# ENERGY PLANNING AND THE DEVELOPMENT OF CARBON MITIGATION STRATEGIES

## USING THE MARKAL FAMILY OF MODELS

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# TABLE OF CONTENTS



[1] Update April 2001 by Ad Seebregts, ECN Policy Studies

# 1. INTRODUCTION

MARKAL is a family of bottom-up energy system models that depicts both supply and demand. MARKAL provides policy makers and planners in the public and private sector with extensive detail on energy producing and consuming technologies, and it can provide an understanding of the interplay between the macroeconomy and energy use. As a result, this modeling framework has helped national and local energy planning, and the development of carbon mitigation strategies. The MARKAL family of models is unique, benefiting from application in wide variety of settings and global technical support from the international research community. Implementation in nearly 40 countries, including developed, transitional, and developing economies indicates wide acceptability. In addition to support from the traditional research community, support is now available through an international consulting firm, the International Resources Group, which provides a staff of skilled users and sources of data. As a result, the framework has wide credibility that is continuing to grow in the international community.

This discussion introduces the reader to the MARKAL family of models and provides an over view of model developments, enhancements, and TIMES, the newest member of the family, which will be formally introduced in April 1999. MARKAL represents one class of model that has been used in the analysis of carbon mitigation efforts (Sanstad and Greening, 1998a). The MARKAL family is only one of several decision frameworks that have been used for this purpose. Since the methodology is adaptable to various scales, MARKAL provides a consistent approach for energy policy decision-making and at the multi-national, country, state or municipal levels. Therefore, MARKAL is a prime candidate for use in a capacity building program, which may evolve in response to commitments to reduce greenhouse gases or to plan energy system infrastructure development.

Along with its general introduction to MARKAL and its potential uses, this paper provides potential MARKAL users with a sense of the international commitment now driving innovation and evolution of the modeling framework. The framework constantly benefits from the contributions of talented researchers in institutions around the world, unlike those models that are the product of a single institution. MARKAL's collaborative approach to model development is implemented through an open architecture provided by the General Algebraic Modeling System. (Learn more at http://www.gams.com/.)

This paper describes the different versions of MARKAL. With few exceptions, individual versions are additive, and they can be used in combination with each other where appropriate. In some instances however, features are mutually exclusive as they represent different modeling techniques that address the same needs. For example MACRO/MICRO/MED, each address changes in demand levels that respond to changes in energy prices. However, because each of these versions has a different underlying theoretical development they may not be used together.

# 2. POLICY AND PLANNING QUESTIONS ADDRESSED BY THE MARKAL-FAMILY

The MARKAL family of models can answer a number of different policy and planning questions. The widest current applications are for the analysis of policies designed to reduce carbon emissions from energy and materials consumption. Since the framework depicts individual technologies, it is particularly useful to evaluate policies that promote the use of technologies. These technologies promote greater efficiency in energy or materials, or development and use of new technologies. Most aggregate modeling frameworks (e.g., macroeconomic models) lack this capacity. Whereas impacts of specific programs may not be identified in output from those other models, the impacts can be identified in the output from MARKAL. Considering that policies affecting technology choice represent one of the primary means for reducing greenhouse gases, this is an important feature.

MARKAL can be used to evaluate the following: R&D programs, energy performance standards, building codes, demand-side management and renewable technology programs, and other policies designed to guide the choice of technologies. By using the MARKAL family of models, users can evaluate the effects of various technology programs on both the average and shadow costs of carbon.

In addition to technology policies, MARKAL can be used to examine market-based instruments. Much speculation has occurred about the interaction between technology policies, energy price instruments (e.g., BTU taxes, carbon permits), and economic growth (Greening, Greene, and Difiglio, 1999). As the price of energy services falls in response to efficiency-induced increases in the supply of energy services, a concern is that many of the reductions from technology gains will be lost. This phenomenon is known as the “rebound” effect. As a result, it is important to design carbon mitigation or energy policies that incorporate technology and market based policies. In addition to energy price instruments, other market instruments, such as early emissions reduction investment credits, technology implementation subsidies, and lending schemes (e.g., funds dedicated or made available international donors) can be evaluated.

Current versions of the model can be used to model interregional, international, and intracountry carbon permit trading schemes. As part of the analysis of permit trading schemes, the representation of Joint Implementation (JI) and Clean Development Mechanism (CDM) projects is critical. Often, in order to gain acceptance for a greenhouse gas reduction strategy in developing countries, a carbon mitigation strategy, from which ancillary or additional benefits (e.g., increased standards of living and improved health due to reduction in local pollutants) accrue, will be required for acceptance and implementation. Those benefits can be identified, and quantified in an expanded MARKAL framework.

Although carbon sequestration projects may also be investigated in current versions of MARKAL, planned enhancements to the model, including linkages with detailed models of the forestry and agriculture sectors and a watershed model, will expand both the detail of output and the range of policies which can be evaluated. These three sectors (i.e., agriculture, forestry, and water) offer potential carbon mitigation strategies. Also, these sectors are impacted by the potential effects of climate change. For developing countries, which are usually heavily dependent on agriculture, inclusion of these three sectors in the planning framework is crucial for the development of integrated natural resource management plans.

Since there is a great deal of uncertainty associated with the formulation of carbon reduction policies, this aspect must be addressed in the analysis process. Uncertainties include CO2 reduction targets, emission permit prices, energy prices, levels of economic output and energy demand, and the paths or trajectories of technological development and adoption. Changes in any of these parameters can affect the choice of specific policy instruments, and the timing of implementation. MARKAL can evaluate the sensitivity of a given policy to these parameters through its stochastic programming feature. This sensitivity adds depth to the policy development process by allowing policy-makers to choose the set of policy instruments most likely to succeed in the face of the uncertainties enumerated above.

The MARKAL family is not limited to the analysis of carbon mitigation strategies. The framework has also been applied in the development of regional and local energy plans, and the evaluation of other types of emissions. For regional and local energy planning, the model may be used to evaluate the timing and capacity requirements for electricity generation and transmission, as well as district heat and natural gas distribution systems. Air quality issues may be evaluated through the use of MARKAL in conjunction with urban air quality models and geographical information systems (GIS). MARKAL has been employed in this type of analysis in several cities in Europe.

The most recent addition to the MARKAL family, TIMES, an optimization framework, significantly expands the number of policy and planning issues that MARKAL can address. For example, this version of the model should allow the evaluation of the effects of time-of-use electrical rates on load curves. Similarly, the vintaging aspect of this member of the MARKAL family should allow more complete evaluation of governmental policies designed to encourage the replacement of obsolete capital equipment. This version of the model also more rigorously evaluates industrial processes through the enhanced portrayal of these processes.

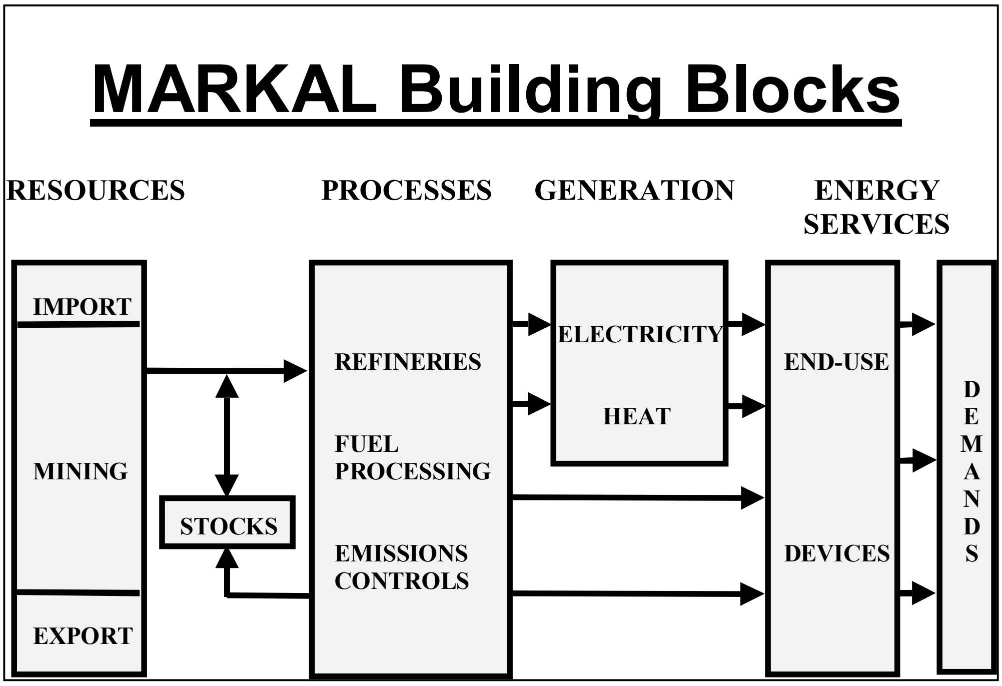
Recently developed enhancements in usability, and expanded support portend further opportunities for the use of MARKAL. The creation of a new user-friendly front/back end, and an increase in the availability of technical support and advice will expand the implementation of the model. Examples of planning tasks undertaken by private firms for which the model could be used include industrial infrastructure development and the financial planning required for various types of capital investment. Networked industries (i.e., electricity, natural gas, and telecommunications) have a number of potentially interesting problems that could be addressed by the MARKAL family of models. The full range of potential problems and applications has yet to be defined.

# 3. MARKAL

MARKAL (MARKet Allocation) is a bottom-up, dynamic linear programming model of a country's energy system. The model, first developed in the late 1970s for energy planning, continues to undergo development and refinement. Energy Technology Systems Analysis Programme (ETSAP) coordinates these activities, and is sponsored by the International Energy Agency (IEA). (More information about ETSAP can be obtained by visiting their web site at http://www.ecn.nl/unit_bs/etsap/).

As with most energy system models, energy carriers in MARKAL interconnect the conversion and consumption of energy. This user-defined network includes all energy carriers involved with primary supplies (e.g., mining, petroleum extraction, etc.), conversion and processing (e.g., power plants, refineries, etc.), and end-use demand for energy services (e.g., boilers, automobiles, residential space conditioning, etc.). The demand for energy services may be disaggregated by sector (i.e., residential, manufacturing, transportation, and commercial) and by specific functions within a sector (e.g., residential air conditioning, heating, lighting, hot water, etc.). The building blocks depicted in Figure 1 represent this network, referred to as a Reference Energy System (RES).

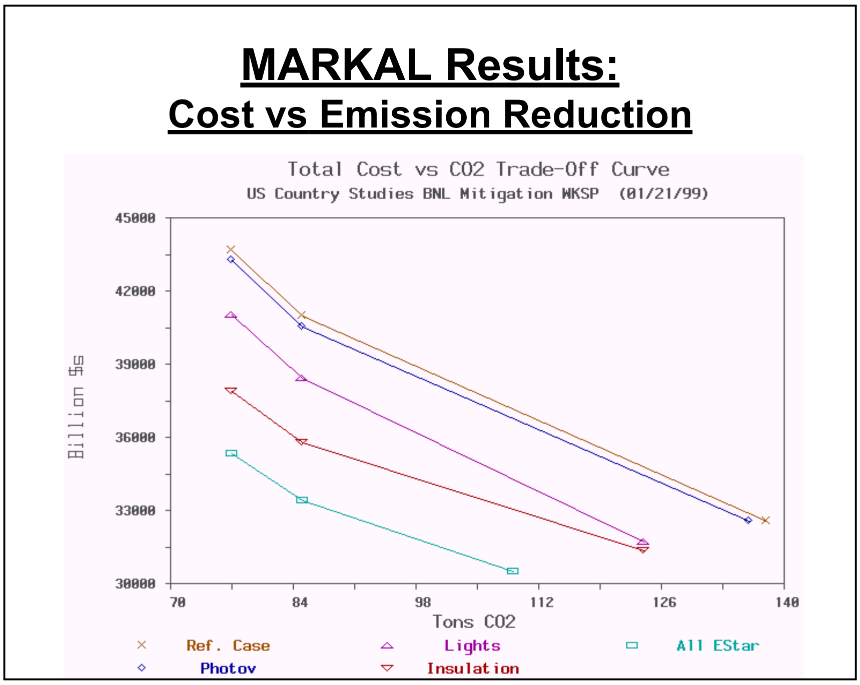
**Figure 1: MARKAL Building Blocks**




The optimization routine used in the model's solution selects from each of the sources, energy carriers, and transformation technologies to produce the least-cost solution subject to a variety of constraints. The user defines technology costs, technical characteristics (e.g., conversion efficiencies), and energy service demands. As a result of this integrated approach, supply-side technologies are matched to energy service demands. The specification of new technologies, which are less energy- or carbon-intensive, allows the user to explore the effects of these choices on total system costs, changes in fuel and technology mix, and the levels of greenhouse gases and other emissions. Therefore, MARKAL is highly useful for understanding the role of technology in carbon mitigation efforts and other energy system planning settings.

