Energy/Environmental Modeling with the MARKAL Family of Models

Ad J. Seebregts [1], Gary A. Goldstein [2], Koen Smekens [1]

[1] Energy Research Centre of the Netherlands (ECN), Policy Studies unit,
P.O. Box 1, 1755 ZG Petten, The Netherlands, e-mail: seebregts@ecn.nl
[2] International Resources Group Ltd., 1211 Connecticut Ave. NW, Suite 700,
Washington, DC 20036, USA, e-mail: ggoldstein@irgltd.com

Abstract

This article presents an overview and a flavour of almost two decades of MARKAL model developments and selected applications. The MARKAL family of models has been contributing to energy/environmental planning since the early 1980's. Under the auspices of the International Energy Agency's (IEA) Energy Technology Systems Analysis Programme (ETSAP) the model started as a linear programming (LP) application focused strictly on the integrated assessment of energy systems. It was followed by a non-linear programming (NLP) formulation which combines the 'bottom-up' technology model with a 'top-down' simplified macro-economic model. In recent years, the family was enlarged by members to model material flows, to employ stochastic programming (SP) to address future uncertainties, to model endogenous technology learning using mixed integer programming (MIP) techniques, and to model multiple regions (NLP/LP).

1 Introduction

MARKAL (acronym for MARKet ALlocation) is a widely applied bottom-up, dynamic, originally and mostly a linear programming (LP) model developed by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA) (ETSAP, 2001). MARKAL depicts both the energy supply and demand side of the energy system. 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 macro-economy and energy use. As a result, this modeling framework has contributed to national and local energy planning, and to 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 more than 40 countries and by more than 80 institutions, including developed, transitional, and developing economies indicates wide acceptability.

This article provides a brief overview of the various model variants illustrated by a selection of results from the vast and still growing amount of MARKAL experience world-wide. Section 2 will give a short description of the main structure of the model and the various members of the family, followed by a few examples in Section 3. More examples and further references can be found at the ETSAP web site.

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.

2 MARKAL: overview

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 Fig. 1 represent this network, referred to as a Reference Energy System (RES).

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.

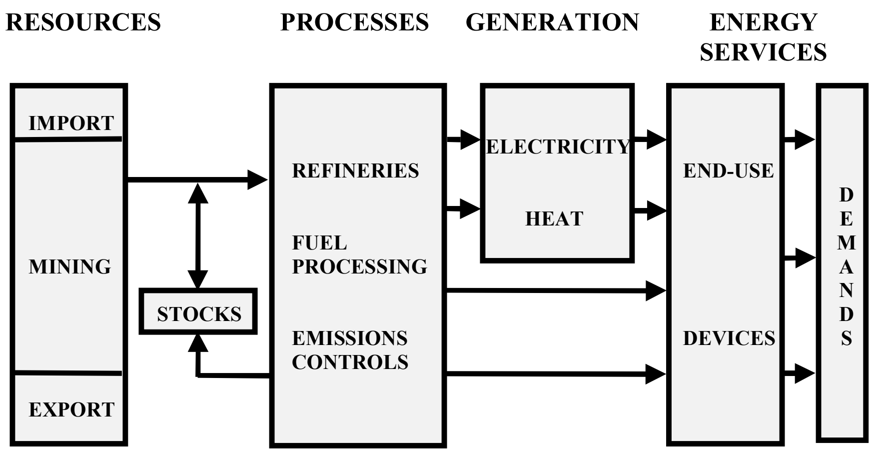


Fig. 1. MARKAL Building Blocks

Table 1 provides an overview of the current MARKAL family of models. 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.

MARKAL's collaborative approach to model development is implemented through an open architecture provided by the General Algebraic Modeling System (GAMS, see (Brooke et al. 1992)). 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 modern data handling and analysis support shell: the Windows based ANSWER, developed by ABARE (Australian Bureau of Agricultural and Resource Economics). ANSWER is implemented in Visual Basic. The MARKAL input data and results are stored in MS-Access databases, with flexible import and output routines (e.g. based on Excel files).

