9. Market Allocation Model (MARKAL) at ECN

Koen Smekens, Gerard Martinus and Bob van der Zwaan

MARKAL (MARKet ALlocation) is a family of dynamic bottom-up energy system models developed and supported by the Energy Technology Systems Analysis Programme (ETSAP), one of the Implementing Agreements of the International Energy Agency (ETSAP, 2006). While originally MARKAL models were of the linear programming (LP) type – which is still mostly the case – the framework today has been extended in principle also to include more refined modelling tools that allow for example for solving more complex programmes such as mixed integer problems (see, for example, Seebregts et al., 2001). MARKAL models are applied in a broad variety of settings, benefit from technical support by a large international research community, and are today implemented in more than 40 countries. This chapter gives an overview of the main features of MARKAL, in particular including concise descriptions of the objective function of the programme (Section 9.1), the simulation of technological change (Section 9.2), the representation of cluster learning (Section 9.3), the modelling of elastic energy demand (Section 9.4), and specific characteristics relevant for the European context (Section 9.5).

9.1 INTRODUCTION

In its basic formulation MARKAL is a linear optimization model with the total system costs as its objective function. By minimizing these total costs over the whole time period considered at once, it assumes perfect foresight. Thus, it reflects a perfectly transparent market with rational behaviour of all market players. Government interventions or specific social preferences, that essentially distort the free market, can be simulated through the use of constraints imposed by the modeller. These may range from generic instruments such as CO_2 taxes to technology-specific choices towards (gradually or abruptly) stimulating or abolishing certain energy options or resources.

The net present value of total costs, *NPV*, is the objective function, and consists of the sum over all regions of the discounted present value of the stream of annual costs incurred in each year of the overall time horizon (ETSAP, 2006):

$$NPV = \sum_{r=1}^{R} \sum_{t=1}^{NPER} (1+d)^{1-t} \cdot ANNCOST(r,t) \cdot \left(1 + (1+d)^{-1} + \cdots + (1+d)^{1-NYRS}\right)$$

in which the indices r and t refer to the region and time period, respectively, R is the total number of regions, and *NPER* the number of periods in the overall planning horizon. The parameter d is the general discount rate, $ANNCOST(r,t)$ the annual (or, rather, 'periodal') total energy system cost (per region and period), while the last factor in the expression represents the intra-period discount factor and *NYRS* the number of years in each period.

$ANNCOST(r,t)$ is expressed as:

$$\begin{aligned}
ANNCOST(r,t) = \\
& \Sigma_k \{Annualized_Invcost(r,t,k) \cdot INV(r,t,k) \\
& +Fixom(r,t,k) \cdot CAP(r,t,k) \\
& \quad + Varom(r,t,k) \cdot \Sigma_s ACT(r,t,k,s) \\
& \quad + \Sigma_c [Delivcost(r,t,k,c) \cdot Input(r,t,k,c) \cdot \Sigma_s ACT(r,t,k,s)]\} \\
& + \Sigma_{c,s} \{Miningcost(r,t,c,l) \cdot MINING(r,t,c,l) \\
& \quad + Tradecost(r,t,c) \cdot TRADE(r,t,c,s,i/e) \\
& \quad + Importprice(r,t,c,l) \cdot IMPORT(r,t,c,l) \\
& \quad - Exportprice(r,t,c,l) \cdot EMPORT(r,t,c,l)\} \\
& + \Sigma_p \{Tax(r,t,p) \cdot ENV(r,t,p)\} \\
& + \Sigma_d\, DemandLoss(r,t,d),
\end{aligned}$$

in which the indices k, s, c, l and p refer to the technology, year, commodity, price level and pollutant, respectively, while e and i refer to whether the commodity under consideration is sold (exported) or purchased (imported). Decision variables, representing the choices that can be made within the model, are in capitals: $INV(r,t,k)$ is the new capacity added per technology, $CAP(r,t,k)$ the installed capacity for each technology, $ACT(r,t,k,s)$ the technology activity level, $MINING(r,t,c,l)$ the quantity extracted of each commodity, $TRADE(r,t,c,s,i)$ and $TRADE(r,t,c,s,e)$ the quantities per commodity purchased (i) or sold (e), $IMPORT(r,t,c,l)$ and $EXPORT(r,t,c,l)$ the quantities per good exogenously imported or exported, and $ENV(r,t,p)$ the emissions of each pollutant. $Annualized\_Invcost(r,t,k)$ is the lump sum unit

