1.4.2 The MARKAL Model

Characteristics of MARKAL

MARKAL is a demand-driven model. Its structure can be described as follows.

Energy is extracted from primary resources, then transformed by supply technologies into a variety of energy carriers such as fuels, electricity, and low temperature heat (for district heating systems); these energy carriers are finally used by a vast array of end-use technologies in order to satisfy various socioeconomic needs expressed as useful demand. Useful demand is a direct expression of a demand for a particular service, e.g., steel, newsprint, train passengers-kilometres, automobile passenger-kilometres, houses to heat, etc. Useful demands are usually disaggregated into five sectors: industrial, transportation, residential, commercial, and nonenergy uses, each of which may be further divided into several subsectors.

Thus, MARKAL is driven by the specification of useful demands in each sector and subsector of the economic system. This implies in particular that the so-called final energy consumption of the various subsectors is not exogenously specified, but is rather determined by the model as a result of competition among the many demand technologies to satisfy the useful demands. The competition will usually result in some substitution among fuels. Where a choice among end-use technologies is not sought, a single hypothetical demand device can represent energy use in that subsector.

MARKAL is a dynamic model that is usually used to represent the energy system for up to nine time periods of five years each. It accepts a set of initial values for the installed capacities of all technologies and for their residual lives. From period to period, capacity of a technology is automatically conserved up to end of its service life. New technologies are allowed to become available at specified future dates.

MARKAL is a techno-economic model since its data base is composed mainly of technical coefficients describing the energy inputs and outputs of a very large set of technologies, their efficiencies, their costs (investment and operation, fixed and variable), their lifetime, their dates of availability, etc.

MARKAL can capture the most important features of energy systems, namely:

- the necessity to satisfy final demands
- the limited availability of primary resources
- the obligation to balance supply and demand for intermediate resources
- the necessity to install sufficient capacity to be able to operate at a desired level
- the capacity accumulation process, through investment, retention, and then phasing out of residual capacity
- the input-output interaction between a set of activities
- other types of constraints, such as upper bounds on market penetration and allowable emissions.

Formulating a MARKAL Model

MARKAL can thus be considered a "model construction kit" for formulating national (or subnational) models.

To build a model, the following data are required:

- list of energy forms to be represented in the model
- list of technologies and their characteristics
- available quantity of domestic primary resources
- price trends for imported and exported resources
- useful energy demand for each sector
- other constraints, such as emission limits.

Technology Description

The description of each technology in MARKAL requires the following technical data:

- list of input fuels
- list of output energy forms
- efficiency of the process
- date of availability of a new technology
- useful life of a technology
- investment cost per unit of capacity
- fixed operating and maintenance cost per unit of capacity
- variable operating and maintenance cost (excluding fuel costs) per unit of total output
- technology-specific emission coefficients.

Variables

In a MARKAL model, the quantities are either exogenous (supplied by the data base) or endogenous (determined by the model). Exogenous quantities are, for instance, useful demands, imported energy prices, unit costs (investment, operation, etc.) of a technology, and technical coefficients of a technology.

The endogenous quantities, or variables, are grouped as follows in MARKAL:

- variables representing energy carriers
- quantity of each energy form (fuel) available in each time period
- variables related to energy supply technologies
- new investment in each technology in each time period
- installed capacity of each technology in each time period
- utilized capacity of each technology in each time period
- variables related to demand technologies

The values of these variables are determined by the linear programming solution.

Constraints

A MARKAL model is composed of a set of logical relationships that tie together the variables. These relationships are called the constraints of the model. The principal constraints are:

- Satisfaction of demands
- Fuel balances
  Limit on operations
- Period-to-period capacity conservation
- Exogenous bounds such as those on the market penetration of individual types of technology
- Other constraints such as maximum allowable emissions from the energy system.

Objective Function

An important point is that MARKAL will determine the values of all model variables simultaneously in such a way as to satisfy the constraints and minimize the objective function. In many applications, the objective function is the total discounted net present cost of the energy system over the whole planning horizon. The objective function may also consist of the weighted sum of this cost and the environmental emissions, as described in Appendix A, section A.2.2. The Japanese vesion of MARKAL, developed at JAERI, even allows for a simultaneous (weighted) three criteria objective, adding security of energy supply to the system cost and environmental emissions.