Table 1. Overview of the MARKAL family of models

Member/version	Type of model	Short description (Reference or example)
MARKAL	LP	Standard model. Exogenous energy demand. (Fishbone et al. 1983)
MARKAL-MACRO	NLP	Coupling to macro-economic model, energy demand endogenous. (Hamilton et al. 1992)
MARKAL-MICRO	NLP	Coupling to micro-economic model, energy demand endogenous, responsive to price changes. (Regemorter and Goldstein 1998)
MARKAL-ED (MED)	LP	As MARKAL-MICRO but with step-wise linear representation of demand function. (Loulou and Lavigne 1996)
MARKAL With multiple regions	NLP	Linkage of multiple country specific MARKAL-MED and MARKAL-MACRO, including trade of emission permits. (Bahn et al. 1998)
MARKAL with material flows	LP	Besides energy flows (electricity, heat) material flows and recycling of materials can be modelled in the RES. (Gielen et al. 1998)
MARKAL with uncertainties	SP	Stochastic Programming. Only with standard model. (Ybema at al. 1998)
MARKAL-ETL	MIP	Endogenous technology learning based on learning-by-doing curve. Specific cost decreases as function of cumulative experience. (Barreto and Kypreos 1999)

3 Energy and Environmental Questions Answered by MARKAL

This section illustrates the use of MARKAL in answering typical energy/environmental policy and planning questions. These examples concern: carbon dioxide emission reduction, market-based instruments, technology dynamics and R&D. These topics are only a selection of the various questions that can be answered by the use of the MARKAL model. More examples and further references can be found at the ETSAP web site (ETSAP 2001).

How to reach carbon dioxide reduction? The widest current applications are for the analysis of policies designed to reduce carbon emissions from energy and materials consumption. Emissions of CO2 due to fossil fuel burning are virtually certain to be the dominant influence on the trends in atmospheric CO2 concentrations during the 21st century (IPCC, 2001), in ways that are expected to adversely affect the climate. Therefore, the development of the world's future energy system is critical in mitigating these adverse effects. Large reductions in CO2 emissions are required in order to stabilise CO2 concentrations. Models like MARKAL can aid in identifying least-cost solutions for meeting future emission reduction targets. Fig. 2 shows a recent example of the study (Gielen et al. 2000).

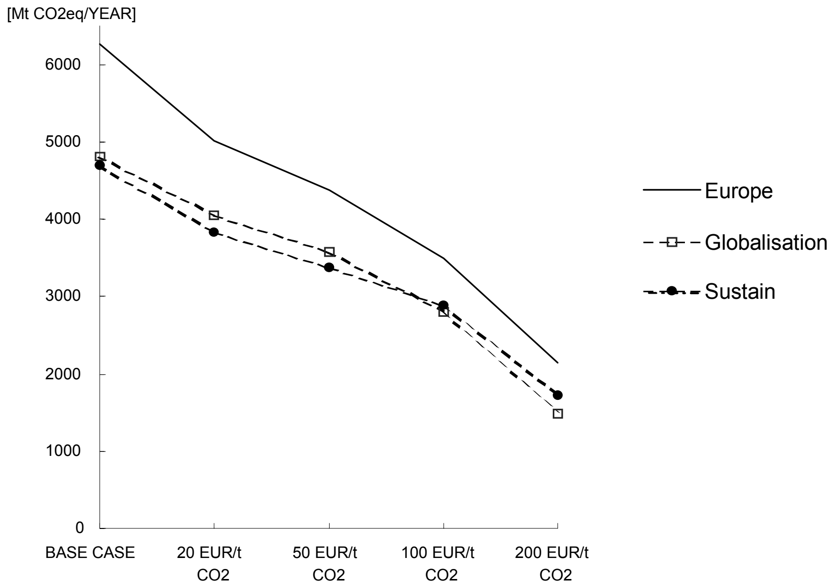
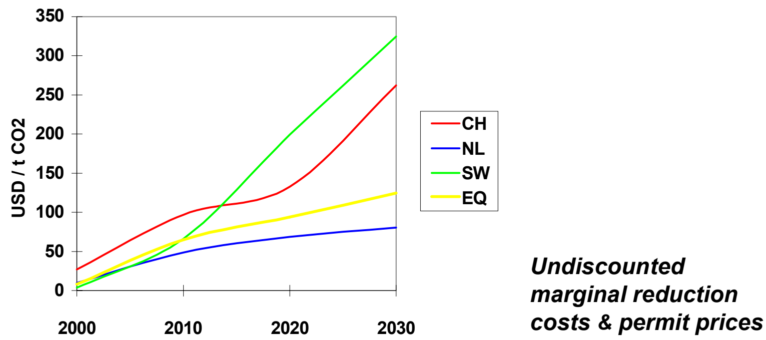


Fig. 2. CO2 emission reduction as a result of increasing GHG permit prices in 3 scenarios, 2030, Western European energy system (Gielen et al. 2000).

