mitigation appears high. Less detailed methods can be used to provide a broader overview in other sectors.

3.7.3.1 Energy demand structure

The way in which energy demands are represented varies somewhat among different models. An example of a demand analysis structure (from the LEAP Demand program) is shown in Figure 3-2. To develop such a structure, the analyst must:

- **Design a “branch structure**.” The analyst specifies the demand sectors (e.g., residential, industry, and transport) to be modeled, then breaks down each sector, to the degree desired and appropriate, into subsectors (e.g., iron and steel production, chemicals, etc.), end-uses (e.g., motive power, process heat) and devices (e.g., electric motors, furnaces, boilers, etc.) as necessary. Each of the four levels may have as many, or as few, branches as are required. Greater disaggregation should be used to model those sectors, subsectors, end uses, and devices where the potential for GHG reduction is greatest. The design of a demand structure often requires frequent references to the available data as the design progresses.

- **Specify the appropriate variables for each branch**. Here the task is to pick the relevant variables that “drive” the demand for energy. Consider the simple representation of cooking in urban households shown in Figure 3.2. At the sector level, either population or the total number of households could be specified. Since cooking generally occurs at the household level, the number of households is usually a better driving variable than population for projecting energy use for cooking. Similar choices need to be made for other branches, e.g., whether energy use in the iron and steel industry should be a function of physical production (e.g., tonnes of an indicator commodity, such as steel, produced) or economic output (e.g., value added for the industrial subsector). These choices will depend on local conditions, data availability, and robustness of the relationships.

Figure 3-2 (full page)

Figure 3-2. Schematic of Demand Structure for Country X (with key driving variables added in parentheses)

The urban household cooking data in Figure 3.2 illustrates the activity level and energy intensity specification for one demand “branch”. The numerical data shown are for the base year, 1990. At the first level, the driving activity is households, of which there are assumed to be 8 million in 1990. At level two, the fraction of these households in the “Urban” subsector is entered (30% in 1990). At the third and fourth levels, the saturation of the cooking end use (100%, since most every household cooks) and fuel shares and energy intensities are entered, respectively. For example, 30% of urban households in 1990 used electric stoves at an annual final energy intensity of 1.44 GJ per household.

Some data values can be taken directly from existing statistical compilations, while the analyst may have to derive or estimate other values based on existing statistics, survey data, or even representative data from nearby countries. In some cases, only more aggregate statistics will be available. For example, the analyst may know the average electricity use per urban household, but only have suggestive data about the saturation and electricity use levels for specific end uses (such as lighting, cooking, or refrigeration). In such cases, the analyst will have to use judgment and refer to other studies.

3.7.3.2 Energy supply structure

The design of an energy supply structure varies considerably among different models. Optimization models, and especially a model such as ENPEP, have more complex representations of the energy supply system, allowing for a detailed description of options for energy extraction, conversion, and distribution that the model can choose among. Some general steps in designing an energy supply structure are:

- **Define the important energy extraction, conversion, and distribution activities in the country.** Energy sector models generally contain a default list of energy transformation “modules” that can be changed to suit local conditions and the mitigation options being considered.

- **Specify process data**. Within each transformation module, the analyst specifies more detailed "process-level" data describing individual facilities or types of facilities such as electricity generation plants. The degree of detail in which data are specified should reflect the importance of each energy supply sub-sector in the mitigation analysis. In many countries, the electric sector is the most important GHG emissions source so the analysis may call for more detailed data on the cost and performance characteristics of individual generation technologies. For each technology, the analyst specifies input fuels, capacity, efficiency, capacity factor, and the capital and operating and maintenance costs, and, if relevant, the co-production of other energy outputs, such as cogenerated steam.

- **Define the operating rules for each transformation sector**. The analyst indicates how facilities will operate to meet demand outputs (e.g., electricity or refinery products). Facilities can operate to meet local demand, to meet export targets, or other criteria. For the electricity sector, for example, specific plants can be dispatched to meet an annual system load curve.