MARKAL Outputs

MARKAL produces the following outputs for each time period:

- capacity expansion (or reduction) required for a comprehensive set of energy supply technologies
- level of activity of those technologies selected
- identification of the end-use technologies that are the most promising in terms of cost-effectiveness
- an accounting of all energy forms used
- a marginal value for each energy form
- a reduced cost for each activity that does not appear at a positive level in the optimal program.

The model treats interfuel and intertechnology substitution in detail. Cost of emission reductions are internalized in the model. The cross-elasticities arising from changes in relative prices of fuels are implicitly obtained in the optimization process.

The model will price all energy forms at their marginal cost in a hypothetical, tax-free world. A linear programming model computes marginal costs even in very complex situations where the output of activities are joint products (like refined oil products, or peak, intermediate, or off-load electricity).

Scenario Analysis

An intelligent use of the model consists in running several scenarios carefully constructed by the user in order to conduct an analysis of the differences as well as the similarities of the corresponding MARKAL results. This can reveal those parts of the energy system that are sensitive to the assumptions made in the various scenarios.

By varying some of these parameters the analyst can evaluate the potential impact of a large variety of possible perturbations of the system (e.g., a change in the price of an imported primary resource like oil, a change in the date of availability of a new technology, or a change in annual allowable emissions).

Whenever the model user changes one or a few of the exogenous coefficients (e.g., demands or technical coefficients or cost coefficients), MARKAL will recalculate a new set of levels for all variables consistent with these changes. MARKAL is thus an ideal tool for evaluating the impact of some scenario modifications upon the energy system as a whole; it provides answers to a broad range of "what if" questions related to demands, exogenous prices, and the inclusion of new or modified technologies.

Interpretation of Results

The optimal program is given by the primal solution, i.e., a set of values for all variables such that all constraints are satisfied and the objective function is optimized.

At times, some a priori promising technologies do not appear at all in the solution, even if they are almost competitive. The number of variables in the solution is no greater than the number of constraints. The first way to cope with this tendency to overspecialize is to increase the number of constraints. One obtains a richer model with more technologies playing a role in the primal solution.

The next step is to examine the dual solution. The value of the reduced cost indicates its distance from optimality, as described in the above example. More precisely, this value corresponds to the reduction of the unit cost of the activity that is needed to make it competitive. Technologies that appear as near optimal in the linear programming solution could be attractive in a real world where more complex decision variables are involved.

Advantages of MARKAL

In brief, the advantages of the MARKAL model are as follows:

1. Technological and cost data are included on the level of the individual type of technology.
2. The time horizon is long enough to change the technological mix.
3. Prices are calculated from technological as well as cost data.
4. Supply and demand are analyzed at the same time.
5. Supply technologies can be compared directly with those for end-use.
6. A wide range of energy systems can be modeled to a chosen level of detail.

It is advantageous to study energy systems at the national rather than supranational level. Among nations, there are different and independent decision makers, different demands, different regulations, different technical options.

However, it is also advantageous to use the same model formulation for different countries. The common rationale and methodology facilitate comparisons and understanding. In many cases, common data such as technology characteristics and international market prices can be used. Addressing the global climate issue, comparable national models should become particularly valuable in evaluating the national consequences of possible international agreements.

1.4.3 Linking with Economic Models

A shortcoming in the use of MARKAL to evaluate the implications of possible extreme reductions in future greenhouse gas emissions is that the exogenously specified energy demand projections are unlikely to remain unaffected. To adjust these demands to the radically different price regime that would exist with severe restrictions on greenhouse gas emissions, it would appear that a top-down macroeconomic model is needed.

In addressing the question of limiting greenhouse gas emissions, a central issue is the coupling between economic growth, the level of energy demands, and the development of an energy system to supply these demands. The debate is often connected with the two alternative modeling approaches.

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A

Top-down macroeconomic models, with their descriptions of feedback effects in the total economy but fewer technical details on the energy system, may tend to overestimate future energy demands. Conversely, bottom-up engineering models, ignoring feedbacks to the general economy and nontechnical market factors but containing rich descriptions of technology options, may tend to take too optimistic a view of conservation and the use of renewable energy sources. Or the principal difference may be that the engineering models ignore new sources of energy demands, and that the macroeconomic models ignore "saturation effects," that is, the decoupling of demand growth from that of GDP.

