INTERNATIONAL ENERGY AGENCY
ENERGY TECHNOLOGY SYSTEMS ANALYSIS PROGRAMME

CONTRIBUTING TO THE KYOTO PROTOCOL

SUMMARY OF ANNEX VII (1998-2002)

May 2002

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HIGHLIGHTS

- Using a suite of MARKAL models as an expert system, a set of recommendations were made as to how best to meet the requirements of the Kyoto Protocol.
- Advances were made in the ability to analyze global issues using linked bottom-up, technology-oriented models to represent international trade in energy, emission permits, capital and some commodities.
- ETSAP participants cooperated in advancing the ability to model technological learning, taking into account clusters of technology and spillover among geographical regions.
- A concerted multinational effort has developed TIMES, the successor to MARKAL, together with three alternative user-interface shells.
- MARKAL continued to be used by member countries to evaluate national and local policies for energy, pollution control and emissions trading.
- ETSAP participants are cooperating with Chinese organizations to plan energy developments in China.
- U.S. Energy Information Administration adopted the ETSAP models and methodology to aid in the preparation of its annual *International Energy Outlook.*
- ETSAP will have a key role in the preparation of the new International Energy Agency publication *Energy Technology Perspectives.*
- Two more countries joined ETSAP: Finland and Greece.

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1. SUMMARY

In Annex VII, the Energy Technology Systems Analysis Programme (ETSAP) continued to extend its repertoire of models and methods for analyzing energy systems, with particular emphasis on supporting on-going international cooperation in reducing greenhouse gas emissions.

The overall goal of the annex was to serve national governments and work in international fora by fostering the development of constructive policy options to reduce emissions of greenhouse gases and to promote needed energy technologies. In particular, the aims were to encourage:

- the widespread use of the ETSAP tools, methodologies, data services and knowledge by the governments of the ETSAP contracting parties
- the constructive use of ETSAP tools by other countries as well as international organizations in multilateral collaboration, discussions and negotiations
- the establishment of linkages with economic and environmental models and approaches that complement the work of ETSAP
- the maintenance and ongoing use of the ETSAP worldwide network of systems analysts
- the demonstration and deployment of new methods, with increased flexibility to depict complex energy systems (1) to evaluate joint actions among countries such as trading emissions and energy, and (2) to treat technological 'learning' in models endogenously.

There were three principal programs in Annex VII:

- *International studies*, to examine the benefits of international cooperation and trading to meet future requirements to reduce greenhouse gas emissions
- *National studies*, appropriate to and funded by the individual Participants, aimed at supporting the objectives of this annex, and
- Ongoing *research and development studies*, primarily to further the development of the TIMES model and its supporting software, the next generation of the MARKAL family of models.

On a bilateral basis, individual ETSAP participants continued their programs of outreach.

- Joint modeling programs were developed by the Netherlands and Switzerland with agencies in China.
- Switzerland promoted the evaluation of projects in Colombia for the Clean Development Mechanism (CDM) of the Kyoto Protocol.
- Norway and Sweden engaged the Baltic countries of Estonia, Latvia and Lithuania in an analysis of cooperation in trading electricity and emission permits.
- Estonia was regularly represented at ETSAP workshops.

- Germany started a cooperative program with South Africa consisting of an exchange of students in the field of energy modeling, and support in establishing a national energy model of South Africa.
- The Netherlands began a collaboration project on integrated energy planning with South African Department of Minerals and Energy, starting with a training program that also included CSIR (the central research and development agency), ESKOM (the national power company), and Capetown University.
- USA evaluated building upgrades in Taiwan as an example for the CDM.
- USA together with Taiwan initiated a program to study joint strategies to reduce greenhouse gases from the Central American countries of Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama.

1.1 International Studies

1.1.1 Meeting the requirements of the Kyoto Protocol

Using a suite of MARKAL models as an expert system, Dutch analysts have drawn some inferences as to how best to meet the requirements of the Kyoto Protocol, namely:

- Take a comprehensive approach that allows as many technical options as possible, specifically including those related to materials as well as energy, and the greenhouse gases other than carbon dioxide.
- Set the emission reduction targets to be achieved in the long run, to allow businesses more time to adjust, and technologies with long-term potential to be disseminated.
- Strive for equality of marginal emission reduction costs across all sectors of the economy and across countries, rather than controlling only individual sectors or some countries.
- Integrate greenhouse gas mitigation strategies with other environmental policies, notably waste and resource productivity, as well as with other non-environmental policies.
- Be very prudent in pursuing policies that deliberately stimulate certain technologies, especially if they are costly for the emission reductions they achieve, to allow businesses to choose the most cost-effective options when emission penalties are taken into account.