3.7.3.3 Calibration to base year energy balance

Once detailed data structures have been established and data entered for the base year, the full data set should be calibrated to reflect official base year energy supply totals. When summed across end uses, subsectors, and sectors, the total energy use and required supply, determined from a set of disaggregate “bottom-up” data, will often disagree with official supply totals. Disaggregated data must then be reviewed and adjusted, based upon the analyst’s judgment. Large differences generally indicate the need for closer analysis. Small differences can be allocated to the least accurately defined demand categories, such as "other industries", or can be allocated to all energy use categories on a pro-rata basis.

3.7.4 Setting Up Emissions Data

Setting up the calculations by which fuel use estimates are translated into estimates of the emissions of GHG and other pollutants has three elements:

- **Decide which gases to consider.** Energy sector activities release a number of different types of pollutants in varying quantities. The analyst must reduce the large field of pollutants to a number that is manageable for the study. Among GHG, CO_2 is almost always the GHG released from energy sector activities in the largest quantities. Other GHG that can be of importance include methane (CH_4) and N_2O. The analyst may also wish to consider other pollutant emissions, such as SO_x and NO_x.

- **Specify emission factors for each energy activity**. Relevant emission factors should be specified for each appropriate energy conversion, transport, and production activity, and each appropriate energy-consuming activity. If not available from the GHG Inventory, GHG emission factors can be taken from the IPCC and other sources, as listed inTable 3-3.

- **Calibrate base year emissions**. Once connections have been made between energy data and emission factors, the resulting national energy sector emission estimates should be compared and calibrated to the GHG emissions inventory, if available. Differences between the base year emissions estimates from the mitigation study and an official GHG inventory may be due to a number of factors, including differences in energy data, differences in emission factors, or off-line computational errors.

3.8 DEVELOPING A BASELINE SCENARIO

Developing a baseline scenario that portrays social, demographic, and technological development over a 20-40 year or longer time horizon can be one of the most challenging aspects of a mitigation analysis. The levels of projected future baseline emissions shape the amount of reductions required if a specific mitigation scenario target is specified, and the relative impacts and desirability of specific mitigation options. For instance, if many low-cost energy-efficiency improvements are adopted in the baseline scenario, this would yield lower baseline emissions and leave less room for these improvements to have an impact in a mitigation scenario.

Development of a baseline scenario begins with the definition of scenario characteristics (e.g., "business-as-usual"). Changes in exogenous driving variables must then be specified and entered into the model, which is then run to simulate overall energy use and emissions over the time horizon selected. The baseline scenario must be evaluated for reasonableness and consistency, and revised accordingly. Uncertainty in the evolution of the baseline scenario can be reflected through sensitivity analysis of key parameters such as GDP growth.

The procedure will vary somewhat depending on the modeling approach used and the nature of a baseline scenario. In an optimization model, the use of different technologies is to a certain degree decided within the model, dependent on how much one wants to constrain the evolution of the baseline scenario. For example, the analyst might choose to construct a baseline scenario in which the energy supply system closely reflects or extrapolates from published plans. Alternately, the analyst might choose to give the model more flexibility to select a future energy supply system based on specific criteria. If one is using an optimization model, it is necessary to introduce certain constraints if one wishes to force the model toward a solution that approximates a "business-as-usual" future.

The rate of economic growth and changes in domestic energy markets are among the most important assumptions affecting projected baseline emissions. Official government GDP projections may differ from other macroeconomic projections. In terms of domestic energy markets, the removal of energy price subsidies could greatly affect fuel choice and energy efficiency, and thus baseline emissions and the impacts of mitigation options.

A preparatory step in developing a baseline scenario is to assemble available forecasts, projections, or plans. These might include national economic development plans, demographic and economic projections, sector-specific plans (e.g., expansion plans for the iron and steel industry), plans for transport and other infrastructure, studies of trends in energy use (economy-wide, by sector, or by end use), plans for investments in energy facilities (electricity expansion plans, new gas pipelines, etc.), studies of resource availability, and projections of future resource prices. In short, all studies that attempt to look into a country's future—or even the future of a region—may provide useful information for the specification of a baseline scenario. However, it is unlikely that every parameter needed to complete the baseline scenario will be found in national documents, or even that the documents will provide a consistent picture of a country's future. As with much of the modeling process, the judgment of the analyst in making reasonable assumptions and choices is indispensable.