A variety of different constraints may be applied to the least-cost solution. These constraints include those related to a consistent representation of the energy system, such as balancing energy inputs and outputs, utilization of capacity, replacement of expended capacity by new investments and satisfaction of demand. In addition, environmental or policy issues, such as greenhouse gas emissions, may be examined in several ways, including sectoral or system-wide emissions limits on an annual basis or cumulatively over time. Alternatively, the imposition of a carbon tax or other fee structure could be modeled if desired. As a result, various costs for carbon may be generated for different levels of emission reductions. In this way, future technology configurations are generated and may be compared. If constraints are also placed on the types of technologies and rates of penetration, the configuration of the entire energy system will change. In all cases, MARKAL will produce the least-cost solution which meets the provided set of constraints.

**Figure 2: Cost of Emission Reduction**




An important fundamental result of running a MARKAL model is Constant Emission Reduction Indicator (CERI) graph that shows the change in total system cost as a function of the level of emission reduction. As illustrated in Figure 2, this is built up automatically from the individual technology choices made by the model, and the associated investment and operating costs. Comparing technologies by presenting the marginal costs on one graph provides an effectiveness ranking with respect to reductions in emissions for the selected technologies.

A number of limitations exist for this version of the MARKAL family. One of those limitations is the assumption of 'perfect information' and foresight, which precludes incorporation of uncertainty in the analysis. The dynamic nature of MARKAL implies that past decisions and future constraints are included in the decision process. Thus, if there is the expectation that limits will be imposed on greenhouse gas emissions, this information will be used in the decision process to expand or decrease the use of certain energy technologies, or to choose less carbon-intensive capital stocks during the planning horizon. As a result, structural changes in the capital stock may be explored, but those changes are limited to what is both economically and technically viable. However, uncertainties may be evaluated through the development of multiple scenarios, which are dependent upon the analyst.

Another major limitation for this version of MARKAL is that a number of key assumptions must be made. Most critical to the analysis are the assumptions made about energy service demand growth. With time, the growth rates of energy demand in many developed countries have declined for some end uses or sectors (e.g., manufacturing) and have, in some cases, actually uncoupled from GDP growth rates, to which assumptions of energy demand have often been tied (Greening et. al., 1998a). Still other end uses (e.g., transportation) may have either grown at rates equal to or exceeding GDP (Greening et al., forthcoming, Greening et al., 1996). For all end uses, many of these changes are at least partly attributable to improvements in technical efficiency and in some cases by economic behaviors. Therefore, for both developed and developing countries, the capability to link changes in energy demand growth to other economic behaviors, rather than leaving them at the discretion of the analyst becomes a necessity. MARKAL-MACRO provides this capability.

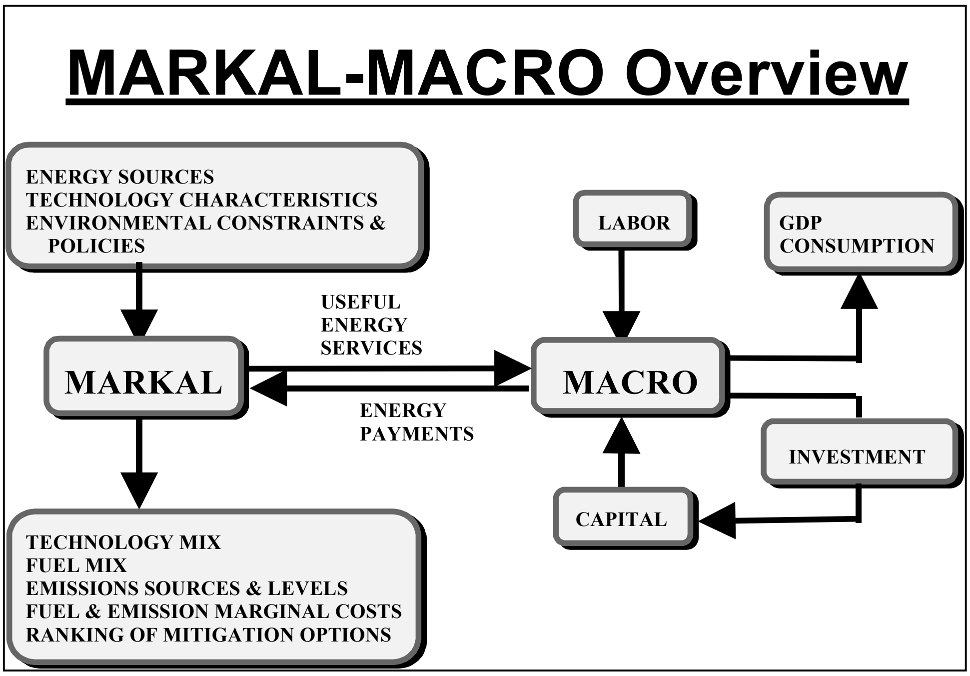
# 4. MARKAL-MACRO

MARKAL-MACRO is a non-linear, dynamic optimization model that links MARKAL, the 'bottom-up' specification of a country's energy system, to a 'top-down' macroeconomic growth model. The difference between a stand-alone MARKAL model and MARKAL-MACRO is the determination of levels of demand for energy services. The user independently determines energy service demand levels for MARKAL and specifies them in the model. However, this fails to capture the effects on energy prices resulting from improvements in energy-using technologies, or the effects on the macroeconomy from changes in those prices. In MARKAL-MACRO, once MARKAL finds the least-cost way to meet the demand, energy costs are passed back to MACRO, which compares energy costs to activity in the rest of the economy. If a decrease in energy costs causes an increase in consumer utility, then a new higher level of demand for energy services is estimated and returned to MARKAL, which repeats the cost analysis. MARKAL-MACRO continues the process until it finds the highest possible level of consumer utility. Figure 3 provides an overview of MARKAL-MACRO.

MACRO is a two-sector (production and consumption), aggregated view of long-term economic growth. This model uses economic output for investment, consumption, and inter-industry payments for the costs of energy. The model determines capital, labor, energy service demand, aggregate investment, and energy costs endogenously (i.e., internally in the model), but not changes in labor supply, which the user supplied. The MACRO portion of the model seeks to find an aggregate investment level to optimize economic growth and maximize discounted consumer utility. This criterion is used to select among alternative time paths for energy prices, macroeconomic consumption and investment. Linkage to MARKAL results in a very simplified macroeconomic model, with embedded rich technology detail. This early foray into integrated “bottom-up/top-down” modeling was first developed at Brookhaven National Laboratory in conjunction with Professor Alan Manne of Stanford University (Manne, 1993).

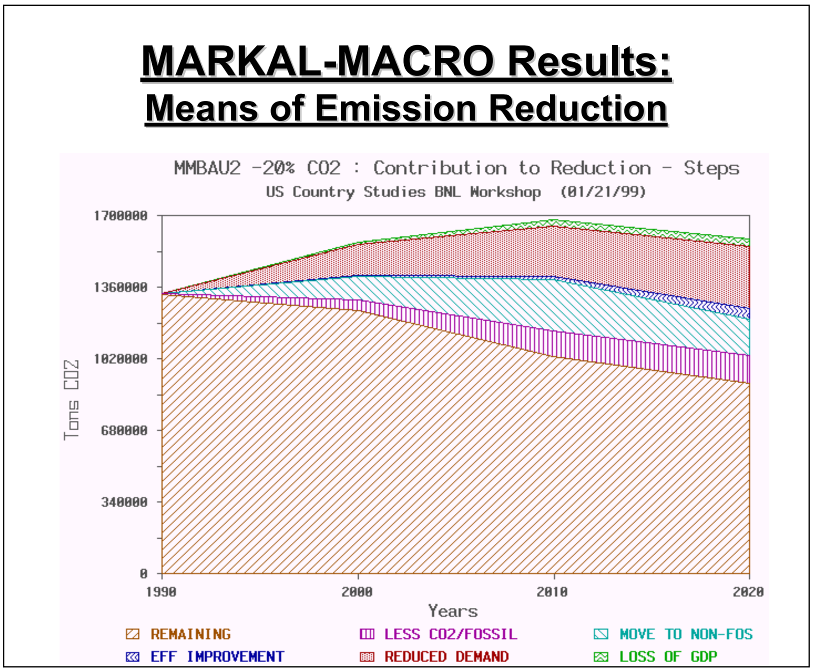
MACRO specifies production as an aggregate, nested, constant elasticity of substitution (CES) production function. The inputs (capital, labor, and energy) may be substituted for each other, but the specification of a CES production function ensures diminishing returns to this process (i.e., substitution will not occur indefinitely). At the top level of the tiered model structure, a capital-labor aggregate may be substituted for an energy aggregate. Capital and labor are disaggregated in lower tiers of the model, which means that capital and labor may substitute for each other directly (e.g., labor intensive processes are automated through capital investment). Through the use of this type of nesting framework, price-induced changes in the production structure will occur as the relative prices of the factor inputs change (e.g., substitution towards capital if the price of a unit labor increases relative to the price of a unit of capital, or vice versa).

**Figure 3: MARKAL-MACRO Overview**




MARKAL-MACRO identifies various sources contributing to the reduction of GHG emissions. Figure 4 provides a summary graph depicting the contribution to emission reductions from adjustments in the energy system, demand levels and GDP. Identification of these different sources is important from the policy development standpoint, as different sources will require different policy measures. It is primarily a market-based instrument that curtails demand growth, (i.e., a price signal). Efficiency increases may off set demand growth, but those efficiency increases may not be as effective as engineering analyses might predict (Greening, Greene, and DiFiglio, 1999). Therefore, the inclusion of a macroeconomic component, which allows for the feedback from the energy system model, results in an extremely powerful analytical tool.

**Figure 4: Contribution to Emission Reduction**




Unfortunately, there are limitations to MARKAL-MACRO's simplified expression of the macroeconomy. The model is only able to roughly capture many of the changes in energy demand resulting from changes in economic structure and other sources (Greening et. al., 1998a). Changes in economic structure result in declines in one segment of the economy, while another segment increases. As a result, the responsiveness to price changes will change with time (e.g., as a more energy-price responsive segment increases, the aggregate energy-price response will also increase). However, MARKAL-MACRO does accept a demand "decoupling" factor for each sector and time period, which provides a simple mechanism for expressing these different changes. Also, this type of representation fails to capture the effects of changes in consumer preferences that may occur, or the effects of increases in income on energy consumption (Greening et. al., 1998b, Greening, Greene, and DiFiglio, 1999). Finally, MACRO assumes a balanced growth path. For developing countries, this may not necessarily be the appropriate assumption. Economic and political conditions can result in disequilibrium. To allow for these types of market conditions, an alternative formulation of MARKAL has been developed. This approach, discussed in the next section, presents energy consumption and supply in a partial equilibrium framework.

# 5. DEVELOPMENT OF MARKAL TOWARDS A PARTIAL EQUILIBRIUM MODEL

A MARKAL model solution in its standard version may be interpreted as competitive market equilibrium for energy markets, where energy demands are fixed. However, the endogenous determination of price sensitive useful energy demand jointly with price sensitive supplies of energy is a more complete representation of market behaviors. Such a partial equilibrium approach represents an alternative to MARKAL-MACRO. It is also possible to determine the effects on GDP (using the partial equilibrium approach) when adjusting energy demands by sector in response to mitigation policies. (Scheper, and Kram, 1994.)

A partial competitive equilibrium can be defined as a demand 'x' and a supply 'y' at a specified price. The equilibrium conditions for a competitive market can be stated as follows:

- one market-clearing price per commodity,
- no excess demand in that market, and
- efficient market pricing (price is zero if excess supply exists),
- where demand and supply are derived from the rational behavior of economic agents (i.e., consumers maximize utility and producers maximize profits and minimize costs).

In the partial equilibrium formulation, the traditional MARKAL formulation has been altered to reflect these assumptions. The traditional MARKAL model generates an aggregate supply curve, which provides the cost-minimizing supply of the energy needed to satisfy the different categories of useful energy demand and the associated market price (i.e., marginal cost). The total cost derived from the solution can then be interpreted as the integral under an assumed supply curve. The exogenously defined useful energy demands have been replaced with energy demand functions. These functions relate the demand to the market price that MARKAL has generated. Further, these functions satisfy the usual conditions of continuity, differentiability, a negative slope, and the constraints imposed by cross price elasticities. Both non-linear and step-wise linear representations of demand have been implemented in MARKAL-MICRO (MICRO) and in MARKAL-ELASTIC_DEMAND (MED) respectively.