1.1.2 Technology learning across regions

Similar technologies in different regions of the world may benefit jointly from the cost reductions that accompany manufacture and use on a larger scale. The MARKAL model was extended by the Swiss participant to assess the effects of such technological ‘learning’ across several geographical regions. An example illustrated the changes in the optimal choice of technologies in a multi-regional global electricity system when there is shared learning and when carbon dioxide emissions are constrained.

1.1.3 Cooperation among the Nordic countries

In Scandinavia, the Nordleden project showed the value of grid-distributed energy trade and increased cooperation among the Nordic countries to reduce carbon dioxide emissions. Possible commitments by the stationary energy sectors of the countries were analyzed that would reduce emissions beyond the Kyoto Protocol requirements to about a 60 percent reduction by 2050.

Earlier studies of the benefits of cooperation in reducing carbon dioxide emissions among the Scandinavian countries were extended to include the Baltic countries. For this evaluation, the Nordic countries of Norway, Sweden, Finland and Denmark were merged into one large model. Using the regionalized MARKAL, this was linked with individual models of the Baltic countries: Estonia, Latvia and Lithuania.

1.1.4 Managing materials to reduce greenhouse gas emissions

Dutch modeling studies of future requirements to reduce greenhouse gas emissions from Western Europe found that managing the flow of materials substantially increases the reductions that can achieved over managing the flow of energy alone. Coupled with detailed studies of individual industrial sectors, MATTER, a version of MARKAL that includes flows of materials, was used to evaluate technologies for reducing future greenhouse gas emissions. To achieve the sharp reductions likely to be needed in the long run, changes in materials technology have the potential to reduce carbon dioxide emissions by another 50 percent over what can be achieved with energy technologies alone.

1.1.5 Is the Kyoto Protocol Fatally Flawed?

The effect on the Kyoto Protocol of the US withdrawal and the Bonn Agreement was examined with the MacGEM model by the Belgian participants. The report concluded that the Protocol’s original emission targets had been completely eroded, but that the agreement had the merit of saving the international climate change negotiation.

1.2 National Studies

1.2.1 Linking local actions with global consequences

Reducing greenhouse gases will also reduce local air pollution, and thus the corollary benefits should be counted in evaluating the cost of reducing greenhouse gas emissions. Reducing local air pollution also reduces greenhouse gas emissions, and therefore reduces the cost of reaching a greenhouse gas reduction target. Belgian analysts have calculated that combining the two emission reduction policies would achieve the same benefits at lower cost.

1.2.2 Sharing emission reductions domestically

The Kyoto Protocol specifies how greenhouse gas emission reductions will be shared among the industrialized countries. But how will these reductions be distributed within each country, and who will bear the costs?

The government of Canada addressed these questions in a comprehensive analysis of alternative ways to comply with the Kyoto Protocol. MARKAL was used to compare various schemes for domestic emission trading. An innovative use of the model was to show how incremental costs of emission reductions will be distributed among energy sectors either through demand or price effects.

1.2.3 National scenario analysis

In Finland, a series of extensive scenario analyses was carried out on the costs and effects on the national economy of various policies proposed to meet the targets of the Kyoto Protocol, extended to the year 2020.

1.2.4 Consequences of a nuclear phase-out

Modelers analyzed the technological, economic and environmental effects of a planned phase-out of nuclear energy in Germany. Eleven models - including both bottom-up and top-down models - were used to examine the consequences of eight scenarios differing in power plant lifetimes, carbon dioxide emission restrictions, and future energy prices. Qualitatively similar results were obtained with the bottom-up models, but the top-down models projected higher phase-out costs. The study concluded that both types of models are needed.