3.8.1 Developing Projections of Energy Demand

In bottom-up approaches, projections of future energy demand are based on two parameters for each subsector or end use considered: a measure of the activity that drives energy demand and a measure of the energy intensity of each activity, expressed in energy units per unit of activity.

Measures of activity include data on household numbers, production of key industrial products, and demand for transport and services. Activity may be measured in aggregate terms at the sectoral level (e.g., total industrial value added, total passenger-km or tonne-km), and by using indicators at the subsector level. These two measures need not be identical. For example, total industrial value added is a common indicator for aggregate activity for the industrial sector, but for specific subsectors, such as steel or cement, one often uses tonnes of production as a measure of activity. In general, physical measures of activity are preferable, but they are not appropriate in all cases (such as in light industry, where there is no aggregate measure of physical production). Measures of activity are discussed in more detail in the chapters on each energy demand sector (Chapters 4-7).

In bottom-up approaches, future values for driving activities are exogenous. In other words, they are based on external estimates or projections rather than being estimated by the model itself. Future values can be drawn from a variety of sources or estimated using various forecasting methods. Estimates of the future levels of activity or equipment ownership will depend on local conditions and the behavioral and functional relationships within each sector.

Projections of the future development of energy intensities in each sub-sector or end use can be expressed in terms of final energy or useful energy.[3] When the choice of end-use options is conducted

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[3] "Final energy" is the energy delivered to end-use devices. "Useful energy" refers to the amount of energy required to meet particular

within the model, however, the energy demand should be given in terms of useful energy to allow the model to select among technologies for meeting the energy requirements.

Projections should start from the base year values, such that the sum of the product of energy intensity and activity level in each sub-sector add up to total final or useful energy use in the base year. In energy statistics, the data are normally presented in terms of final energy. If the projections are to be given in useful energy units, the statistical data should be converted using estimated base year efficiencies for each end use.

Ideally, the projections of energy intensities should be based in part on historical developments. To the extent statistical data on a disaggregated level are available, they give limited information for economies that have undergone significant structural changes or changes in taxation/subsidies on energy. Even if reliable historical data are available, assumptions on the development of the energy intensities have to be made using careful judgment about the status of existing end-use technologies and future efficiency improvements that should be included in the projections.

It is important to distinguish between improvements included in the exogenous demand projections and improvements that are explicitly included as technology options in the model. For example, future improvements of building insulation standards can either be directly included in the demand projections as an improvement of intensity for space heating, or modeled as "technology options" that can be chosen individually in the assessment, depending on their attractiveness in the different scenarios. The distinction is especially important in optimization models. One can assume that the insulation standards will be implemented (e.g., through use of regulations), or allow the model to choose the implementation. In the latter case, the insulation option will be implemented if its cost is less than the cost of supplying the heat using available options for space heating.

3.8.2 Calculate and Review Results of the Baseline Scenario

Once the assumptions to be used in the baseline scenario have been mapped out, the next step is to enter the projected values for key parameters. When the data set is complete, the model calculates the results of the baseline scenario. The analyst should check results to ensure that they appear reasonable and logical. When reviewing initial demand results, many questions should be raised, such as: Do the growth rates of fuel demand in each sector make sense, based on the input assumptions, past trends, and expected developments? Are there changes in demand patterns that seem unlikely?

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demands for energy services. It is typically estimated by multiplying final energy consumption by the average conversion efficiency of end-use equipment (e.g., of oil-fired boilers). Applying the concept of useful energy is more difficult in the transport sector although one can use the estimated conversion efficiency of generic engine types in various vehicle classes.