Linking the two types of models would seem to offer the possibility of using the features of one to compensate for the shortcomings of the other. The top-down macroeconomic model would adjust the energy demands to the different price regime introduced by carbon limitations. The bottom-up engineering model would supply the technical detail absent from a macroeconomic model. It has been argued, however, that the linked model formulation, although attractive in theory, is not empirically realistic and does not improve the accuracy of the results which continue to depend upon the one or two poorly measured parameters, AEEI and ESUB (See section 1.4.1.)

MARKAL-MACRO

In an experiment, MARKAL-MACRO was developed by the USA in Annex IV to be the prototype of a new tool for energy-economic analysis. A simplified version of the MARKAL model of the United States energy system was "hard-linked" to MACRO, a long-term neoclassical macroeconomic growth model. The combined model estimates the costs and evaluates technologies for reducing environmental risks such as regional air pollution and global climate change.

APPENDIX A. THE MARKAL MODEL

The analyses reported here are all made with the MARKAL model. MARKAL (acronym for MARKet ALlocation) is a dynamic, process oriented optimization model

A.1 Basic Principles

The term "model" is used here in two senses. The MARKAL and EFOM models are software that enable a user to represent a complex energy system -national, regional, local, or sectorial- as a linear program. The national models for the several countries combine this software with a data base specific to the energy system being modeled.

The data base specifies the energy demands -industrial, commercial, residential, and transportation- that will need to be satisfied over the next several decades. It describes the available sources of supply of energy, either domestic resources or imports of oil, coal, natural gas, nuclear fuel, and renewables. And it provides a menu of technologies for extracting, transporting, converting, and using energy, both existing technologies and those expected to be available within the time horizon of the model. The essential characteristics of the technologies are specified: for example, their investment cost, operating and maintenance costs, service life, fuel use, efficiency, availability, output, and maximum expected market penetration. As a linear program, the model then chooses the best combination of these technologies to satisfy the projected energy demands.

A linear program is a set of linear equations (or, more precisely, inequations that specify "greater than" or "less than" relationships) with variables and coefficients and constraints defined by the user as input data. A typical variable is the amount of installed capacity (which will be determined by the model) of a specified coal-burning power plant producing electricity. A typical coefficient is the investment cost per installed kilowatt of such a plant. A typical constraint is the maximum growth that can be expected in such installed capacity during future decades. A typical inequation states that the installed capacity of such a power plant must be less than or equal to the maximum projected capacity in a future year.

A function of the variables -- called the objective function -- is minimized or maximized subject to the specified constraints. In a typical MARKAL model, for example, the total cost of the energy system over the entire time horizon is minimized subject to limited resource supply and other constraints.

The solution to the linear program describes a set of energy technologies and energy flows that constitute an energy system that is feasible and optimal. Feasibility means that all the numbers add up correctly and that all the constraints are satisfied. Optimality means that of the hundreds or thousands of feasible solutions, this is the one that has the least cost (if cost is the objective function).
To see how the MARKAL linear program finds an optimal energy system, consider the following simple example.

A.1.1 MARKAL Demystified

The problem, illustrated in figure A.1.1, is to meet the projected need for electric generating capacity at least cost, choosing from three candidate energy technologies X, Y, and Z. In the top graph, the required total capacity during some years in the future is shown together with the residual amount of existing capacity which gradually declines over time. Initially, no additional capacity is needed because the residual value exceeds the required capacity. Soon, however, the two curves cross over, and additional capacity must be built. (The required margins of safety to assure system reliability are assumed to be included in the curves shown.)

The three lower graphs show the maximum market penetration that can be achieved by the three candidate technologies beginning at the point where additional capacity is required. The greatest rate of build-up is possible in Technology Z, which might be, for example, a conventional pulverized coal plant. Technology X, a new development, cannot actually be introduced until later.

Technology X will be the least expensive of the plants, measured in terms of cost per kilowatt-hour of electricity generated, and Technology Z the most expensive. That is, A is less than B is less than C.

The first decision is to choose which technologies to provide in time to fill the gap between the required and the residual electric generating capacity (figure A.1.2). The two technologies initially available are Y and Z. Inasmuch as Y is less expensive than Z, as much of Y as possible is therefore built. The additional capacity is provided by Z, the actual use of which is less than its maximum potential market penetration.