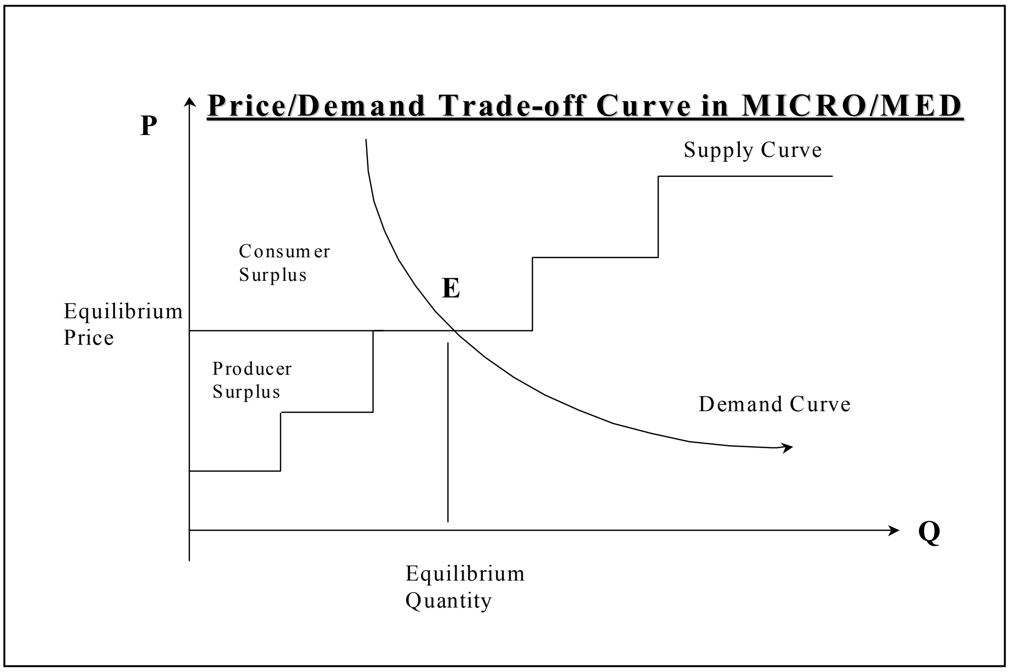
Within the objective function of the model, the sum of consumer and producer surplus is maximized and the equilibrium between supply and demand is derived. These relationships are presented in Figure 5. Measures of consumer surplus are defined as the difference between the total value consumers receive from the consumption of a particular good and the total amount they pay for the good. Consumer surplus is the area under the demand curve above the market price. Measures of producer surplus (i.e., profit) are defined as the difference between the price and the marginal costs of production or the area between the supply curve and the price. This equivalence is based on the following assumptions

- for consumers, the price corresponding to a given quantity on the demand curve represents the willingness to pay for one more unit of energy or the value given by energy to the consumer.

- for producers, which are assumed to be price-takers with free entry and exit from the energy supply industry, supplies are determined by the long run marginal cost, with total costs of production minimized. Therefore, the price corresponding to a given supply represents the marginal cost at which firms are willing to produce one more unit.

- for both entities, the maximum benefits are obtained when the price of energy is equal to the marginal costs of production.

**Figure 5: Relationships depicted in MARKAL-MICRO/MED**



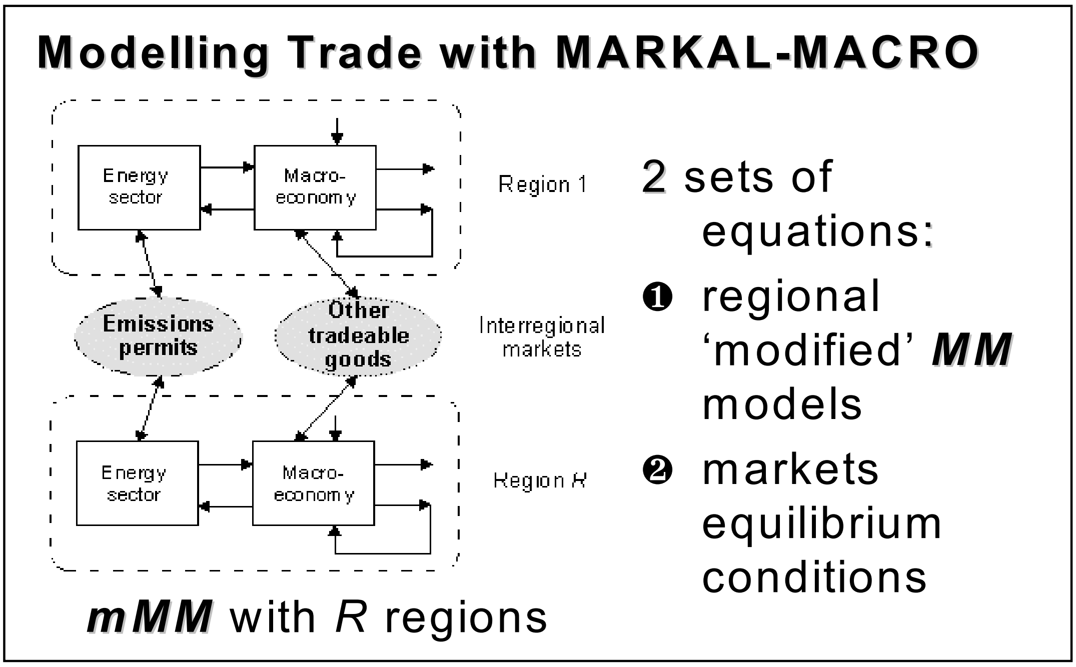

In MICRO responses in price are assumed to be symmetric, i.e., the change in demand is the same whether prices are increasing or decreasing. However, time-series analysis of energy trends indicate that energy demand exhibits a lag in response (Gately, 1993). Rates of capital turnover and technological innovation in the consumption of energy result in an asymmetrical demand response, and demand may not return to previous levels. MED does permit elasticities and variances to be specified independently for upward and downward movements in demand to partially deal with this. In addition, in its current implementation, this framework uses uncompensated own-price elasticities of demand, which do not fully reflect income effects. However, energy consumption does increase with income. Further, rates of increase decline relative to rates of increase in income as income increases above certain levels, (i.e., demand is quasi-homothetic—Greening and Greene, 1998). To provide for income effects, MED has been expanded to accommodate income elasticities. With these added capabilities, and by remaining within the realm of linear optimization, MED has a great deal of potential.

(This work was initially carried out at the Catholic University of Leuven (Belgium) and Groupe d'Études et de Recherche en Analyse des Décisions (GERAD of Canada) respectively. For more information on the current version of this member of the MARKAL family, contact Denise van Regemorter, denise.vanregemorter@econ.kuleuven.ac.be, at KUL for MICRO or Amit Kanudia at GERAD for MED, amit@CRT.UMontreal.CA).

## 6. LINKING MULTIPLE MODELS

Traditionally, MARKAL has been applied to a single geographic area, normally a country, state or municipality. However, the need to examine the potential benefits of cooperation between regions or other stakeholders has become an increasingly important for the development of cost-effective climate change mitigation and energy infrastructure development strategies. Flexible mechanisms such as permit trading, Joint Implementation (JI), and Clean Development Mechanism (CDM) projects are gaining importance in the development of carbon mitigation strategies. Since JI/CDM projects are assumed to be bilateral arrangements between two countries (or partners in each country), evaluation of a specific projects' GHG emission levels and costs requires analysis for both countries. The combination of two (or more) MARKAL models maintains all the richness of the technology applied. As a result, individual or cumulative ("bubble") emission limits can be allocated to stakeholders from specific projects, trading opportunities can be evaluated, least-cost options identified, and the associated benefits quantified. Similar considerations exist for the development of regional energy infrastructure (e.g., electricity transmission grids). To meet these needs, as illustrated in Figure 6, multiple country-specific MARKAL-MED and MARKAL-MACRO models have been combined.

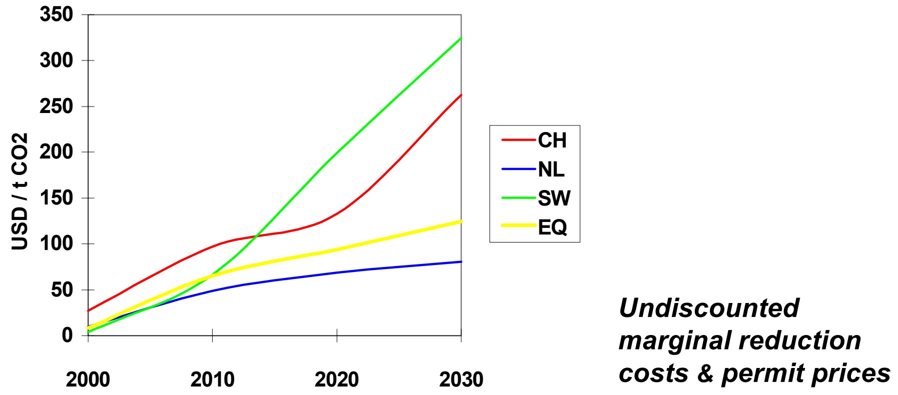
**Figure 6: Linking Multiple Models**




With the linked version of MARKAL, emission permits and energy products may be either traded freely (among the cooperating partners), or according to explicitly specified trade patterns. Specific technology choices can then be made and the displaced technologies identified. The feedback between the overall macroeconomy of each country and the respective energy systems is maintained through trade in other commodities, while the specific effects on the energy system are captured through trade in carbon permits or the implementation of joint projects.

As Figure 7 shows, incorporating emissions permits into a carbon mitigation strategy can dramatically affect the marginal cost of reducing emissions. For Switzerland (CH) and Sweden (SW) the costs of reducing carbon emissions by 20% are less if these two countries compensate the Netherlands (NL) for undertaking greater reductions. Since each individual model retains all of its technology detail, the differences in the evolution of the energy system with and without cooperation can be examined. As shown in Figure 8, in this case without cooperation (nc) substantially reduced levels of electricity production are required, and more expensive national mitigation options are needed. But with a carbon permit trading scheme, the impact on the power sector is not as severe.

**Figure 7: Benefits of Trading Emission Permits**




| Scenario | Country | 2000 | 2010 | 2020 | 2030 |
|---|---|---|---|---|---|
| -20% | CH | -0.8 | -1.5 | -1.7 | -3.7 |
| | NL | -0.6 | 4.6 | 12.2 | 25.5 |
| | SW | 1.4 | -3.2 | -10.8 | -22.2 |