When reviewing supply results, the analyst may need to ensure that all fuel demands are being met, either through domestic production or by imports. For the electricity system, the analyst should make sure that an adequate reserve margin is maintained throughout the planning period and that there is a reasonable balance between baseload, intermediate, and peaking resources.[4] If supply resources are insufficient, demands should be curtailed, prices augmented, or new supply resources added. If excess capacity (e.g., unneeded power plants) and/or resources are present, expansion plans should be delayed or curtailed, if possible. (In an optimization model or a system simulation model, these supply-side "checks" are generally performed by the model.)

The final step is to calculate the emissions consequences of the scenario. Here again, the analyst should review results to see if they are reasonable. Are the emissions of the expected order of magnitude? If not, and errors in the data sets have been eliminated as possible causes, some emission factors may be incorrect or missing.

Once the initial baseline scenario is prepared, it should be reviewed to assess whether it presents a comprehensive and plausible future for the country in light of real-world constraints. Some specific questions might include:

- Can the indicated growth rates in energy demand be sustained over the study period? Is it a reasonable rate, given recent experience in the country and region?
- Is the level of capital investment needed to sustain the indicated levels of industrial growth likely to be forthcoming?
- Will the country be able to afford the bill for fuel imports that is implied by the baseline scenario?
- Will the level of capital investment needed for energy supply system expansion be available given competition for limited financial resources?
- Is the indicated increase in transportation use plausible given current and planned transportation infrastructure?

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[4] The reserve margin is the difference between total installed electric generation capacity and the annual peak demand, divided by the peak demand. In general, reserve margins of 15 to 25% are considered adequate for ensuring reliability of electric service. Larger reserve margins might indicate an electricity generation system that is over-built (and thus more expensive than necessary) or poorly maintained. Baseload resources are power plants that run most of the time to meet a constant level of demand day and night. Peaking plants run less frequently to meet demand only at “peak” periods (e.g., in the morning or evening) when demand is highest.

- Are the emission factors in use appropriate for future technologies?[5]

Answers to these questions might indicate the need for adjustments to the baseline scenario or sensitivity analyses of key parameters.

3.9 DEVELOPING MITIGATION SCENARIOS

The process of developing a mitigation scenario or scenarios involves establishing a scenario objective and combining specific options in an integrated scenario. Integrated scenario analysis is essential for developing accurate and internally consistent estimates of overall cost and emissions impacts since the actual emissions reduction from employing a specific option can depend on the other options included in a scenario. For instance, the level of reduction in GHG emissions associated with an option that saves electricity is dependent on the electricity generation resources whose use would be avoided (e.g., coal, oil, hydro, or a mix). In reality, the type of electricity generation that the efficiency option would avoid will change over time, and, if lower GHG-emitting electricity resources are also introduced in the scenario, the GHG savings of the efficiency option may be reduced. Integrated scenario analyses are intended to capture these and other interactive effects.

Where using an optimization model, the difference in input data for the baseline scenario and the mitigation scenario(s) is typically less than in an accounting model, where the choice of technologies is exogenous to the model. An optimization model chooses from the whole set of available technologies to satisfy the given constraints.

3.9.1 Objectives for Mitigation Scenarios

Several objectives are possible for designing a mitigation scenario. The objective will depend on political and practical considerations. Types of objectives include:

- Emission reduction targets. For example: 12.5% reduction in CO_2 emissions by 2010, and 25% reduction by 2030, from baseline levels. An alternative is to specify reductions from base year levels, which avoids making the amount of reduction dependent on the specification of the baseline scenario.

- Identification of options up to a certain cost per tonne of emissions reduction. The emissions reduction given by the resulting technology mix would reflect the level of reduction that could be achieved at a certain marginal cost.

- “No regrets” scenario. This scenario is a common variant of the previous type of objective, where the screening threshold is essentially zero cost per tonne of GHG reduced.

- Specific options or packages of options. Examples of this type of scenario might be a “natural gas” scenario, a “renewable energy” scenario, or a “nuclear” scenario.

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[5] CO_2 emissions per unit of fuel use (or production) are unlikely to change much as new technologies are introduced. Emission factors for other gases are more likely to be affected by technological changes.