1.2.5 Coordinated local energy planning

The MARKAL model played a key role in planning waste management for the Basilicata region of southern Italy. Decisions had to take into account the complex of laws, land use, air quality standards, anticipated greenhouse gas emission limits, energy resources, social restrictions, waste characteristics, and available technology in minimizing the cost of waste disposal. The results contributed to regional plans for waste management, air quality, and energy use.

1.2.6 Updating estimates of elasticity

To analyze the interaction of energy and the economy, it is important to know how energy consumption will respond to changes in income and energy prices. In the past, particularly after the oil crisis of the 1970s, many studies were made of this issue. There is now more extensive and reliable statistical data. To take advantage of the more recent information, the income and price elasticity of final energy consumption in Japan was analyzed. The results are used to estimate future energy demand and provide input data needed for energy- economy interaction models.

1.2.7 Hedging against uncertain long-term emission reduction requirements

Although greenhouse gas emission targets have been set by the Kyoto Protocol for the period around 2010, the long-term need to reduce carbon dioxide emissions remains uncertain. In the face of this uncertainty, the stochastic version of the MARKAL model was used to calculate a near-term hedging strategy for the electric power generation and low temperature heat system of Japan.

1.2.8 Nuclear energy for high-temperature heat

Nuclear energy is already used extensively for generating electricity in Japan. However, a large amount of fossil energy is still used for non-electric energy demand such as industrial heating and transportation. The evolution of Japan's energy system over the very long term was examined to evaluate the possible role of high-temperature gas-cooled reactors and their use to provide heating services, especially from the viewpoints of economics and reduction of carbon dioxide emissions.

1.2.9 An advanced automobile concept for reducing carbon dioxide emissions

In Japan as in other countries, automobiles are the source of a large and growing proportion of carbon dioxide emissions. For large emission reductions in the long term, major changes will be needed. To this end, a team in Japan evaluated a novel concept for recycling carbon dioxide emissions from vehicles powered by fuel cells. For reasons of safety, methanol would be used as the on-board fuel.

1.2.10 Modeling the pulp and paper industry

A model of the Norwegian paper and pulp industry was developed using MARKAL. The purpose of the model is create a data set, using different prices for electricity, oil and biomass, to calculate pseudo price elasticities. The model can also be used to analyze various energy efficiency measures, such as environmental taxes, energy efficiency grants, and other policy measures.

1.2.11 Energy planning in China

The Swiss ETSAP participant cooperated in the China Energy Technology Program run by the ABB company. The Swiss institute was charged with leading the efforts in life-cycle assessment, environmental impact assessment, risk analysis, and energy/economy system modeling. The latter work, performed in cooperation with the Global Climate Change Institute of Tsinghua University, made use of the MARKAL and MARKAL-MACRO models.

1.2.12 A project for the Clean Development Mechanism in Taiwan

Under the Kyoto Protocol, a ‘Clean Development Mechanism’ was established which authorizes emissions trading with a developing country as a means by which an industrialized country can help meet its obligation to reduce greenhouse gases. Before a CDM project can start, the participants - the host country and the investor in an industrialized country - must set and define baselines and criteria for quantification of emission reduction. A study of building upgrades in Taiwan was made by United States and Taiwan analysts to demonstrate that these issues can be addressed within a single modeling framework. The MARKAL-MACRO model was used to evaluate the costs and benefits of what a CDM project might be, together with its impact on economic development.

1.3 Research and Development

1.3.1 Development of TIMES, the next generation of the MARKAL family

Conceived in Annex VI of ETSAP, the TIMES model has been substantially completed, validated, and begun to be applied in Annex VII. With the experience gained over two decades of applying MARKAL to real world problems, with the many fresh ideas arising from this experience, and with the expanding need for a detailed technology-oriented model that can be scaled from the municipal level up to a multiregional global model, ETSAP decided to take on the development of the new model.

TIMES builds on the best features of MARKAL and the Energy Flow Optimization Model (EFOM), hence the acronym TIMES (The Integrated MARKAL-EFOM System). TIMES will greatly expand upon MARKAL's traditional strengths and inherent flexibility, building on the advanced features added to MARKAL over time.

A multinational group cooperated in developing TIMES, including representatives from Belgium, Canada, Germany, the Netherlands, Italy, and the USA.