investment cost, $Fixom(r,t,k)$ and $Varom(r,t,k)$ respectively fixed and variable operation and maintenance costs, $Delivcost(r,t,k,c)$ the delivery cost per unit of commodity to the technology considered, $Input(r,t,k,c)$ the amount of commodity required to operate one unit of technology, $Miningcost(r,t,c,l)$ the cost of mining, $Tradecost(r,t,c)$ the transport or transaction cost, $Importprice(r,t,c,l)$ the (exogenous) import price per commodity, $Exportprice(r,t,c,l)$ the (exogenous) export price, $Tax(r,t,p)$ the tax on emissions, and $DemandLoss(r,t,d)$ the welfare loss incurred by consumers when the service demand d is less than its value in the reference case.

The assumption of perfect foresight of the future concerns both 'external' pressures such as taxes or emission constraints and 'internal' changes such as technology availability or cost reductions. Model choices are thus made on the basis of the anticipation of both external and internal constraints or opportunities. As such, the programme minimizes the overall energy system costs, while both implicit and/or explicit modelling constraints are duly met. This feature is particularly instrumental for internalizing technology learning-by-doing and corresponding technology cost reductions: through perfect foresight the model accounts for the empirically observed phenomena that increased investments in technology deployment may be rewarded (at least partly compensated or even fully paid back) in the form of future cost decreases.

MARKAL is demand-driven, and in its standard formulation energy demand is exogenously determined. In other words, the modeller specifies the demand for energy services as external input. This exogenous energy demand determines the composition of the energy system, in which demand and supply of energy services are balanced. Energy requirements are fulfilled through end-use technologies that consume various types of fuel. Fuels are produced in conversion processes or directly supplied, so that (final) energy demand cascades through the system down to primary energy supply. The relative competitiveness of each of the chains from primary supply to end-use, together with physical constraints such as the availability of resources, determine which of the technologies enter the solution of MARKAL.

Technologies are characterized as: (i) resource, (ii) conversion, (iii) process, and (iv) end-use related. Depending on the classification of a technology, it is characterized by a number of specific parameters that may be technical in nature (related to for example efficiency, emission factors and fuel use) or more economically determined (such as its lifetime, required investment and operation costs, or the applicable discount rate). The use of technology-specific discount rates facilitates the inclusion of investment behaviour and preferences of different actors. Technology parameters are generally exogenous. As with the energy demand level, they have to be exogenously provided for all model periods. To facilitate their usage they are gathered in one database that serves as input to every model run. The set of data, their definition and classification, that is, the time series of all exogenous variables involved, in combination with the objective function and modelling constraints together constitute a specific MARKAL version.

9.2 TECHNOLOGICAL CHANGE

Originally, MARKAL used exogenously determined time-dependent trajectories for the investment costs of energy technologies. These cost trajectories were based on expert views and on the existing scientific and engineering literature. It was realized, however, that the underlying driver of the gradual decreases in energy technology costs may really be technology deployment, rather than time, and that the cost reductions were achieved through the experience obtained with fabricating and operating the technologies. Also, the exogenous simulation of technology costs implied that the model tended to postpone the deployment of a given technology until it became competitive compared to its alternatives, at which point its competitiveness often resulted in a sudden and usually unrealistically massive deployment of that technology. This necessitated the imposition of specific growth limitations allowing for a more gradual phasing in of technologies. The specification of such growth limitations required detailed modelling expertise and manual interference in the input data that did not always guarantee a consistent parameterization and often generated various modelling intricacies. Thus, to render MARKAL more realistic the modelling of time-dependent exogenous technology evolution and the implementation of growth limitations were gradually abandoned.