Another important aspect of defining the scenario objective is to decide on whether only CO_2 or several GHGs will targeted. Non-CO_2 GHGs, such as CH_4 (methane) or N_2O, can be separately targeted for reduction, or a combined reduction target can be specified using global warming potentials (GWPs).

3.9.2 Developing Integrated Scenario(s)

The manner in which one develops an integrated scenario containing a combination of mitigation technology options differs among energy sector models. In an accounting model such as LEAP, the analyst selects specific options based on their cost of saved carbon and other characteristics, and specifies their penetration. In an optimization or simulation model, the selection of technologies is done by the model according to its internal logic and criteria specified by the user.

It is often desirable to develop several mitigation scenarios, as different combinations of options might have similar total direct costs but differ with respect to criteria such as balance of payments or local environmental well-being. Since many objectives are important to national policy, and modeling approaches cannot capture all costs and benefits, the absolute lowest cost scenario may not be the preferable one.

In addition, the analyst may choose to assemble a range of plausible assumptions for key input variables and test their impacts as sensitivity analyses.

3.9.2.1 Penetration rates of mitigation technologies

A key task is to determine reasonable penetration rates for technology options. Penetration rates denote the speed at which a technology or practice can be adopted ("enter the market"). For large investments, such as power plants or large industrial investments, the penetration rate will generally be expressed in terms of the timing and size of discrete changes or capacity additions. For instance, for technical and infrastructure reasons, there might be a limited amount of wind power that can be installed by a specific future date. Alternatively, the intermittent nature of wind power generation might limit its maximum achievable penetration if no storage capacity is available.

For smaller investments, such as consumer appliances or smaller industrial investments, penetration rates are typically expressed in terms of the percent penetration per year of improved technologies or practices. For instance, an achievable market penetration rate for high-efficiency refrigerators might be 50% of new purchases per year. If 6% of all refrigerators are replaced (or purchased by households who previously had none) each year, the total penetration rate of energy-efficient refrigerators into the total stock of refrigerators would be 3% per year. In addition to annual penetration rates, there might be a maximum achievable penetration level, akin to the limitation on wind power implementation described above, if a certain percentage of the market is unlikely to adopt a option for technical or behavioral reasons.

In general, lower-GHG technologies can be introduced either (a) when existing equipment reaches the end of its economic life and needs replacement; (b) when new equipment is needed to meet growing demands; (c) as a retrofit measure which modifies existing equipment; or (d) by replacing existing equipment before the end of its economic lifetime. As a consequence, several factors can influence penetration rates, including:

> Equipment lifetime. For example, a coal plant may last for 30 years, a refrigerator for 15 years, and an incandescent light bulb for 1 year or less. Stock models can be used to track the replacement of “vintages” of technologies and indicate the timing and opportunity for technological improvements. Stock models can be represented in the integrating energy models. Alternately, more detailed stock models may be used for specific technologies.

Technical, infrastructure, or financing limitations. The local availability of products, technologies, skilled labor, and capital can influence how rapidly a mitigation option can be adopted.

The policy instrument used. For example, to accelerate the adoption of energy-efficient refrigerators, either efficiency standards or incentive programs could be used; the two options would likely achieve rather different penetration rates.

In an accounting model, the analyst specifies a particular penetration rate for each option. With an optimization model, the analyst typically specifies maximum (or minimum) penetration rates that restrict the model s selection.

3.9.2.2 Review Results

A model will produce a variety of reports, including summaries of costs, savings, and emissions reductions achieved. The analyst should review the results for consistency and reasonableness. In an accounting model, the energy supply system should be checked to ensure that it is sufficient to meet projected demands without significant excess capacity. Reduced electricity demand will delay the need for new capacity, and the results should be reviewed to ensure that a reasonable reserve margin is maintained but not substantially exceeded.