1.3.2 Goal Programming

A new variant, goal programming, of the MARKAL family of models was demonstrated in the USA. Goal programming is a flexible approach where reductions in pollutant emissions are set as targets, rather than as constraints, and are included in the objective function. These targets may be met, exceeded, or not met, depending upon the specification of other targets, such as total energy system cost, and the set of options available to meet the targets. As a result, multiple goals can be represented in the planning problem.

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This final report expands on these brief summaries of selected papers prepared during Annex VII, divided into three sections: international studies, national studies, and the research and development program.

2. INTERNATIONAL STUDIES

2.1 Meeting the Requirements of the Kyoto Protocol

Using a suite of MARKAL models as an expert system, Dutch analysts have drawn some inferences as to how best to meet the requirements of the Kyoto Protocol. Existing MARKAL models that focus on global trading, Western Europe's energy and materials systems, the role of biomass, the petroleum industry, and the municipality of Shanghai were supplemented with small, dedicated models designed to answer specific questions. The calculations suggest that the price of emission credits could be as low as 3 to 8 EUR per ton of carbon dioxide equivalent, if all flexible mechanisms and all reduction potentials can be used.

In a paper prepared for a seminar on climate negotiations and emission trading, Dolf Gielen and Tom Kram of the Energy research Center of the Netherlands (ECN), concluded that substantial improvements in both the effectiveness and efficiency of greenhouse gas mitigation policies can be achieved if governments:

- Take a comprehensive approach that allows as many technical options as possible, specifically including those related to materials as well as energy, and the greenhouse gases other than carbon dioxide
- Set the emission reduction targets to be achieved in the long run, to allow businesses more time to adjust, and technologies with long-term potential to be disseminated
- Strive for equality of marginal emission reduction costs across all sectors of the economy and across countries, rather than controlling only individual sectors or some countries
- Integrate greenhouse gas mitigation strategies with other environmental policies, notably waste and resource productivity, as well as with other non-environmental policies
- Are very prudent in pursuing policies that deliberately stimulate certain technologies, especially if they are costly for the emission reductions they achieve, to allow businesses to choose the most cost-effective options when emission penalties are taken into account.

2.1.1 The Other Greenhouse Gases

Currently, the greenhouse gases other carbon dioxide account for about one-fifth of Western European emissions. The amounts of the two major gases - methane and nitrous oxide - are expected to decline due to coal mine closures, waste policies, and changes in the chemical industry. However, significant potential exists for further reductions if proper policies are introduced. The next most important group of gases, hydrofluorochlorides, is expected to increase, although substitutes are available.

Including these other greenhouse gases in a global trade model increases the trade in emission credits. About one-quarter of the trade in greenhouse gas emission credits is due to these other gases in Western Europe, and about half in a global optimization case.

2.1.2 Biomass

The relevance of non-energy emission reduction was illustrated by the case of biomass in Western Europe. The model results suggest that up to 30 Mha, an area nearly the size of Norway, can be made available for greenhouse gas policies by 2030. However, it would be cost-effective to use three-quarters of this land for afforestation, rather than harvesting biomass. Biomass can be used to produce transportation fuels and as a feedstock for plastics and other synthetic organic materials. Electricity production from clean biomass (rather than waste) is not a good strategy because there are many more cost-effective alternatives for emission mitigation, whereas energy recovery from waste is a good strategy. The economic potential of biomass calculated with the model is only about one-third of the technical potential calculated in sectoral studies, as shown in the following table. The difference can be attributed to competition among land use options, competing mitigation options, and interactions among them. For example, increased energy efficiency achieved by other means reduces the advantage of using biomass for emission reduction in energy supply.

Table 2.1 *Techno-economic potential of biomass for greenhouse gas emission reduction, 2030.*

Use of biomass	Technological potential	Economic potential*	
	[Mt CO_2 eq.]	[Mt CO_2 eq.]	[%]
Afforestation/soil carbon	180	150	83
Carbon storage in products	105	25	24
Energy substitution	400	100	25
Materials substitution	500	100	20
Energy recovery from waste	100	25	25
Total	1285	400	31

*At a permit price of 200 EUR/t CO_2 eq.

The economic biomass emission reduction potential of 400 Mt CO_2 represents 9% of the 1990 emissions.