***Net export of $CO_2$ permits (Mt/year)***

**Figure 8: Country Details in 2030w/Cooperation (c) or not (nc)**

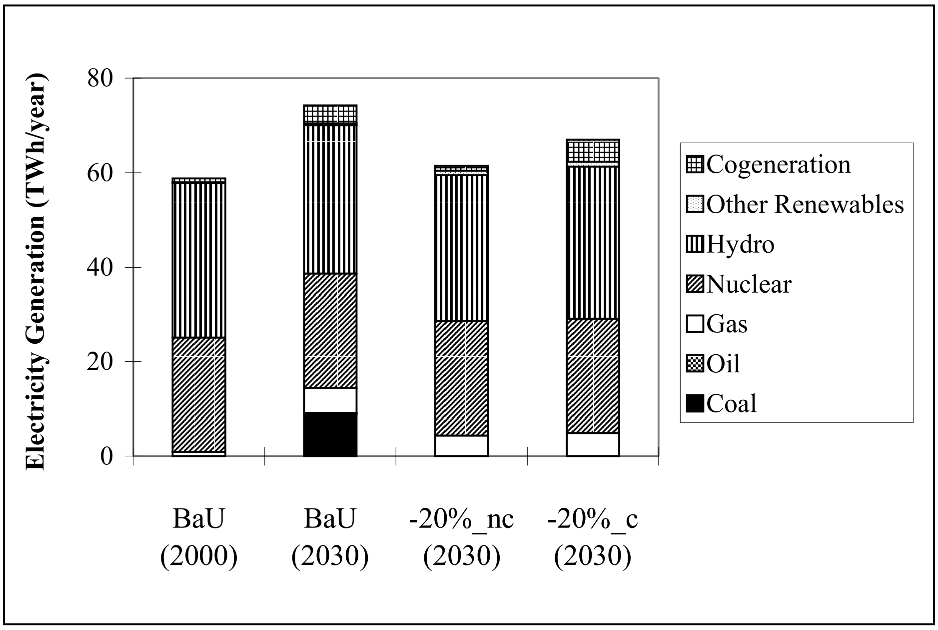


**Figure 9: CO2 Marginal Costs for the Cases Analyzed.**

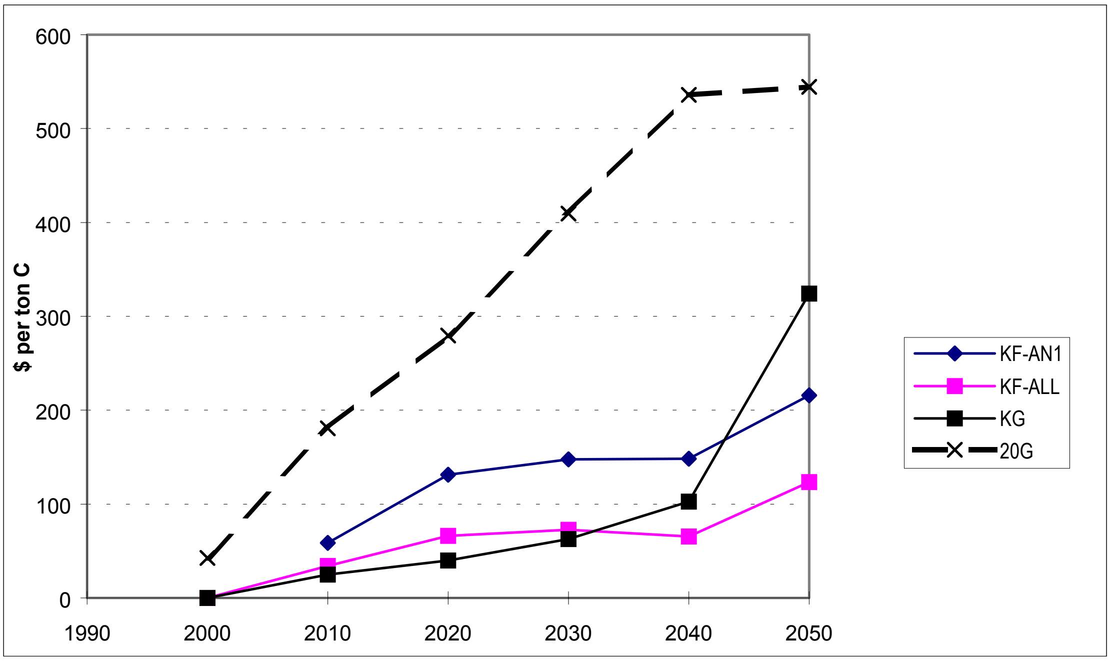



**Figure 10: Emission Reduction Accounting Energy vs. Energy + Materials**

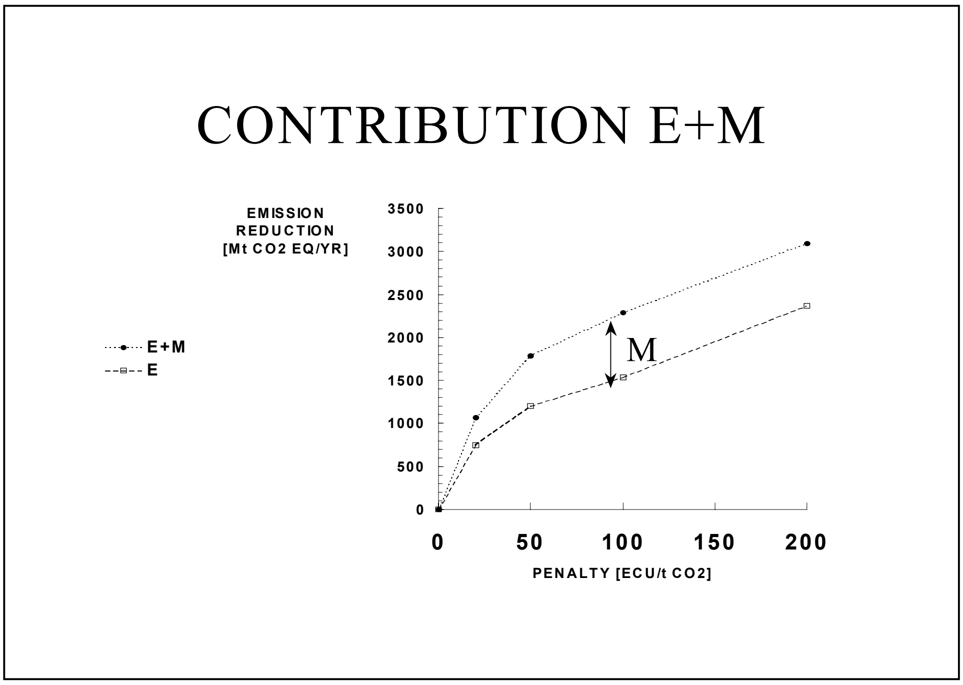
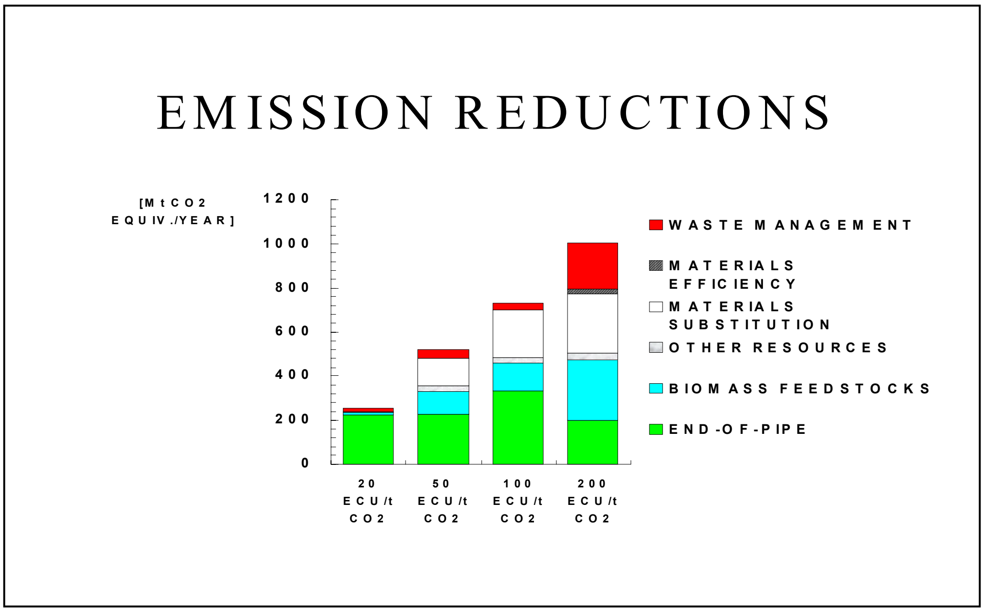


**Figure 11: Emission Reduction Accounting Energy vs. Energy + Materials**




A current undertaking integrates MARKAL-MACRO with MERGE (Manne, 1993), a global trade model. MERGE links a number of ETA-MACRO sub-models to produce a complete global system. ETA-MACRO models are in principle very reduced MARKAL-MACRO models. This approach replaces one of the five ETA-MACRO regions represented in MERGE, in this case the US, with its MARKAL-MACRO counterpart. The resulting integrated framework retains the full technology richness available in MARKAL while at the same time providing for global trade in energy, and CO2 permits. The benefits of full trade are reflected in the reduced marginal cost when all parties participate.

The work presented here is extracted from an informal technical report and the 1998 Annual Report from the ETSAP team at the Paul Scherrer Institute (PSI). Further detail is available at http://www1.psi.ch/www_f5_hn/Systems/ENECO/eneco_ho.html. Figure 6 depicts a linked multi-regional version of MARKAL-MACRO, which while operational at PSI is not currently a viable production model. However, at GERAD (http://www.crt.umontreal.ca/~amit/emg/), a multi-region MARKAL/MED has been successfully applied in a production environment to link the US, 6 Canadian provinces and India.

# 7. MATERIAL FLOWS

Studies have shown that approximately one third of all GHG emissions can be attributed to the materials system (Gielen, 1998). Therefore, changes in material flows can significantly influence GHG emissions. To examine the relationship between energy and materials, the flexible-flow structure of MARKAL was expanded to include material flows. MARKAL tracks materials from production through disposal using the same flow structure as applied to energy, along with provisions for accounting for the value of recovered materials. The MATTER (MATerials Technologies for greenhouse gas Emission Reduction) project, performed at ECN (http://www.ecn.nl/unit_bs/etsap/markal/matter/), applied this version of MARKAL to Western Europe.

The following GHG emission reduction strategies have been considered in an energy/materials system:

- industrial process improvements,
- CO2 removal from industrial plants and storage in depleted gas fields and aquifers,
- reduction of non-CO2 GHG emissions through end-of-pipe technology and process substitution,
- reduction of materials consumption through product substitution (e.g. re-useable packaging),
- materials substitution,
- renewable biomass feedstocks,
- improved waste collection and separation systems, and
- waste recycling, cascading and energy recovery.

Integrated assessment of improvements in the energy- and the materials systems is important because different reduction strategies influence both the efficiency and related operations of the other. For example if the introduction of renewables results in a less-carbon-intensive electricity generation mix, production from more carbon-intensive waste incineration plants becomes a less attractive option. As a consequence of such interactions, the assessment of the potential and of the cost-effectiveness of reduction strategies requires an integrated systems approach. In addition, a dynamic approach is required because of the time lag between materials consumption and waste release beyond the product life. For example, changing materials consumption in one year can influence the recycling potential in future years. Moreover, GHG emission reduction strategies may take decades until fully realized. Changing technology, changing consumption patterns, changing resource prices and changing environmental policy goals are issues, which must be considered in such a dynamic analysis.

Figures 10 and 11 (see pp. 14-15) summarize the primary model results from the ECN effort. Rigorous accounting of material flows and related emission reduction opportunities can account for as much as 30% of overall emissions reductions. These results demonstrate that integrated long-term materials strategies can be developed for Western Europe and other areas. (More information regarding the MATTER model is available from ECN, Dolf Gielen, gielen@ecn.nl.)

## 8. TECHNOLOGY INNOVATION BY ENDOGENOUS TECHNOLOGY LEARNING

Technology dynamics (learning) within energy system models have been traditionally limited to relatively short time horizons, with the assumptions defined by the user. The initial pioneering work on the endogenous representation of technology learning (ETL) in energy system models like MARKAL was done by Chalmers University in Sweden (Mattsson, 1997, GENIE model) and IIASA (Messner, 1997, reduced version of MESSAGE model). The Paul Scherrer Institute (PSI) developed the basic source code to incorporate technology learning in MARKAL (Kypreos and Barreto, 1998; Barreto and Kypreos, 1999). Both PSI and ECN have performed MARKAL calculations with this ETL feature. The work was part of a EU sponsored research project TEEM, which included major modeling centers in Europe (ICCS/NTUA, KUL, IEPE, ECOSIM, ECN, PSI, ESD, and IIASA). The project has resulted in the development of an endogeneous representation of this process in a number of modeling frameworks including MARKAL. Using estimated relationships between cumulative world wide sales and technology investment costs, which typically decline with experience, the process of 'learning by doing' can be modeled. As a result, MARKAL users will be able to gain insights into the longer-term effects of experience gained with a less-carbon intensive technology.