The first change in the choice of technologies occurs when Technology X, the cheapest, becomes available (figure A.1.3). At that point, Technology X begins to be built to the limit of its potential market penetration. Technology Y, the next cheapest, continues to be used to its limit. Finally, the difference between the required capacity and the sum of X and Y is supplied by Technology Z, the actual use of which continues to be less than the maximum that could be built.

If you followed this example, you understand how MARKAL works.

If the object is to minimize cost (that is, the objective function is cost), the model chooses the least costly combination of technologies that satisfies the specified demand. Beginning with the least costly technology, each candidate technology will be used up to its maximum market penetration potential. At the margin, one technology will probably be used at less than its maximum.

These results are shown in the primal solution of the linear program. Additional information on the value of the technologies is given in the dual solution which is obtained at the same time.

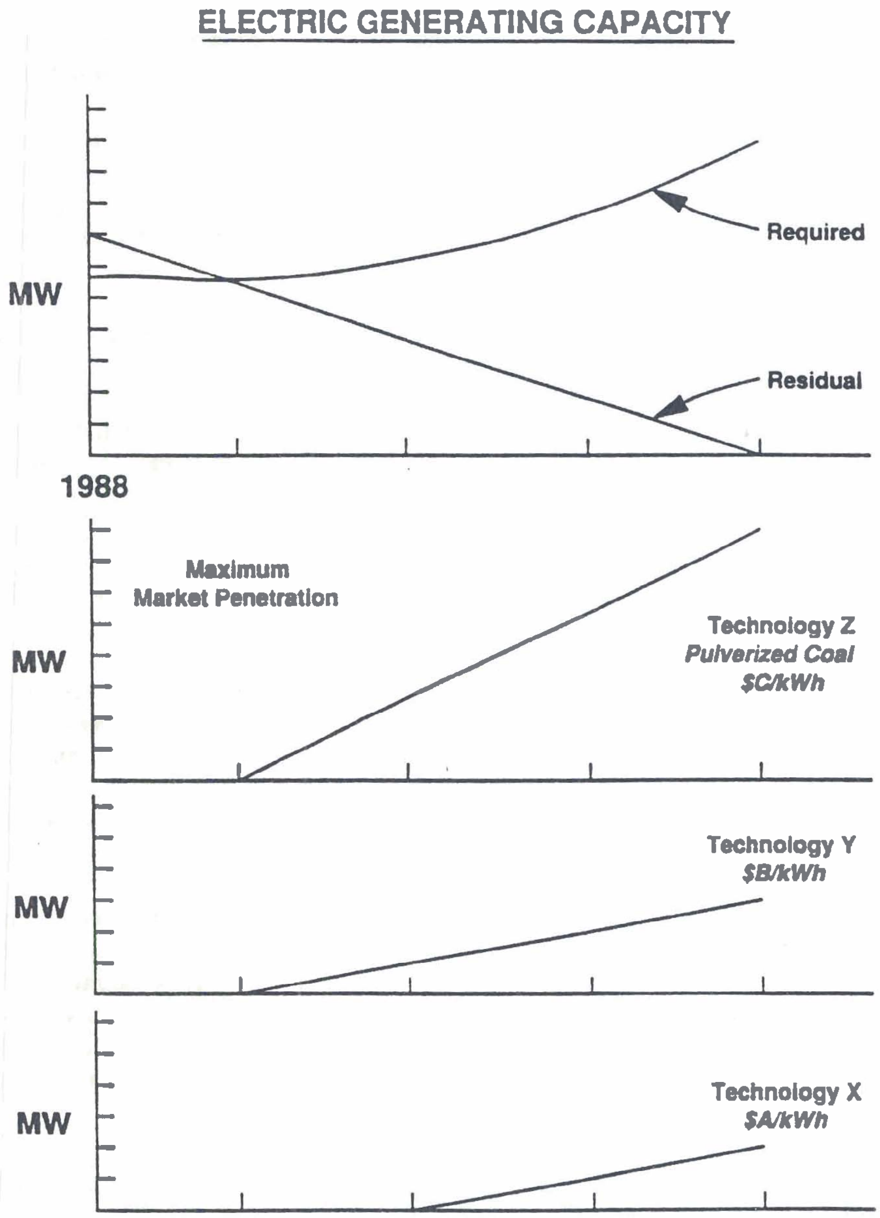

Figure A.1.1 *Example Problem: Data*

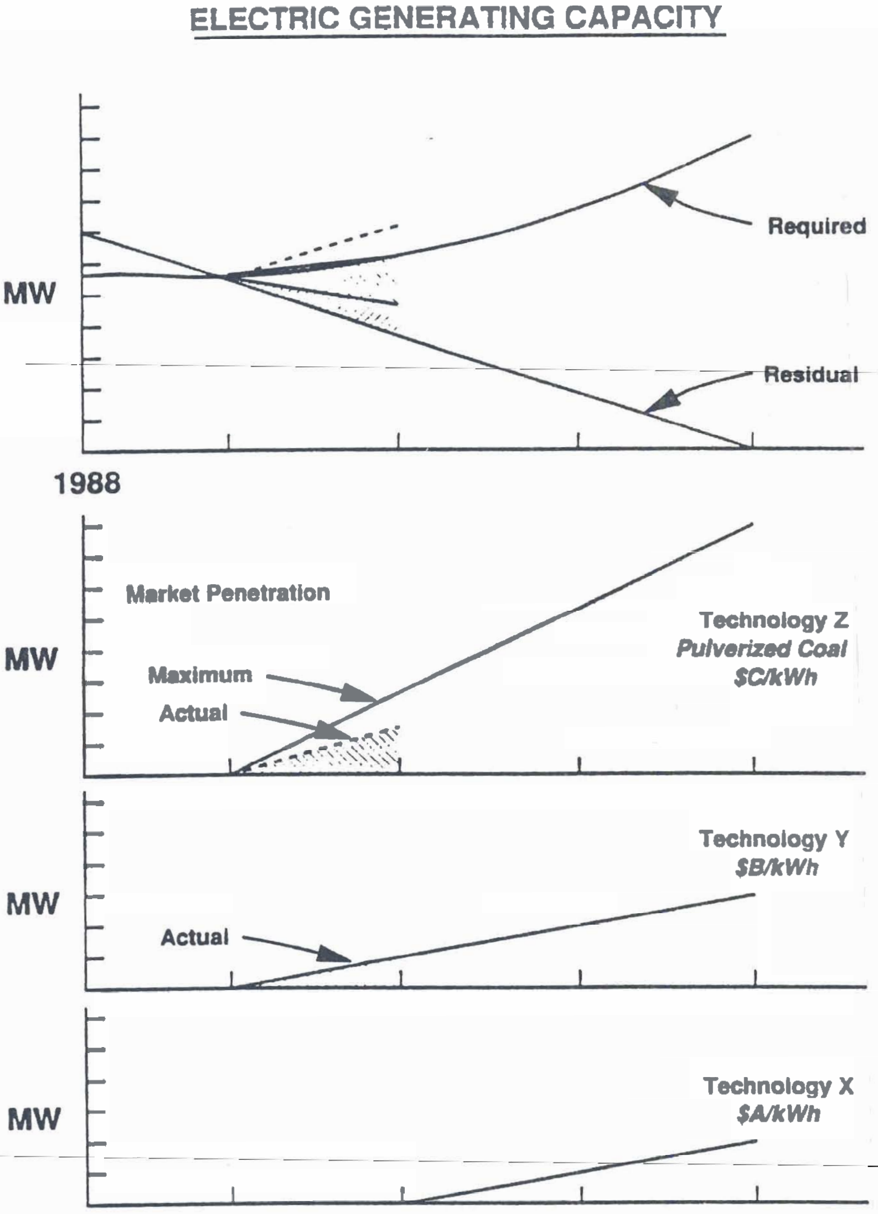

Figure A.1.2 *Example Problem: 1st Period Solution*

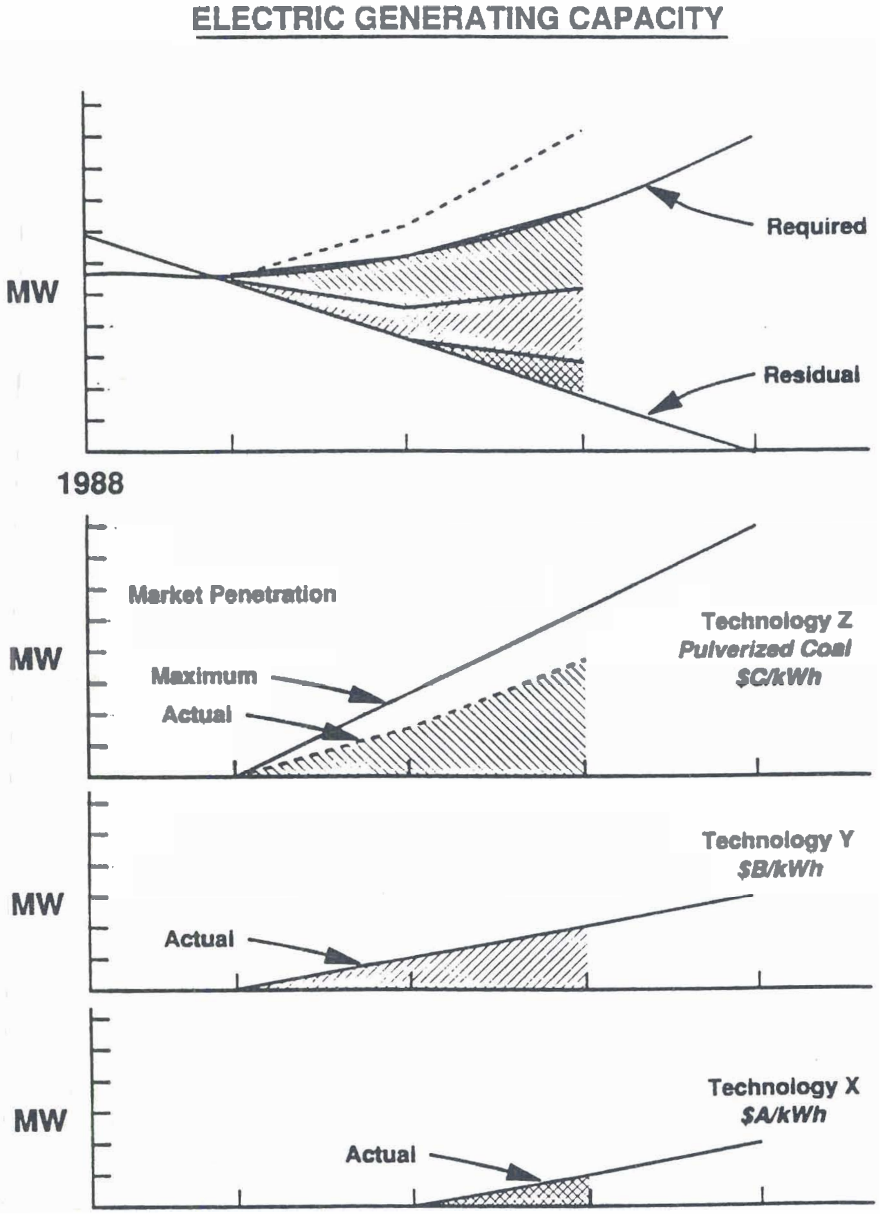

Figure A.1.3 *Example Problem: 2nd Period Solution*

A.1.2 Shadow Prices

Suppose one additional energy unit of Technology X were to become available (figure A.1.4). The least expensive mix of technologies would then include one more unit of Technology X. Technology Y, the next least expensive, would again be used up to its maximum market penetration. However, one less unit of Technology Z, the most expensive, would be used.

The effect on the total cost of the energy system consisting of the three technologies is to add one unit at cost A and subtract one unit at cost C. The net change in cost is (A - C) which, since A is less than C, is a negative number. The MARKAL linear programming solution shows this number for each bounded variable (like Technologies X and Y) as the "dual variable" or "shadow price."

The shadow price makes it possible to compare the value of an additional unit of capacity of different technologies. Note that this value is not simply the cost per kilowatt-hour, as usually measured, but the difference between this cost and that of the technology that is "bumped" out of the solution.

In this simple example, not much information is added to the comparison of Technologies X and Y. In a large system, however, an additional unit of different technologies may bump different marginal technologies. In each case, the shadow price indicates the value of an additional unit of the technology by the difference it would make in the total system cost. Thus, it is possible to compare on the same scale the value to the energy system of technologies as disparate as an electric generating technology, on the one hand, or an end-use conservation technology like building insulation, on the other hand.