2.1.3 Flexible Mechanisms and Secondary Benefits

Two approaches were used to analyze flexible mechanisms: MARKAL models of specific developing countries and regions, and the aggregation of the resulting emission abatement curves for global analysis. The example of the municipality of Shanghai illustrates the value of the secondary benefits of greenhouse gas emission reductions that also reduce emissions of sulfur dioxide, nitrogen oxides, and particulate matter. Measured by the value of damage reduction, these secondary benefits amounted to 42 percent of the total. However, comparatively cheap end-of-pipe technologies exist for reduction of these emissions, and the cost of these alternatives provides a more conservative basis to evaluate these concomitant reductions than estimates of damage reduction.

2.1.4 Carbon Leakage

The possible migration of some industries to regions with no limit on carbon dioxide emissions - carbon leakage - is an argument for exempting these industries from emission restrictions. In contrast to the top-down economic models often used, MARKAL-type energy and materials models can evaluate this possibility by accounting for long-term technological options. One approach is to calculate the increase in domestic prices of products that would occur with increasing levels of taxes on greenhouse gas emissions. Table 2.2 identifies European products that would increase in cost by 100 EUR/t or more as emission taxes increase.

Table 2.2 *Products sensitive to greenhouse gas emission taxes, measured by an increase in cost per ton of product of 100 EUR or more.*

Greenhouse gas emission tax	Products with a cost increase of at least 100 EUR/ton of product
50 EUR/t CO_2 equivalent	Beef
	Aluminum ingots
	Aluminum scrap
	Cumene
100 EUR/t CO_2 equivalent	Soda
	Steel coils
	Graphic paper
	Particle board
200 EUR/t CO_2 equivalent	Chemical pulp
	Demolition wood
	Sawn timber
	Waste paper, separately collected

Other products evaluated that were not this sensitive to greenhouse gas emission taxation included chicken meat, corn, straw, wheat, ammonium nitrate, cement, steel scrap, energy wood chips, mechanical pulp, and roundwood.

For the petrochemical industry, a global model that covers the life cycle of all major products 'from cradle to grave' was used to show trade among six regions of the world. The results indicated that significant changes in production location would occur. Even considering many technological options to reduce greenhouse gas emissions, production in Western Europe and North America would decrease substantially because the resources are located elsewhere.

However, the relocation of the petrochemical industry would reduce greenhouse gas emissions. With an emission tax of 150 EUR/ton CO_2 only in Western Europe, North American and Japan, emissions from the industry would decrease by almost one-fifth. If the tax were global, emissions would decrease by more than half.

2.1.5 Policy Instruments

The study found very significant gains in effectiveness and efficiency of greenhouse gas mitigation if policies were to include materials options and to ensure the equality of marginal abatement costs. The total costs of reducing emissions could be reduced by as much as 40 percent.

'Policy continuation' means no cost increases allowed in sectors vulnerable to carbon leakage, a specified minimum level of renewable energy for electricity, limited land for biomass production, and accounting for transaction costs. This is compared in Figure 2.1 to an ideal policy in which materials measures are taken into account, and equivalence of marginal abatement costs is achieved. The difference between the two can be interpreted as mainly the effect of international cooperation.

In general, the marginal cost of emission reduction increases at an increasing rate with increasing greenhouse gas emissions. At the same marginal cost, greater emission reductions are achieved with the ideal policy than continuation of present policy. By 2030, these reductions would be much greater than in 2010 at the same marginal cost.

A departure from these trends occurs at low emission reductions where the marginal cost of reductions of policy continuation in 2030 far exceed those for 2010. This is due to the high marginal cost of mandating minimum levels of renewable energy. This is not to say, however, that such policies should not be adopted. In the future, more demanding greenhouse gas reductions may be needed, and governments should start now to implement the technologies that may be needed to meet a more ambitious objective.