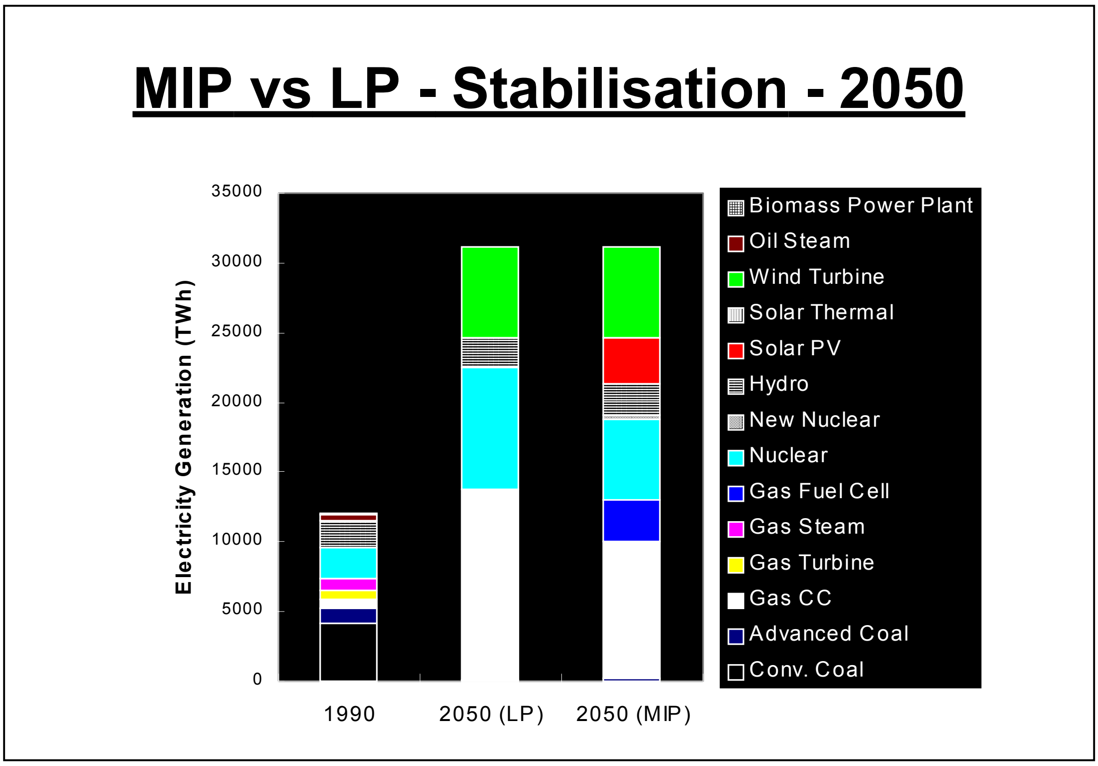
As shown in Figure 11, photovoltaics and fuel cells enter the mixed integer program (MIP) solution, as a result of learning, as opposed to the standard linear program (LP) solution.

A number of questions had to be resolved in the development of an endogenous depiction of technological learning in the MARKAL framework (Seebregts et. al., 1998). In previous versions of MARKAL, the parameters characterizing a technology were made consistent (i.e., aligned) with each other by the user. However, with the exception of the starting point, this process cannot be performed in a model with endogeneous learning. This means the costs of a technology cannot decrease in a market (or country) in response to learning occurring in another market (country). Therefore, a mechanism was developed to perform the process of alignment. The implemented mechanism involves the selection of "key technologies." Key technologies are a component in many other technologies, e.g., gas turbines, fuel cells, and boilers (Seebregts et al., 2000). For the EU MARKAL model of ECN, twenty technologies were assigned to this classification.

The current implementation of technological learning in MARKAL assumes that the key technologies will undergo a steady and stable future development. A number of factors can alter this assumption, yet, no single economic theory explains the process (Greening and Khrushch, 1996). As a result, various criteria must be applied in the selection of key technologies, which exhibit the effects of technological learning. Endogenisation of technology learning is appropriate for technologies, which match one or more of the following criteria (Seebregts et al, 1998):

- a major reduction in investment costs as a result of technology learning,
- a large expected impact of technology learning on model outcomes,
- technologies, which are clearly distinctive with respect to the applied energy conversion process, and
- the presence of a direct competing technology with endogenised learning.

**Figure 12: Affects of Technology Learning**




From several perspectives, the TEEM effort provided a number of insights on the inclusion of technology learning in a modeling framework. From a modeling perspective, the selection of key technologies allowed for the generation of global solutions (rather than local optimal solutions). Further, the addition of technology learning provided some useful insights for the development of carbon policies. The TEEM results clearly show that a carbon policy can increase the adoption rate of renewables. However, for a more detailed evaluation of the effect of R&D, the "spill-over" of learning effects from one technology to another, including implications on efficiency improvements and future O&M costs additional work will be required.

However, this work did identify the most sensitive parameters. Learning is most sensitive to the progress ratio (rate at which the investment cost of the technology declines), the initial investment cost, and the initial and maximum cumulative capacity. In particular, for technologies which currently have high costs and are only marginally applied, changes in these parameters can have substantial impacts on the model's output. Depending on the starting point on the S-shaped diffusion curve (young versus mature), greater or lesser impacts will occur. The assumed maximum cumulative capacity will also determine the ultimately achievable levels of cost reductions. Because these parameters are at least partially amenable to changes in policy, these results can have a number of ramifications for that process. For example, investment costs and the progress ratio can be impacted by changes in tax laws (investment credits) and subsidies.

Additional information on the TEEM project and results may be obtained from Leonardo Barreto, Leonardo.Barreto@psi.ch, at the Paul Scherrer Institute in Villigen, Switzerland, and Ad Seebregts. seebregts@ecn.nl, at ECN, Petten, The Netherlands. Since March 2000, a follow-up research project SAPIENT is being performed, sponsored by the EU. The ETSAP partners ECN, PSI, and IER are involved in that project.

# 9. STOCHASTICS

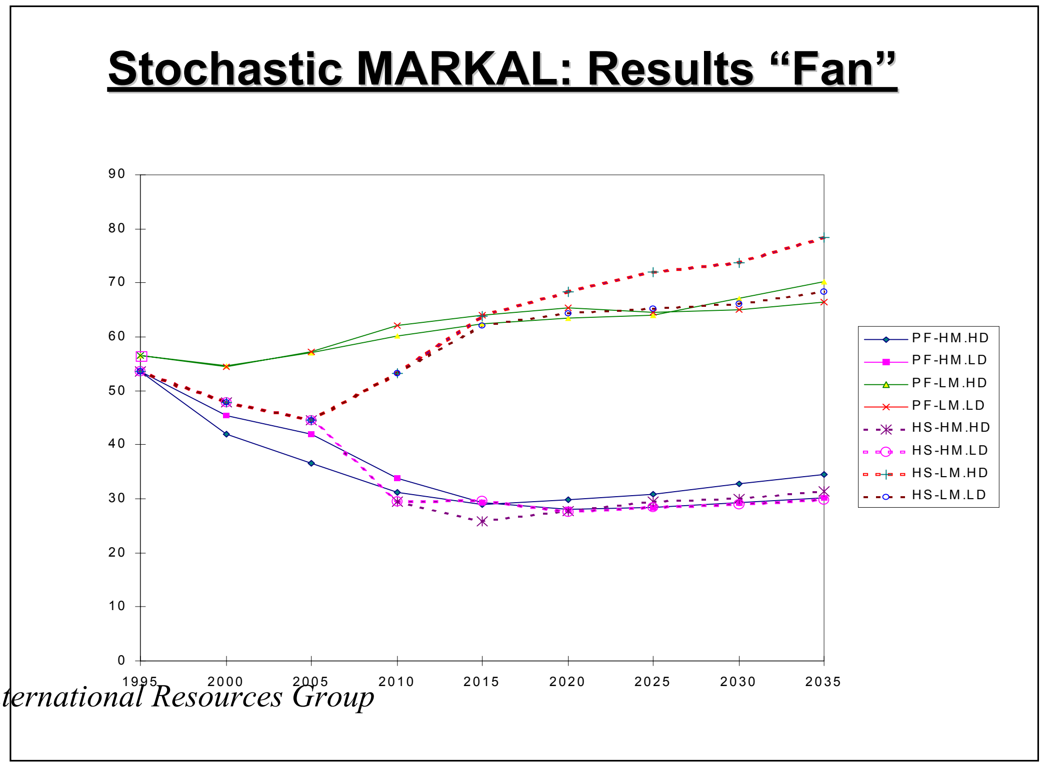
Analyses in support of climate change decision making are characterized by uncertainty. Carbon reduction targets, carbon emission permit prices, future costs of energy, levels of economic output (energy demands), and future penetration rates of particular technologies are among those uncertainties. These uncertainties are often among the most influential drivers in a model solution. Traditionally, uncertainty has been dealt with by scenario analysis. Different scenarios are developed based on an analyst's assumptions, and compared to discern the implications of their various outcomes. However, a more sophisticated way to include uncertainty within the MARKAL model employs stochastic programming.

Stochastic programming provides the best near-term strategy in light of long-term uncertainties. With traditional discrete scenario analysis, each scenario represents a specific view of the future. With stochastic programming a range of possible futures are identified and solved collectively as a single view of the future, but with consideration given to several plausible paths. As a result, near-term decisions consider long-term uncertainties, and "hedging" strategies, which are robust with regard to enumerated future conditions, are identified. This is particularly important in the context of energy systems planning since near-term decisions often have long-term implications. This is typically the case with major capacity investment decisions such as power plants and distribution systems, buildings, and industrial facilities.

Uncertainty is included in a dynamic stochastic programming model through the use of different states-of-nature. Probabilities and different values for each of the uncertain parameters are assigned to each state-of-nature. In addition to these input assumptions the user must also indicate the point in time when the uncertainty is resolved. For example, uncertainty may exist whether high or low levels of CO2 emissions will be allowed in the future. However, resolution of this uncertainty will occur by 2005. In calculating an optimal solution, MARKAL minimizes the ***expected (probability weighted average) discounted cost*** of the energy system. In calculating the expected cost for a time period, MARKAL provides a single, deterministic solution until the moment of resolution of the uncertainty. After that moment, MARKAL will calculate the expected cost by weighting the cost of the energy system for each state of nature with the probability assigned to it.

Through its dynamic nature, MARKAL will explicitly consider the consequences of pre-uncertainty-phase energy system decisions on the uncertainty-phase energy system configuration. As a result in a stochastic solution of the CO2 reduction example, more renewable technologies will be deployed earlier, than if only the low reduction path was considered. However, fewer of these technologies will be included if only the high reduction scenario were followed. Even with the same probability assigned to both events, it is unlikely that renewable deployment will be evenly divided between the two states as illustrated in Figure 12. Therefore, the final quantity of renewables identifies the "hedging" role of this technology. Similarly, if new investments in coal-fired power plants do not enter in the stochastic solution there is a high probability that, new coal-fired capacity will not be in operation for the expected lifetime under a higher carbon reduction target.

**Figure 13: Results for a Stochastic Analysis of CO2 Reduction**



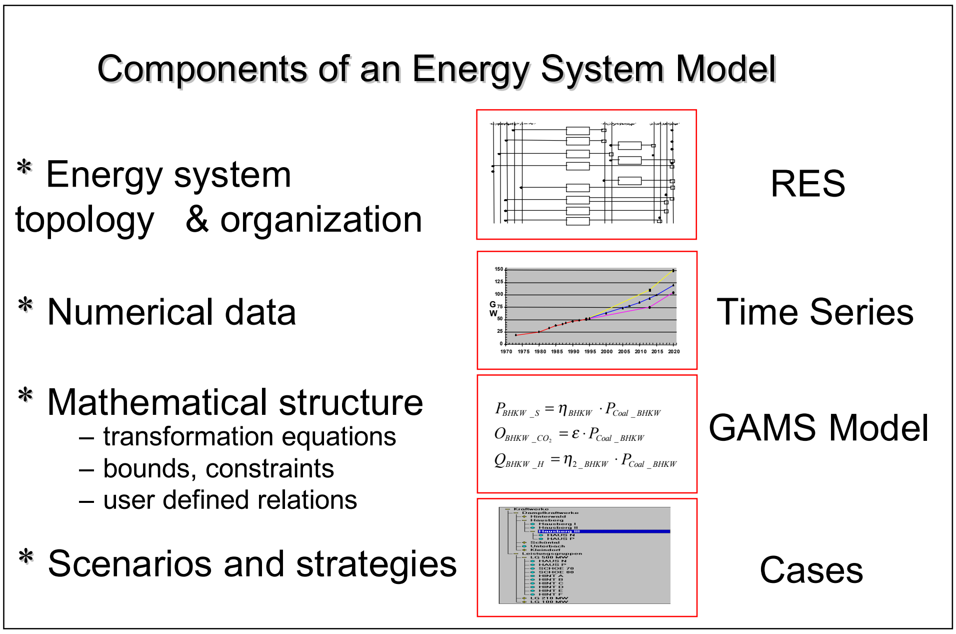
While stochastic MARKAL represents an improvement in the handling of uncertainty, this version of the model does have some limitations. Energy demands within this framework must be defined exogeneously by the user. At this time, this version does not provide for a linkage with MACRO, and does not incorporate the features of MICRO. Also, this implementation of the model only allows for two states-of-nature, and permit trading cannot be evaluated – i.e., there is no provision for linkage between regions. However GERAD has a special (Extended) version of MARKAL available that does incorporate trading between regions, and permits multi-stage stochastics.