A.1.3 Reduced Cost

What of technologies that are not chosen in the optimal mix? Two technologies may differ very slightly in cost, but because of the way the linear program operates the optimal mix of technologies may include all of one and none of the other. It is therefore of interest to know how much improvement is needed in those technologies that do not appear in the solution. This is indicated in the MARKAL solution by the "reduced cost."

In the example, suppose that Technology X were not the least but the most expensive. In a cost minimizing solution, it would be the last, not the first to come in. However, it could be forced into the solution by giving it a lower bound, say, at its maximum market potential. Suppose then that an additional unit were forced in, as in figure A.1.4. Again, it would bump the marginal Technology Z. The difference in the total cost of the energy system would again be (A - C), but in this case the number would be positive; there would be an increase in the total cost of the energy system.

The increase in cost is not A, the cost per kilowatt-hour usually reported, but the difference between A and C, the cost of the marginal technology that is bumped. This "reduced cost" measures how much the cost of Technology X would have to be further reduced to enter the solution.

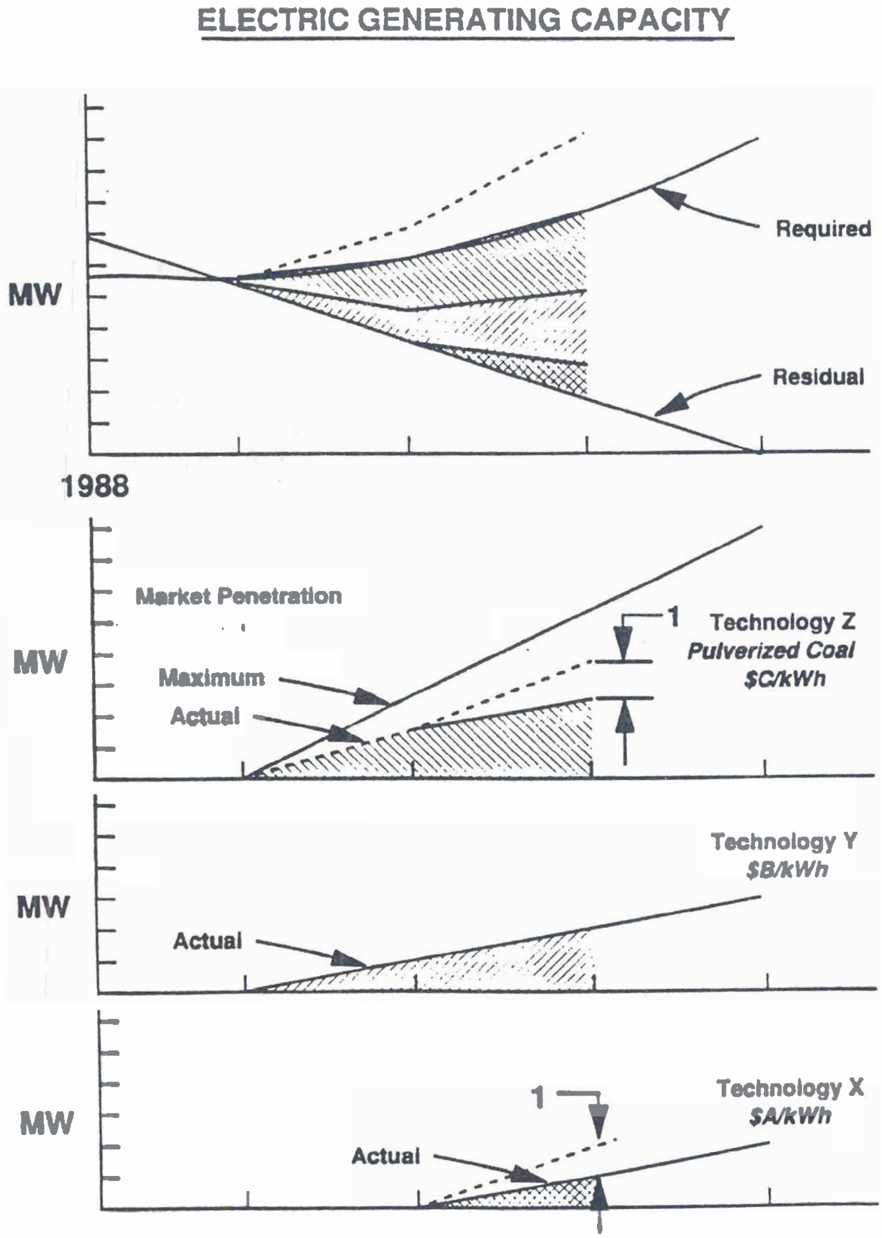

Figure A.1.4 *Example Problem: Shadow Price and Reduced Cost*

A.2 Modelling Emission Reduction

Suppose we now wish to take into account the need to reduce environmental emissions from the electric generating system. If Technology X generated the least emissions and Technology Z the most, there would be no difference in the solutions. Let us assume, however, that Technology Y produces the most emissions per unit of electricity produced.

There are two ways to treat emission reductions, either as a constraint or as part of the objective function.

A.2.1 Modelling Environmental Constraints

In the previous example, the only constraint on the amount of a new technology that is introduced is the maximum market penetration. Suppose now that a maximum amount of allowable emissions from the electric generating system is established.

The choice of technologies will still be made on the basis of their comparative cost if cost is the objective function. Technology X will be chosen first. Then, Technology Y -- the next least expensive but most polluting -- will be chosen to its maximum market potential unless the total emission constraint is reached. Finally, Technology Z will again make up the difference.

Conceivably, the additional amount of Technology Z will cause the total emissions to then exceed the total emission constraint. In that case, the amount of Technology Y will be reduced and replaced with Technology Z -- increasing the cost of the total system -- until the emission constraint is satisfied.

Modelling emission reductions as a constraint corresponds to establishing regulations that set limits on the maximum amount emissions.

A.2.2 Modelling Emission Reductions with the Objective Function