What is the effect of market-based instruments? In addition to technology policies, MARKAL can be used to examine market-based instruments (e.g. see also Fig. 2). Much speculation has occurred about the interaction between technology policies, energy price instruments (e.g., taxes, carbon permits), and economic growth. 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. Instruments such as the trade of emission permits (part of Kyoto protocol) have also been addressed with MARKAL, see Fig. 3 (Adapted from: Bahn et al. 1998). Emission permits can reduce the marginal cost of reducing emissions.

How to model technology dynamics and the impact of R&D? In a usual MARKAL model, technology characteristics may change in time but are exogenous parameters e.g. the investment cost a technology. The learning-by-doing curve concept can be used to model technology dynamics in a more consistent manner, but it introduces a non-linear relationship between model variables. MIP approximates the non-convex and non-linear objective function by piece-wise linear functions, and with use of a branch-and-bound algorithm a unique optimal solution can be found. PSI developed basic source code to incorporate technology learning in MARKAL (Barreto and Kypreos 1999; Seebregts et al. 2000). Fig. 4 shows an example of results obtained with this feature. In addition, two R&D variants are indicated: increase of R&D (re-allocation from research funds from nuclear to renewable energy) is assumed to have a beneficial effect on the progress ratio of solar PV and wind energy (faster decrease of investment cost). The progress ratio expresses the rate at which the cost declines each time the cumulative production (i.e. experience) doubles.



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)

Fig. 3. Benefits of trading emission permits (Bahn et al. 1998) between the Netherlands (NL), Switzerland (CH) and Sweden (SW).

Recent developments

TIMES (The Integrated MARKAL-EFOM System) is the evolutionary replacement for MARKAL. This modeling framework was introduced in 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. More details can be found at (ETSAP, 2001) and in (Goldstein et al. 2001).

Monte Carlo analysis is a method to analyse and propagate data uncertainties in models. It is a relatively time-consuming (i.e. computationally) method. However, with the current speed and memory capabilities of PC's, Monte Carlo analysis with complex MARKAL models now becomes feasible (Seebregts et al. 2001). Monte Carlo analysis can possibly be used complementary to conventional MARKAL practices as: Scenario analysis, sensitivity analysis, and stochastic programming.

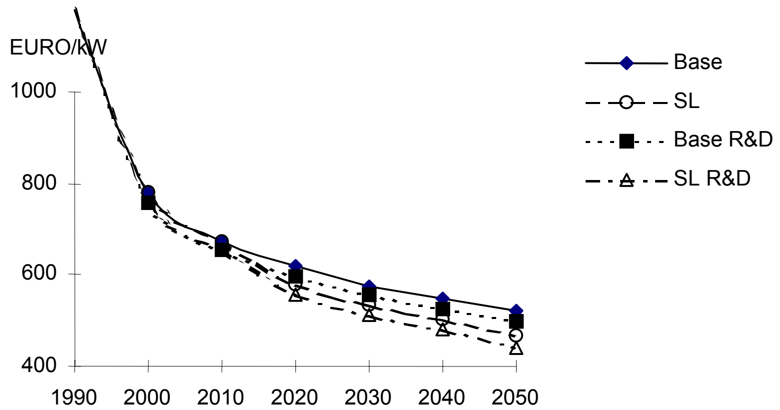


Fig. 4. Specific cost development of wind turbines. MARKAL-ETL was used, Western European energy system. 'Base' is a scenario without CO2 emission reduction; 'SL' denotes a emission reduction scenario which favors the deployment of wind turbines and hence, a faster decrease in costs.

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 energy/environment policy and planning questions. The Windows based "shell" ANSWER places the model framework within the reach of the user, who may not have knowledge of programming or optimization theory.

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. TIMES will be the next generation member of the family.

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