(The figure shown here is courtesy of Amit Kanudia of GERAD, Canada, amit@CRT.UMontreal.CA.).

## 10. ANSWER

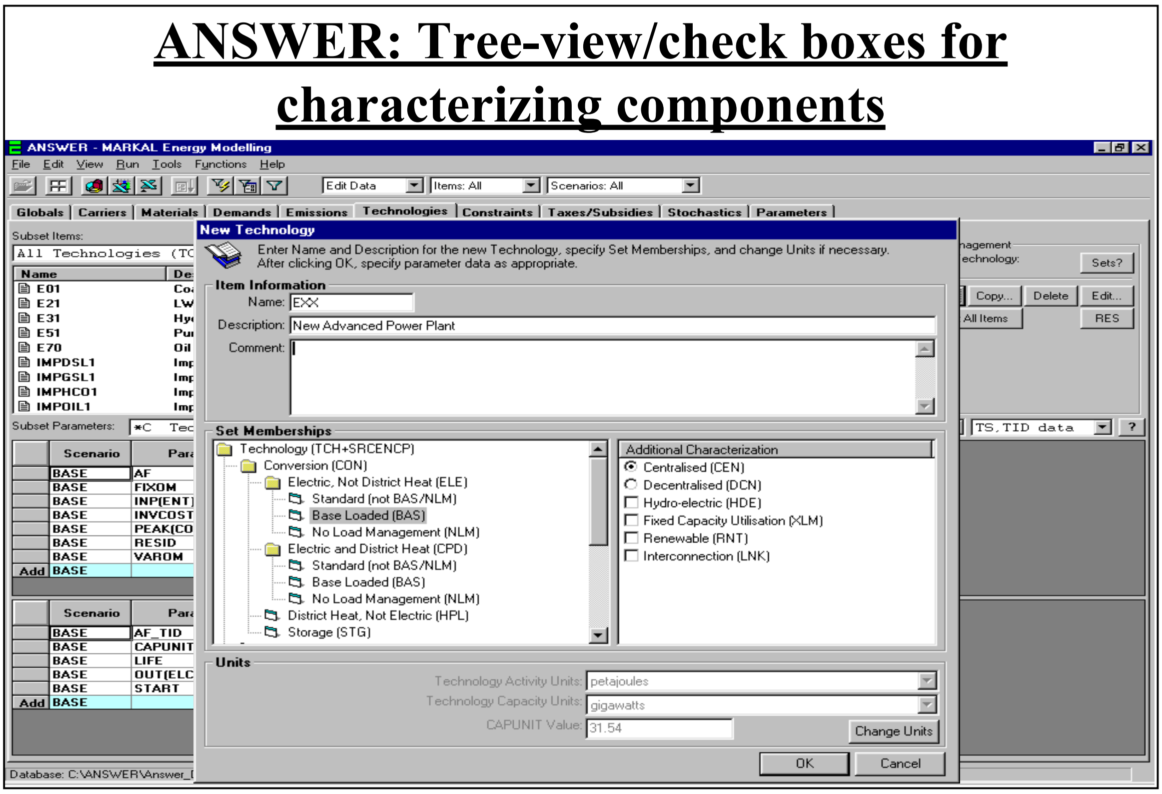
As Figure 13 illustrates, a complex modeling system such as MARKAL-MACRO consists of four components. However, although the theory and mathematics underlying the model are complex, MARKAL users can effectively work with the model without a complete command of the computational methods employed. This goal is achieved through the use of a data handling and analysis support "shell." This shell handles the interactions between the user and the rest of the modeling system.

**Figure 14: Relationships between Modeling Components of an Energy System**



ANSWER, the new front/back-end for MARKAL, was introduced during 1998. This Windows based facility substantially reduces the learning time required for new MARKAL users. A tight integration between the three components associated with working with a RES (Reference Energy System) greatly reduces the length of time required to build a model, and avoids many of the potential mistakes that can occur. ANSWER provides for the rapid definition of the topology (the interconnection of the technologies by their energy carriers), the classification or grouping of technologies (e.g., supply, conversion, demand, etc.), and data entry (the actual description of the individual components in the network). Improvements in the data handling facility ensure that the RES is correctly defined, component identification and classification are complete through the use of 'trees,' and that process/commodity descriptions have the correct attributes and units. Figure 14 illustrates some of these features. When a new technology is created, all relevant compulsory parameters are set to defaults or brought directly to the user's attention. As part of this improved data handling facility, context sensitive, pull-down menus and a "Help" feature have been provided.

**Figure 15: RES Component Assignment**




ANSWER provides a number of enhancements over the original front end (MARKAL User's Support System, MUSS) for the analysis and presentation of input assumptions and results. These enhancements include:

- data editing capabilities via 'direct cell editing,' similar to a spreadsheet, with data gathering and organization possible using Microsoft EXCEL.

- utilities for scenario management of model data, and for case management of model runs and results.

- screening/filtering options (e.g., data for a given classification of technologies, such as central generation facilities, may be examined as a group).

- input or results may be simultaneously examined side-by-side, with data while cascading through the RES.

- powerful graphics and report writing capabilities via a link to EXCEL and paste capabilities into WORD for Windows, along with three-component charting in ANSWER.

- full support for the latest production MARKAL-MACRO GAMS code.

ANSWER presents a single consistent screen format for all data handling operations (for both inputs and results). Information associated with any RES component can be easily accessed through this same interface. Figures 15, 16, and 17 illustrate these features.

**Figure 16: Attribute Form Comparing Input Data**

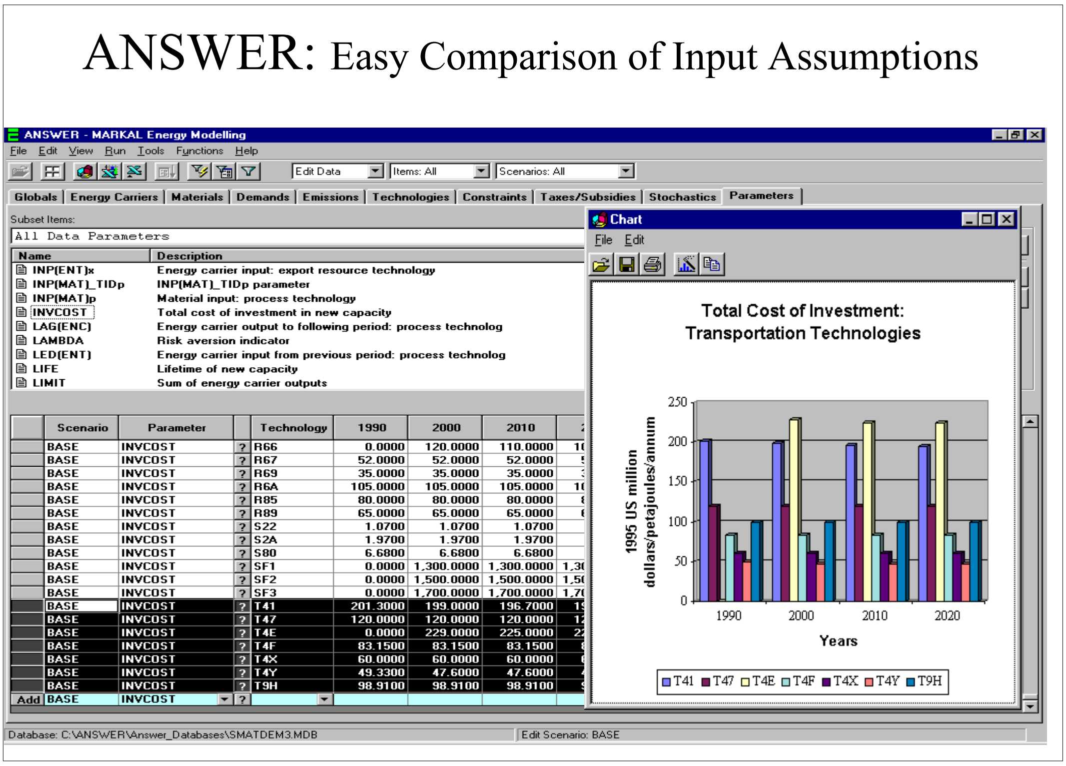
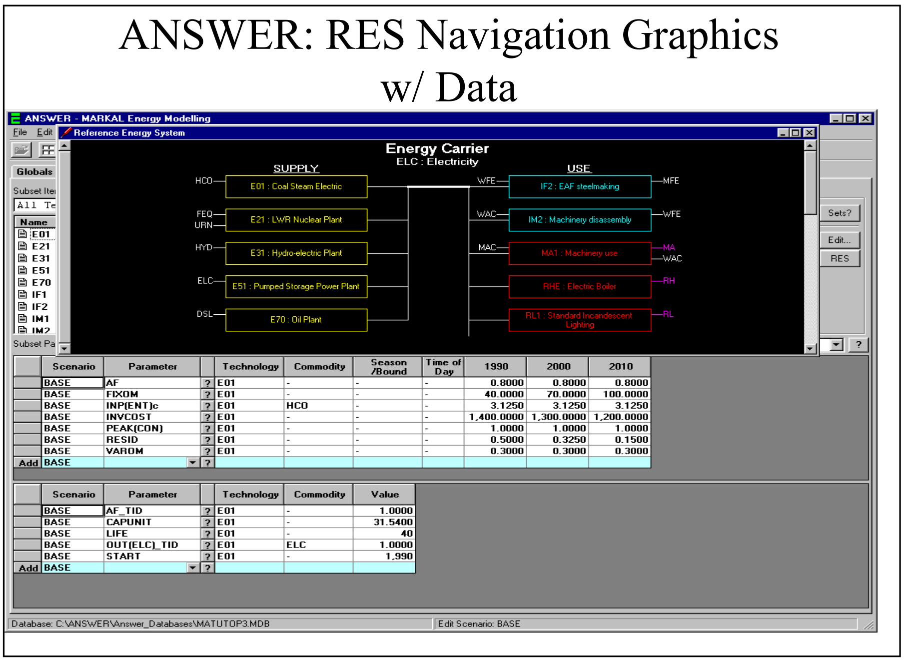


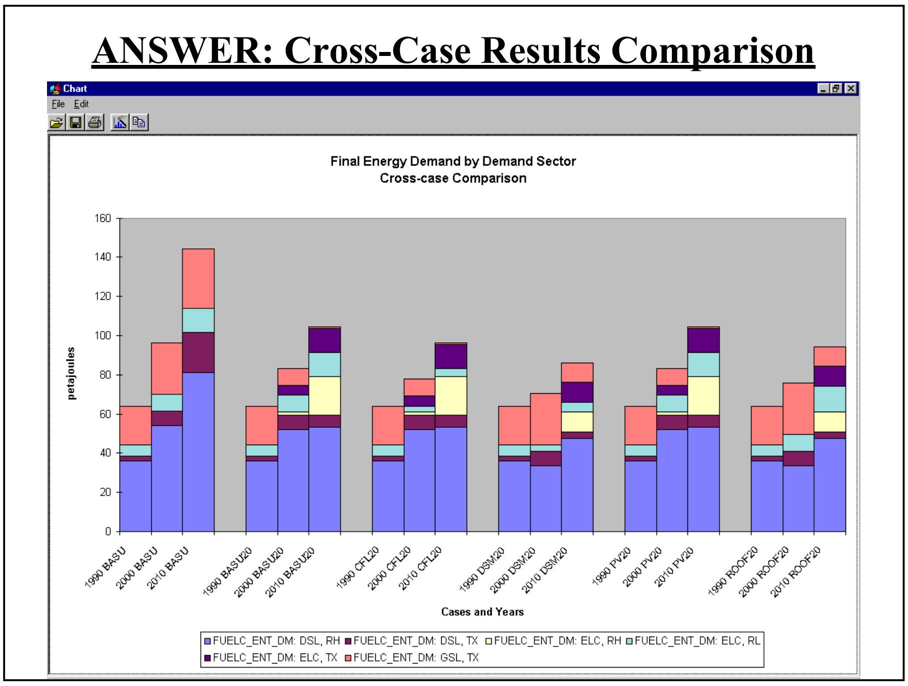
Figure 16 shows an attribute oriented view of the data produced by simply selecting the desired parameter from the Parameters Tab's attribute list. An optional filter may be applied to limit the selected data subset. In Figure 16, investment costs for each demand device have been retrieved, and those associated with the transportation sector have been graphed. Graphs may be generated by highlighting rows in the spreadsheet and selecting the desired style of graph.