3.10 COST CURVES FOR GHG ABATEMENT[6]

GHG reduction in the energy system can be achieved through changes at many stages of the system, involving a wide variety of different energy technologies. Fully cost-efficient abatement should consider all available abatement options, at end-use, conversion, and production stages, on an equal footing. A cost-efficiency analysis of GHG abatement in the energy system should therefore be able to compare all these different options in an integrated procedure. A cost curve expressing the costs per unit of emission reduction as a function of quantity of GHG reduced must thus be an aggregate of a number of different technical and structural changes in the energy system, many of which are interdependent. The capability of representing these interdependencies and how the detailed energy system information is mapped into a one-dimensional form differs significantly among the different models.

In an accounting model, it is implicitly assumed that the economic and GHG emission "value" of each technology can be determined independently because each technology is assumed to represent a marginal adjustment of the total system. However, if fundamental, non-marginal, structural changes of the supply system, such as fuel substitution and the introduction of combined heat and power (CHP) systems, are considered, the economic and GHG emission "values" for the energy demand technologies are not unique and cannot be determined independently of the supply system. Any investment alone can influence the total economy and GHG intensity of the energy system, and technologies must therefore be assigned different economic and GHG emission "values" depending on the system in which they take part.

In integrated models like ENPEP and MARKAL, the supply side responds to even marginal changes on the demand side. However, this integrated approach also makes it difficult to relate emission reductions at each point of the curve to specific single-technology options.

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[6] Parts of this section draw on the UNEP Greenhouse Gas Abatement Costing Study, Phase One Report (UNEP, 1992).

There are several ways of establishing cost curves and which method to chose depend largely on the type of model used. In the following, we discuss three different approaches for constructing cost curves.

3.10.1 Methods for Construction of Cost Curves

- **The partial solution**. In this method, each technology option is evaluated separately with respect to incurred costs and GHG emissions. Results are compared, option by option, for the GHG-reducing option with the baseline. Alternatively, the GHG-reducing option might be compared to a total reference case. Incremental changes in GHG emissions and costs are calculated and ranked according to costs as shown in Figure 2-2. Here option A is chosen as the most valuable option.

  The procedure is little more than a stacking of abatement options. Ranking of the options is done separately for each, ignoring interdependence among the options. The cost curve is built up of partial independent segments. The solution is simple, but theoretically unsatisfactory, and can lead to serious misinterpretations.

- **The retrospective systems approach**. This approach requires the development of a baseline with which to compare the mitigation case. The first step in this approach is a separate ranking of the technology options, using an energy systems framework. This step is identical to the partial approach**.** In the next step, the most valuable option (option A in Figure 2-2) is included in the model run, and incremental results compared to the reference case are calculated to give the block in the cost curve. Next, the second most valuable project is included in the model and new calculations are performed. Results are compared to the former ones, a new cost curve block is established, and so on.

  The advantage of this approach compared to the partial solution is that the interdependence between the given option and every other previous option on the cost curve is taken into account. The results for option B will thus depend on the introduction of option A, while option C will depend on both options A and B and so on. However, this approach does not include the impacts that the implementation of more expensive options can have on the options already chosen. For example, if option G in Figure 2-2 is a hydro power plant, implementation of this option can change both the CO_2 intensity and cost of the electricity in the energy system. If option E is an option for saving electricity at the end-use level, the implementation of option G will change both the amount of GHG reduced and the costs for option E. This lack of consistency in the retrospective approach is an important drawback, especially in cases where implementation of demand-side options results in significant changes on the supply side. Another drawback is that the retrospective method implies that once an abatement option is included in a scenario, it will be a permanent part of all subsequent scenarios.
  Both the partial solution and the retrospective approach result in a stepwise cost curve, and these two methodologies are often applied when establishing cost curves using accounting models.

- **The integrated systems approach**. This approach requires the existence of a well-defined baseline, and an integrated energy system model where the supply side automatically responds to even marginal changes on the demand side in each model run. Both ENPEP and MARKAL facilitate this fully integrated approach. The idea is to determine any point on the cost curve as the least-cost solution for the total energy system, in which all demand and supply system parameters can vary. This approach aims to take into account all the interdependencies within the system, as represented by the energy systems model.