To reflect the observation that technology cost reductions are often the result of increasing physical deployment, learning curves were implemented in MARKAL. Indeed, many sources had meanwhile indicated that a learning-by-doing or learning-by-investing relationship could be observed between the evolution of investment costs, for example per unit of capacity, and the cumulated capacity or sales build-up (see, for example, IEA, 2000). The learning curves describing these phenomena, relating the costs of technologies to their capacity or sales, can be expressed by:

$$SC(t) = SC(0)\left(\frac{CC(t)}{CC(0)}\right)^{-b},$$

in which SC are the specific investment costs, for example in €/kW_e, and CC the cumulative capacity, in this case in kW_e. The constant b is the 'learning elasticity', generally rewritten into the more familiar progress ratio p:

$$p = 2^{-b}.$$

The progress ratio is a measure of how fast a technology learns, as it indicates the decrease in specific costs for each doubling of installed capacity. This means that by providing the initial values for capacity and investment costs, as well as the progress ratio, the potential for cost reductions is fully fixed. In an additional step made solely for the purpose of including learning curves in MARKAL, the learning curves are piece-wise linearized. For such a linearization an additional parameter has to be given, the maximal achievable capacity, determined in coherence with the chosen segmentation. With this endogenization of the investment costs, MARKAL calculates the optimal investment levels and timing thereof, using as knowledge the perfectly foreseeable investment cost decreases according to learning curves.

Over the years, the number of technologies for which learning curves were simulated in MARKAL gradually increased, and it became clear that learning spillovers between technologies had to be reflected. To account for the observation that different technologies may share a common component that is subject to learning, the concept of 'cluster learning' was introduced.

9.3 CLUSTER LEARNING

In order to diversify and correct the description of technological change, 'technology clusters' were modelled (Seebregts et al., 2000). With the previously simulated phenomenon of learning-by-doing, the basic assumption was that a technology learns as an integral and independent entity. In an extension of that formalism, the technologies that learn are viewed as being built up by underlying entities or components. These low-level components individually learn, rather than the high-level overall technologies. The set of technologies that share a certain component are referred to as a cluster. Consequently, a cluster of technologies also shares the same learning process of their common component. Since technologies may consist of several components that learn, and components may be part of several sets of clustering technologies at once, the formulation of cluster learning introduces the concept of spillovers between technologies.

For many of the technologies previously considered as independently learning entities the concept of technology clusters provides a more refined, consistent and correct description of the phenomenon of learning. For example, a natural gas combined cycle power plant consists of a gas turbine, a recovery boiler, and a steam turbine as principal elements, all three characterized by learning phenomena. As these elements or key components are also found in many other technologies, using the cluster learning approach accounts for the learning in these components of all the corresponding technologies at once.

Cluster learning quite naturally allows for the simulation of technology spillovers: if a technology containing a specific component that learns is deployed, all other technologies sharing this component will automatically benefit from that learning process as well. Thus, incurred experience naturally flows from one technology to all related technologies. In MARKAL the phenomenon of cluster learning is introduced through a single matrix, the so-called cluster matrix. In the cluster matrix, the key components serve as columns and the technologies as rows, while the entries in the matrix cells represent the capacity share of the key component in the technology on a unit per unit basis.

Joint learning does not need to be restricted to technologies within one sector, but can easily be extended to technology spillover effects between different sectors of the overall energy system. An intuitive example is provided by fuel cell technology. A basic fuel cell component is not only found in stationary applications such as for electricity and heat production but also in mobile applications like vehicle engines. While in an earlier stage the main focus was on learning and cross-technology spillovers within the power sector, later learning and spillover effects outside the power sector were included as well. The number of technologies and technology components that are subjected to learning is now so large that the limits of computability have been reached.

9.4 DEMAND ELASTICITY

As MARKAL is a demand-driven model, and can in principle only be run with an external specification of final demand for energy services for all time periods, projections of final energy demand have to be obtained from other sources or models. Traditionally, these demand levels are price-insensitive, that is, they remain unchanged if the prices of the supplied commodities change. The dash-dotted line in Figure 9.1 represents this fixed demand level. MARKAL generates a supply curve that satisfies the objective function and is stepwise because it is built up by discrete technologies. The total cost derived from the solution can be interpreted as the sum of the integrals under all supply curves.