**Figure 17: RES and Data**




The simple production/use RES window can be used to navigate through the RES by clicking on the energy carriers. Technology data can be retrieved by clicking on a process box.

**Figure 18: Multi-Case Comparison of Results with Embedded Graphics**




Comparison of modeling assumptions or results for different cases can be made by accessing data by the RES component. In addition, as shown in Figure 18 standard report tables are also produced by the model for each run.

ANSWER continues to evolve. An ANSWER Analysis Assistant that will allow users to customize reports is under development. There are also plans for the development of a GHG technology database. Users will be able to access and directly import technology characterizations when building new models, or when introducing new technologies to existing databases. This will increase the speed at which new models may be built.

ANSWER was developed by the Australian Bureau of Agricultural and Resource Economics (ABARE) in close collaboration with International Resources Group (IRG) on behalf of the ETSAP partners. For more information on ANSWER contact Ken Noble (KNoble@abare.gov.au) at ABARE or Gary Goldstein (ggoldstein@irgltd.com) at IRG.

## 11. ADVANCED LOCAL ENERGY PLANNING

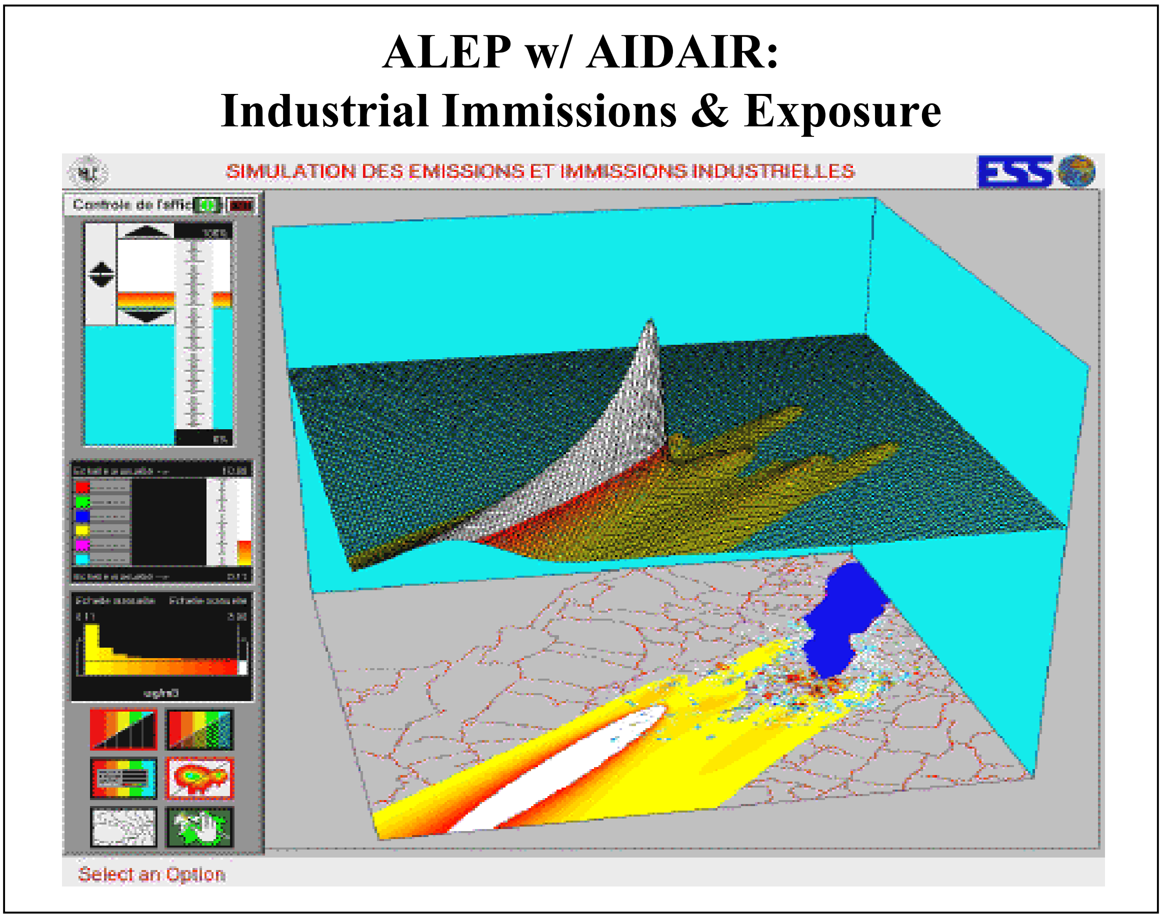
Several members of the MARKAL family may be used to assess energy and environmental policies at the community level within the context of the entire energy system (Wene, 1988, Jank, 1994). Global issues (e.g., the Kyoto Protocol) have to be translated into national commitments, which, in turn, require local planning and action. In addition, concerns over local air quality, other types of pollutants, and changes in the regulatory environment have resulted in new environmental regulation and restructuring. During the course of addressing these issues, local communities have been asked to determine goals for their community, and build a consensus on implementation of an energy plan. For this process, a model such as MARKAL can provide an integrating framework for both planning and the political process.

MARKAL serves a number of purposes at the local level. The model manages the complexity of a highly interdependent system where there are a number of competing objectives with diverse interests. For example, a local public utility with generation resources is often connected to a regional grid. As part of that connection, the utility is asked to help maintain and support the viability of that system. Within the utility service territory, the utility must be able to satisfy demand at any point in time under the appropriate regulatory regime. With restructuring and deregulation in some areas, the utility must do this with the least-cost mix of generating capacity. In addition, the utility must also address the concerns of public interest groups, ordinary citizens, and at some level the local regulatory body. Furthermore, interest in assessing a possible expanded role for combined heat and power, as well as natural gas, requires facilities for planning distribution systems.

A modeling framework used for local energy planning must provide for the flow of information to all interested parties, provide an environment for conflict resolution, and for learning about problems. The energy modeling framework should also complement other models in use, such as geographic information systems (GIS) and urban air quality models. The model must also be able to deal with uncertainties that might arise from the data, the assumptions, or the understanding of potential future conditions. To meet all of these purposes requires a set of models, which have been well designed and proven over time.

For local planning purposes, MARKAL has been used in a number of different settings. This includes some dozen communities in Sweden, the cities involved in the International Energy Agency's Advanced Local Energy Planning Programme (i.e., Delft in The Netherlands; Mannheim, Germany; Goetenborg, Sweden; and Torino and Naples in Italy), and Geneva, Switzerland. Output from these types of efforts have included urban energy balances, the identification of local fuel switching opportunities, the evaluation of potential technical efficiency improvements, and plans for the future development of energy infrastructures. As depicted in Figure 19, the work in Geneva links MARKAL to GIS, dispersion and impacts modules as part of the AIDAIR project, as depicted (For more info. see http://ecolu-info.unige.ch/reserche/mutate/slide_shows/dss/GISOptim/ppframe.htm).

**Figure 19: AIDAIR GIS Display of Ground Level Emission Concentrations and Human Exposure**




## 12. TIMES

TIMES (The Integrated MARKAL-EFOM System) is the evolutionary replacement for MARKAL. This modeling framework, which will be formally introduced in Washington, D.C. at the ETSAP meetings during the last week in April 1999, expands the robustness with which MARKAL can address new application areas (ranging from local energy planning to technology-rich global modeling). Like MARKAL, TIMES is an optimization framework, which produces the least-cost solution subject to emissions or other constraints. The increased flexibility of the model allows for the analysis of a number of problems, which previously required undesirable compromises or were beyond the analytical limits of MARKAL.

The features of the new model allow for the evaluation of a number of problems of interest in energy planning and carbon mitigation. For example, in the area of carbon mitigation the new inter-regional linkage feature may be used to evaluate the effects of carbon permit trading and the implementation of CDM projects. This same feature will allow the evaluation of regional energy infrastructure needs. Several of the features of TIMES will allow for a more realistic portrayal of the process of technological change, or the processes of innovation and diffusion. The vintaging of technologies, (i.e., the increase in cost over time as a technology ages) allows for the modeling of the replacement and investment decisions of different technologies. As a result of this type of enhancement, the analysis of early reduction credits and subsidies for less carbon- or energy-intensive technologies becomes more realistic.

The development of a flexible number of divisions of time, and variable period lengths with an unlimited number of periods increases the number of problems which may be modeled for energy planning and carbon mitigation efforts. For example, TIMES may be used to model the effects of time-of-use electrical rates on load curves. Also, the variable period lengths allow for the evaluation of the effects of carbon mitigation policies in not only the short-run, but also in the intermediate- to long-run time horizons of five- or ten-year increments. This increases the time horizon over which policies may be evaluated, while at the same time keeps solution of the model tractable.

Some of the main features of the current implementation of TIMES, which distinguish it from MARKAL, include:

- standard naming conventions for attributes of all technology types,
- extremely flexible process descriptions allowing for easier representation of both simple and more complex process descriptions, as depicted in Figure 20,
- allowance for the specification of fuel- and process-dependent efficiencies (in MARKAL additional processes and a dummy commodity are necessary to enable the modeling of flexible input/output flows) , as depicted in Figure 20,
- variable period lengths and an unlimited number of periods,
- flexible number of divisions of time within a year,
- vintaged processes may be described, (e.g., fixed operating and maintenance costs increase due to more frequent maintenance intervals for older electricity generation facilities),
- changes in a technological process can be reflected using the vintage period as an additional index (i.e., a single process behaves like several different processes depending on its vintage period),
- distinctions between the economic and technical lives of a technology,
- inter-temporal equations to permit examination of retrofitting and life extension options,

- year-dependent changes in attribute values (e.g., fixed operating and maintenance costs increase due to higher labor costs),

- an inter-regional exchange feature enables easy linkage of different regions and allows for the analysis of such problems as carbon permit trading, carbon leaching, energy and energy intensive product trade, and the development of electrical grid capacity, as shown in Figure 20, and 21,

- an annualized objective function that carefully handles the incremental buildup in small capacities (e.g., cars), as shown in Figure 22, and the lead time for large projects (e.g., hydro-electric plants).