A least-cost curve can in principle only be established through use of a cost-minimizing optimization model. In an optimization approach, the model itself selects the configuration of the energy system that satisfies different emission targets at a minimum cost. To identify a theoretically consistent curve showing the least cost at any emission reduction level, the model should have the same options available to chose from in each run with increasing emission reduction levels. In simulation models like ENPEP, one can also establish a one-to-one relationship between emission reduction and cost through imposing constraints on emission levels in the model. However, this will not necessarily reflect a strictly least-cost curve.

The disadvantage of the integrated systems approach is that the interdependencies between supply and demand options make it difficult to identify impacts of single options separately, and a strict ranking of options is not possible since the emission reductions achieved as one moves up the cost curve result from the use of several interlinked options.[7]

The difference can be illustrated by comparing Figure 2-2 with Figure 3-3. Instead of showing the contribution from different technology options step by step (as in Figure 2-2), the interval where the options contribute in the integrated systems approach can be illustrated as shown in Figure 3-3.

As the figure illustrates, emission reductions at each level are achieved through the use of a mix of options, rather than stepwise reduction through single options. Despite the difficulty of singling out specific options at each reduction level, the approach represented in Figure 3-3 is still the most satisfactory since it more closely reflects the real situation in an interlinked energy system.

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[7] The impacts on costs and/or emissions of introducing single options can be studied in an integrated model through running the model with and without the option available. The difference in costs and/or emissions between the two cases yields the cost/benefit of the specific options in a fully integrated system. For example, the value for the entire energy system of introducing high-efficiency refrigerators can be calculated by comparing the total system costs of stabilizing emissions when the refrigerators are available to the case when they are not. In optimization models, the "shadow prices" give information on the relative value to the energy system of making one unit of a specific technology more available. This makes it possible to compare technologies on the same scale independent on whether they are supply or demand technologies. Ranking of options that are not chosen in the optimal solution can also be done through investigating their so-called "reduce costs," which is the reduction of unit cost that is needed to make the technology competitive in the system. Technologies that appear near to the optimum in a linear programming solution could be attractive in a real world where more complex decision variables are involved.

Figure 3-3. CO_2-Reduction Curve Using the Integrated Systems Approach

As mentioned in Chapter 2, it is important to be aware of what the costs presented in the curves include. When derived from engineering models, cost curves usually address direct energy system costs. As such, they contain the same limitations as the models themselves in not incorporating transaction and other hidden costs, which may vary considerably between different options. Moreover, they represent a sectoral notion of costs as opposed to macroeconomic measures such as GDP impacts.

3.11 EVALUATING MACROECONOMIC IMPLICATIONS OF MITIGATION SCENARIOS

The “bottom-up” approach only captures the direct economic impacts of technologies and, if included, the costs of policy instruments—efficiency programs, standards, import tariffs, taxes, and so on—that might be used to achieve adoption of the technology options selected in a mitigation scenario. It is desirable to conduct some assessment of the impacts on the macro-economy in terms of growth in a particular sector, employment, and other indicators. One approach for evaluating some of these economic impacts is to integrate bottom-up results with "top-down", macroeconomic analyses. Capital investment, fuel expenditures, and import and export levels can be used as inputs to a top-down model to assess the macroeconomic impacts of mitigation scenarios.

Bottom-up/top-down integration may be done at different levels of sophistication. At the simplest level, the capital investment, fuel expenditures, and import and export levels required for energy activities may be compared with those for the whole economy. Alternatively, they may be compared with a country's GDP.

Estimating the effects of energy-sector scenarios requires a linkage to a macroeconomic model. The one-sector MACRO component of MARKAL-MACRO provides a way to estimate the impact on GDP of pursuing different scenarios. In a multi-sector framework, the energy sector results may be used as final demand drivers in an input-output (IO) framework. The IO model will yield estimates of direct and indirect incremental changes in output, employment, environmental, and other associated impacts. The estimates may also be used in conjunction with a CGE model (e.g., the LBL-CGE model) to determine the impact on the government budget, for example. Regardless of which approach is used, it is extremely important for the modeler to place the bottom-up results in the context of macroeconomic parameters which are important to policy-makers.

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