Recently, MARKAL has been extended to simulate a price-elastic demand for energy. The exogenous demands for energy services have been replaced

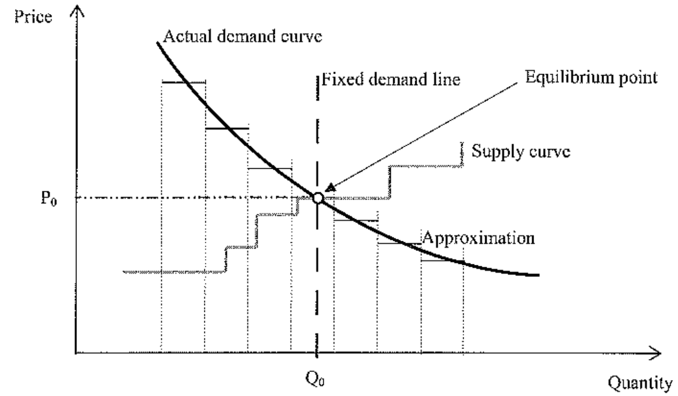

Figure 9.1 Price-independent Demand Level of a Standard MARKAL Model (dash-dotted line), and Supply and Demand Curves as Used in the Elastic-Demand Formulation of MARKAL

with energy demand functions that relate energy demand to market prices. The market price of energy services is assumed to be equal to the marginal cost as represented by the shadow price from the standard MARKAL solution. A rather simple demand function characterized by a prespecified price elasticity is assumed that does not allow for substitution between different demand categories. In order to solve the resulting non-linear problem through a mixed-integer programme, the demand curve is stepwise linearized, and to keep the variations of demand within the range deemed acceptable by the modeller, the maximum allowed deviations upwards and downwards from the equilibrium point are specified.

In the absence of an additional modelling constraint, MARKAL generates the same equilibrium point as it does in its non-elastic demand version. If, however, an external constraint is imposed on the energy system that effects the price level of one or more of the final energy services, for example when a CO_2 emission target is set, the model may adjust the demand levels and supply curves to minimize the overall system cost. Compared to the non-elastic version of MARKAL, an additional option for meeting such a modelling constraint is thus allowed for: in this case MARKAL can opt to change the demand level along the stepwise curve, rather than deploying (expensive) emission-reduction technologies.

Thus, in the elastic-demand form of MARKAL, a change in demand level can induce a change towards a different supply curve. Consequently, the equilibrium point will shift along the demand curve. The objective function now becomes the minimization of the area under the supply curves, or the maximization of the surface between the demand curves and the supply curves. The surface between the demand curve and the equilibrium price level is a measure for the consumers' surplus, while the surface between the equilibrium price level and the supply curve is a measure for the producers' surplus, as illustrated in Figure 9.2.

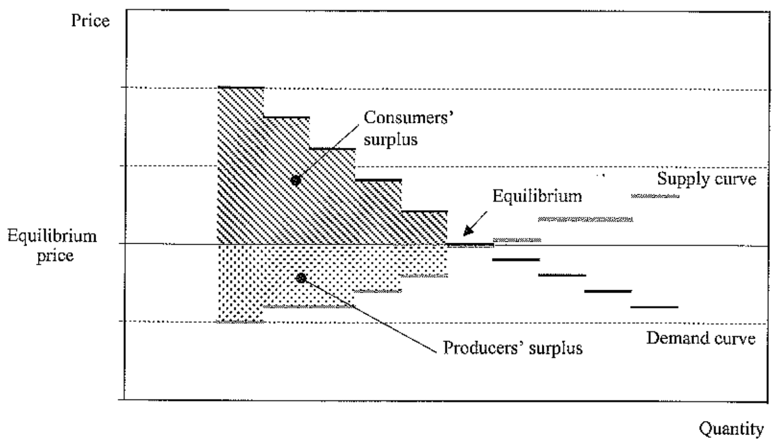

Figure 9.2 Producer and Consumer Surplus

The main reason for introducing a form of price-elasticity in MARKAL is that under stringent CO_2 reduction scenarios it is highly unlikely that the energy system will maintain its original demand level. For example, if a very high CO_2 tax is imposed, the corresponding expected carbon emission reductions are simply too significant to be realized by abatement technologies alone. While the currently employed partial equilibrium method to introduce a piece-wise linearized elastic energy demand does naturally not include the full complexity of the macroeconomy, it at least constitutes an option to include the most important effects of price-elasticity without forfeiting the technology richness of a bottom-up model like MARKAL. The results from this MARKAL version indeed point out the price-responsive behaviour of the different actors in a complex energy system when confronted with for example a binding climate constraint.