The other way to take environmental emissions into consideration is to include them in the objective function. In the example, the objective was to minimize cost, and the technologies were chosen in order of their relative cost per kilowatt-hour: A, B, then C. The objective could be instead to minimize emissions, and the technologies would then be chosen in order of their relative emissions per kilowatt-hour.

A more realistic objective would be to minimize some combination of cost and emissions. The objective function in this case would be the weighted sum of cost and emissions. The weighting would take the form of a coefficient applied to the amount of emissions, so that the sum would be in units of cost. For example, the coefficient could have units of dollars per ton of carbon dioxide, in which case it could be interpreted as a "carbon tax." The technologies would then be selected, again up to the limit of their maximum market penetration, in the order by which they compare by this weighted sum of cost and emissions. For example, they would then be chosen in order of a cost per kilowatt-hour that includes a carbon tax.

A.2.3 Summary of the Example

In sum, this simplified example illustrates the following points about the workings of MARKAL:

- The energy system is constructed of the set of technologies that satisfies demands at least cost (if cost is the objective function).
- Technologies are selected in the order by their cost (if cost is the objective function) up to the point where the constraints are satisfied.
- Maximum market penetration and allowable levels of emissions are examples of constraints that limit the use of a technology.
- Emission reduction may be considered either by constraints (equivalent to emission standards) or in the objective function (equivalent to an emissions tax).
- The value of a technology depends not only upon its nominal cost and emission characteristics, but by what it replaces (or is replaced by) elsewhere in the energy system.
- MARKAL makes it possible to compare on the same scale the value of technologies anywhere in the energy system by measuring their effect on the objective function.

The above example is, of course, greatly simplified. The example can be formulated as a linear program with 6 variables and 8 equations. A typical MARKAL model consists of 4,000 to 6,000 variables and a comparable number of equations.

In the example, electricity is the single energy carrier considered. MARKAL, however, makes a distinction in the electricity used in six types of demand periods: summer day, summer night, winter day, winter night, intermediate day, intermediate night. This permits an approximate description of the peak demand phenomenon in electricity generation. MARKAL also give a representation of the reserve requirements necessary for assuring the supply of electricity.

In the example, the demand for electric generating capacity is specified as an input. In MARKAL, the demand for energy services, or "useful energy demand," is the input, and electricity is itself only one candidate for meeting these demands.

A.3 PC-MARKAL and MUSS Development

The MARKAL model now operates in a "user-friendly" PC-based processing environment centred around an integrated analysis support tool, the MARKAL Users Support System (MUSS). The system features the conveni-