**Figure 20: Multi-fueled Process with Associated Efficiencies/Emissions**

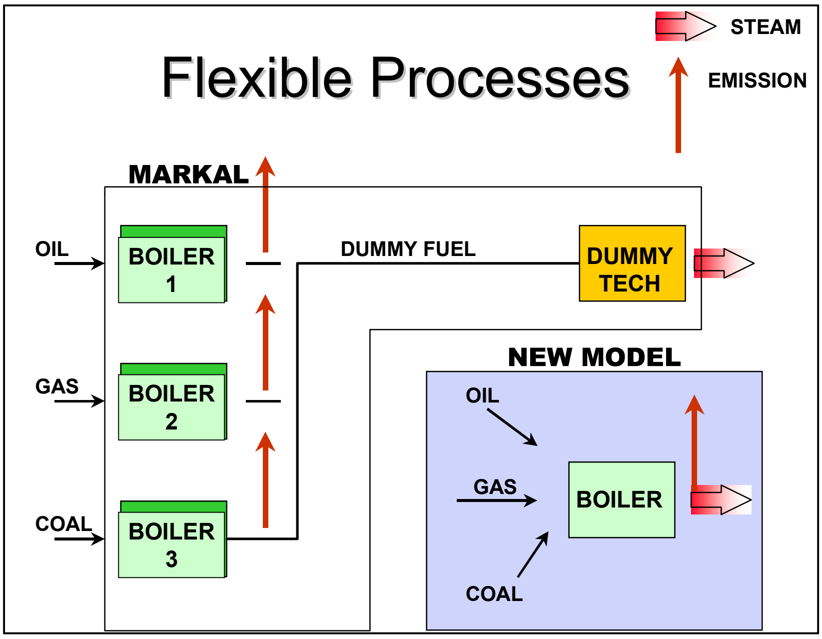


**Figure 21: Trade of Any Commodity Between Regions**

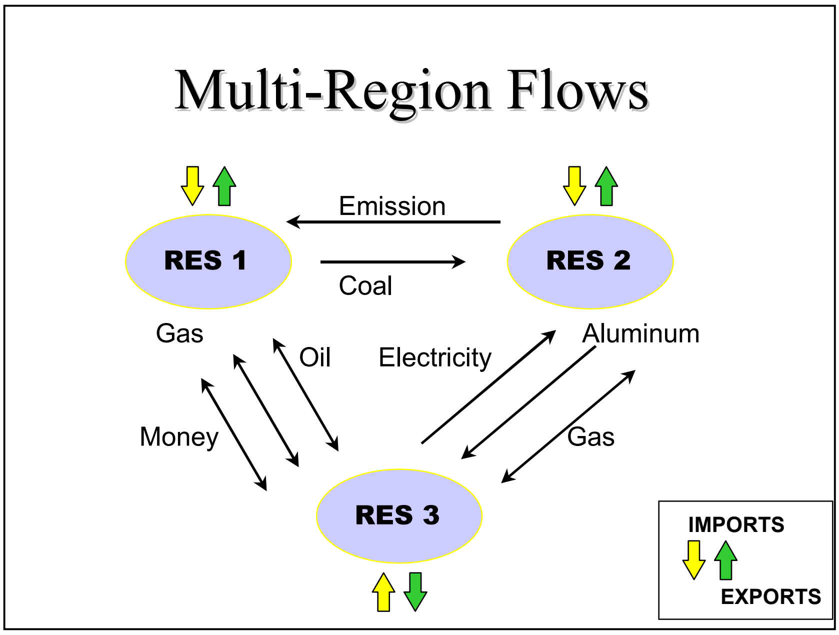
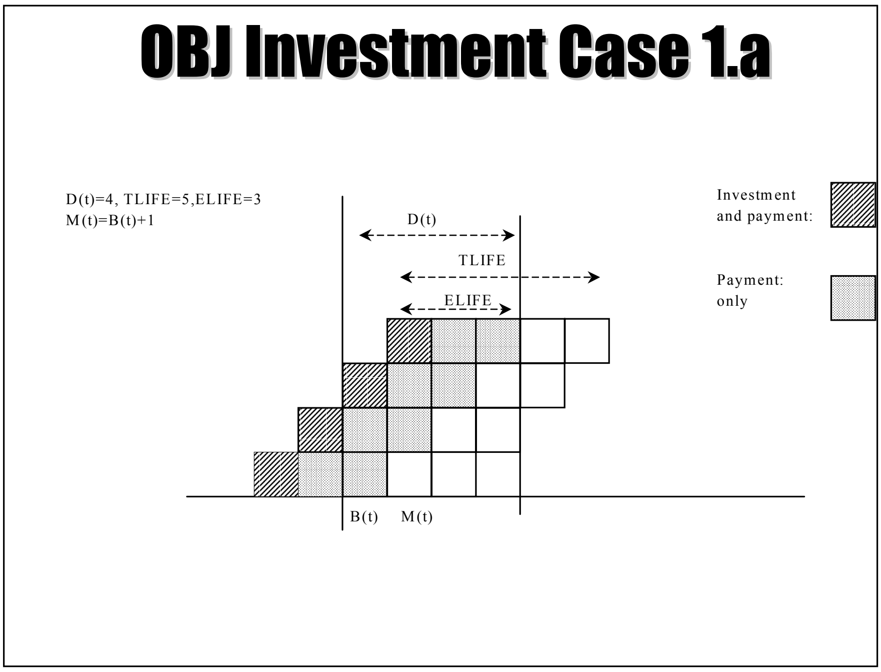



**Figure 22: Incremental Accounting of Capacity Build-up**




As TIMES and MARKAL share the same modeling paradigm, knowledge and experience gained using MARKAL is directly relevant to later work with TIMES. With this in mind a migration path has already been tested to move a model from MARKAL to TIMES. While TIMES will be introduced in Spring 1999 it will not be embedded within the necessary user-friendly "shell" such as now exists with ANSWER for MARKAL. However, ETSAP views TIMES as its model of the future and is proceeding with the task of defining the requirements for a support system for TIMES. For more information on TIMES visit www.crt.umontreal.ca/~amit/themodel.

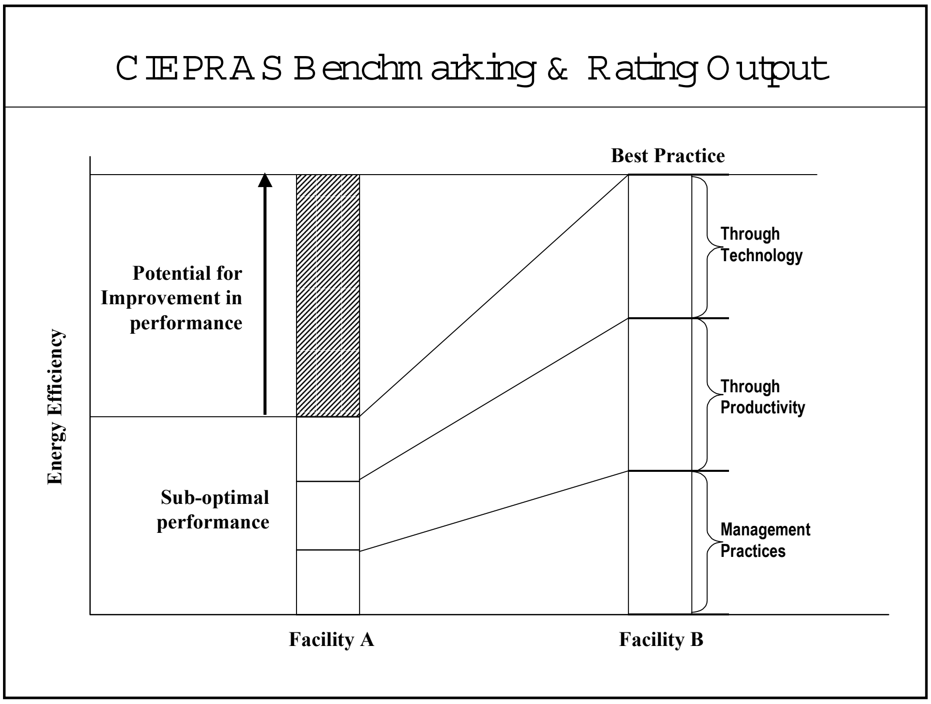
## 13. OTHER ENHANCEMENTS PLANNED FOR MARKAL

A number of other enhancements are planned for MARKAL in the short-term to further expand analysis capabilities of the GHG issue. These include (1) linkage to IRG's Compact and Innovative Enterprise Performance Rating and Analysis System[*] (CIEPRAS™); (2) development of a technology database and the expansion of the coverage of the multi-region version of MACRO/MED; (3) inclusion of a watershed module developed at the World Bank; and (4) linkage to the Forestry and Agriculture Sector Optimization Model (FASOM).

Outside of the electrical generation sector, the industrial sector has the greatest potential for rapid response to greenhouse emissions mitigation pressures. The industrial sector is driven by the constant need to increase overall productivity. Energy use patterns are one of the centrally important components of achieving this goal, but also the target of carbon mitigation efforts. At the same time, industry is also the focus of controls on other effluent releases. At International Resources Group (IRG), a benchmarking and evaluation framework has been developed and deployed to help industry grapple with these issues. This system, CIEPRAS, provides a tool, which can be utilized to evaluate individual industrial facilities for the establishment of a monitoring and reporting framework. This framework is consistent with the requirements for ISO14000 certification. Also, this tool provides a means of benchmarking an individual facility against industry averages and best practices. The energy efficiency aspect of this approach is portrayed in Figure 23.

[*] CIEPRAS™ is designed to provide cost-effective environmental management systems for industrial pollution control, other point sources, commercial developments, and urban or natural systems. CIEPRAS™ is a registered trademark of IRG.

**Figure 23: CIEPRAS Benchmarking of Energy Efficiency Components**




Combining CIEPRAS with MARKAL capabilities has the potential to overcome the relative lack of data on mitigation opportunities for the industrial sector for non-developed countries. At IRG consideration is being given to providing a direct link between CIEPRAS and MARKAL. The combined tool will provide measurement-quality data regarding the current levels of emissions and technologies. This combination will also provide estimates of the potential for emissions reductions and costs of specific improvements in energy efficiency and other mitigation options. Linkage between the two frameworks will result in the development of the most cost-effective carbon mitigation strategies for the sector as a whole. From this, the associated system-wide impacts (e.g., displaced capacity requirements in the power sector) and benefits (e.g., reduction in the marginal cost of reduction) of mitigation strategies available to the sector will be easily discerned. Reciprocally, a version of MARKAL with flexible demands (MACRO/MICRO/ MED) can provide forecasts to CIEPRAS of future energy costs and demand levels. This integrated approach will add value to both methodologies and thereby the environmental decision-making process.

To complement the linkage of MARKAL and CIEPRAS, another potential improvement under investigation includes the development of an internet-based database to support the analysis of carbon mitigation options. Typical data that might be included in the database are historical energy consumption, characterizations of energy supply and end-use technologies, economic parameters such as discount rates, rates of inflation, income elasticities with respect to fuel, and other, economic, and demographic data by country. This database will provide the necessary inputs more country models

(MARKAL/MACRO/MED). This effort would supplement work underway at GERAD to expand MED towards global coverage. Reduced MED models are being constructed for regions such as China, Russia, ROW, and other countries not yet available in the MARKAL framework. Models for these additional countries will be combined with the Canadian, US, Western Europe, Japan, and other OECD models. It is anticipated that this modeling framework will be operational this year. PSI, in close cooperation with IRG, is considering a decomposition approach to split MEDI from MACRO. Iteration between the two models will result in a Global MARKAL-MACRO/Trade model.

For many countries, the availability of water supplies is a major issue for development planning. Substantial amounts of energy are used for desalinization or irrigation (e.g., Kuwait, Jordan). Crucial to any energy system planning effort is the inclusion of this component in a carbon mitigation planning effort. Since climate change will impact water supply, efforts to adapt to changes in quantities and availability of water will be an important part of overall planning efforts. To meet these needs, plans are underway to incorporate a watershed model into MARKAL. The candidate watershed model was previously developed at the World Bank. As a result, the analytical rigor and robustness of the model has been demonstrated in the analysis of projects for this entity.

Global-scale changes in climate will likely have significant impacts on land use patterns, including impacts on agricultural and forested lands. A significant number of developing countries have economies which are heavily dependent on agriculture, so depiction of this sector in any modeling framework will be critical. In addition, if the potential impacts of such projects as reforestation or similar carbon sequestration projects are to be evaluated, these activities must be included in an analysis framework. We are currently investigating the feasibility of a linkage between FASOM, a spatial equilibrium model of the forestry and agricultural sectors, and MARKAL-MACRO. This type of framework will provide for the analysis of: (1) carbon sequestration projects, (2) agri/silvi-culture opportunities, and (3) shifts of crop land to other purposes.

## 14. CONCLUSION

The MARKAL family of models represents a series of extremely powerful tools for the analysis of energy planning with its associated environmental impacts. Through time, the model has evolved from a simple optimization framework used only by researchers, to a very sophisticated package with many potential applications to the analysis of policy and planning questions. The recent addition of a Windows based "shell" places the model framework within the reach of the user, who may not have knowledge of programming or optimization theory. With expanding levels of support, the model is expected to obtain even wider acceptance.

With a number of versions of MARKAL available, all of which are incorporated into a single production version, the user may select the model with the most appropriate set of underlying economic assumptions for the particular issue to be addressed. The original version of MARKAL required the exogeneous specification of all of the parameters. Development of three other variants of the model (MACRO/MICRO/MED), have resulted in the introduction of price sensitivity to the forecasts of demand. The most recent introduction of technology learning into the framework begins to address one of the major remaining questions in the modeling of the energy system, i.e., introduction of reductions in technology costs and increases in penetration rates as experience is gained with the technologies. This crucial advancement will result in improved long-range forecasts. The continuing evolution of the modeling framework has also provided a means of explicitly addressing uncertainty and the flows of other materials in addition to energy through the system. Finally, the ability to link several MARKAL models has resulted in an expansion of the types of regional issues and climate policies that may be analyzed.

With the introduction of the newest member of the MARKAL family, TIMES, this spring, and the other planned enhancements, the model will extend beyond just the planning of the energy and material system. TIMES with its increased flexibility in the description of energy consuming processes, and economic detail will provide an even more powerful analytical tool. The introduction of agricultural, forestry, and water modules will produce an integrated framework for natural resource planning. As a result, the MARKAL family is rapidly moving from its earliest incarnation as a regional energy planning model to an all-encompassing tool for use in any number of planning situations.

The MARKAL family provides a means of translating global commitments for the mitigation of GHG emissions into specific actions and projects. The cost effectiveness and benefits of these individual activities as well as the added benefits arising from cooperation opportunities need to be evaluated and quantified. The MARKAL family of models provides a flexible, well understood, proven, verifiable and evolving methodology that can contribute insights to assist with informed decision-making.

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