9.5 MARKAL FOR WESTERN EUROPE

The MARKAL model currently used by the Energy Research Centre of the Netherlands (ECN) (see Figure 9.3) is dedicated to the Western European energy system, with the 15 pre-2004 EU members together with Norway, Iceland and Switzerland treated as one single region. National boundaries or

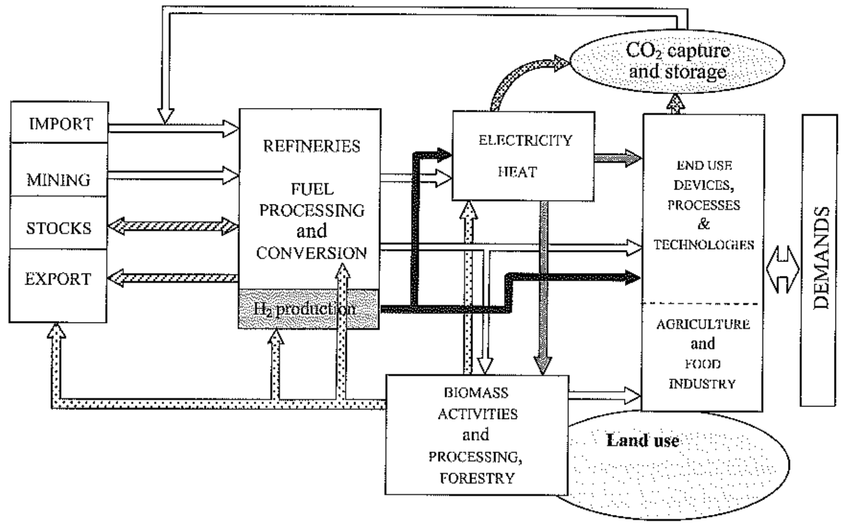

Figure 9.3 Schematic Overview of the MARKAL Reference Energy System at ECN

intercountry exchanges of commodities (both energy and materials) are not considered in this model version, but fuel and material imports into and exports from the region are simulated. This MARKAL version covers the 1990–2100 time frame, modelled in periods of ten years each.

Some subregional aspects of the energy system are considered. For example, in the residential sector the variability in space heat demand is sufficiently relevant to warrant a distinction between the northern, middle and southern part of the region. Consequently, both demand and end-use technologies possess in this case additional regional characteristics. Also the influx from solar radiation displays such variations that a more detailed technological specification is required. In this case, only the corresponding technologies have regional characteristics: associated hereto remains the electricity demand in the entire region. For all other demands and technology chains, technologies are of a generic type (for example a pulverized coal power plant, a diesel car, a residential gas boiler, or an electric arc furnace for steel making).

MARKAL allows for the expansion and analysis of specific energy technologies. For example, the existing model has recently been extended to include a detailed description of the possible evolution towards a hydrogen economy. For the TranSust project, the focus has been on the internal and external cost features of CCS technologies and, as described elsewhere in this volume, on the carbon and energy intensity of the overall energy economy (see Smekens and van der Zwaan, 2006).

REFERENCES

ETSAP (2006), 'Introduction and overview of the MARKAL model', Energy Technology Systems Analysis Programme, downloadable at: http://www.etsap.org [last accessed July 2008].

IEA (2000), *Experience Curves for Energy Technology Policy*, OECD: Paris.

Smekens, K. and B.C.C. van der Zwaan (2006), 'Atmospheric and geological CO_2 damage costs in energy scenarios', *Environmental Science and Policy*, **9**, 217–27.

Seebregts, A.J., G.A. Goldstein and K.E.L. Smekens (2001), 'Energy/environmental modelling with the MARKAL family of models', OR2001 Conference Contribution, 3–5 September, Duisburg, Germany, downloadable at: http://www.ecn.nl/docs/library/report/2001/rx01039.pdf [last accessed July 2008].

Seebregts, A.J., T. Kram, G.J. Schaeffer and A.J.M. Bos (2000), 'Endogenous learning of technology clusters in a MARKAL model of the Western European energy system', *International Journal of Global Energy Issues*, **14**(1–4), 289–319.