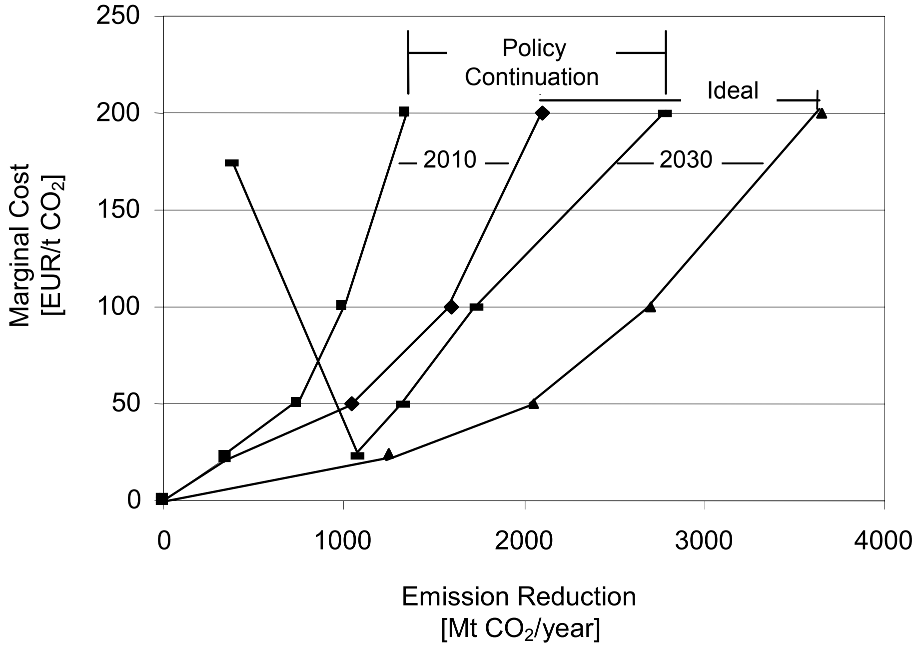

Figure 2.1 *Marginal cost of greenhouse gas emission reductions with continued policies and under an ideal policy, 2010 and 2030.*

2.2 Technology Learning Across Regions

Similar technologies in different regions of the world may benefit jointly from the cost reductions that accompany manufacture and use on a larger scale. Leonardo Barreto and Socrates Kypreos of Paul Scherrer Institute, Switzerland, have extended the RMARKAL model to assess the effects of such technological 'learning' across several geographical regions. Two different models have been defined using RMARKAL: a nine-region electricity model and a five-region global model, both with carbon dioxide emission trading, trade of fuels, and learning options with global spillovers. Here an example illustrates the changes in the optimal choice of technologies in a multi-regional global electricity system when there is shared learning and when carbon dioxide emissions are constrained. A complete report on the issue can be found in the dissertation of Barreto.

The interaction between technological learning and trading carbon dioxide emissions, both of them affected by geographical boundaries, exerts a significant influence on the final outcome of the model. In the example, the choice of photovoltaic electric generators is found to depend in part upon whether successive reductions in their cost occur separately in individual regions, or more substantially through the joint benefits of use in several regions. The choice also depends upon whether there is carbon dioxide emission trading between industrialized and developing regions.

Earlier, Kypreos and Barreto incorporated learning curves - the successive reduction in investment cost with more widespread use - in the single-region MARKAL using the technique of mixed integer programming. The model allows early up-front investments to introduce promising, but initially expensive, technologies that prove to be cost-effective in the long term. Another member of the MARKAL family of models is the multi-regional RMARKAL, which allows the examination of several coupled energy systems. To consider the possibility of a spillover of learning between regions, modifications were made to the multi-regional RMARKAL to allow technologies to learn across regions.

A typical learning curve describes the cost of a technology as a function of cumulative installed capacity. This may represent learning-by-doing, learning-by-using, or learning-by-interaction. Learning curves characteristically decline exponentially, that is, the greatest cost reductions occur initially, tailing off with increased amounts. On double logarithmic grids, this relationship appears as a straight line. (Figure 2.2)

In the multi-regional model, the use of related technologies in different regions can be assumed to contribute to their joint cost reduction. Globalization of energy markets may promote a global learning process. International co-operation in R&D, demonstration, and deployment (the so-called ERD3 strategy) of new technologies may stimulate spillover of learning between countries, reducing cost barriers to the introduction of new technologies.

The global electricity generation system is represented in the model by nine regions. Five industrialized regions represent the countries identified as Annex I in the Kyoto Protocol, and four developing regions represent the non-Annex I countries, Barreto and Kypreos examined the choice among thirteen electricity generation technologies. Six of these are considered to be on learning curves that will reduce their cost as shown in Figure 2.2.

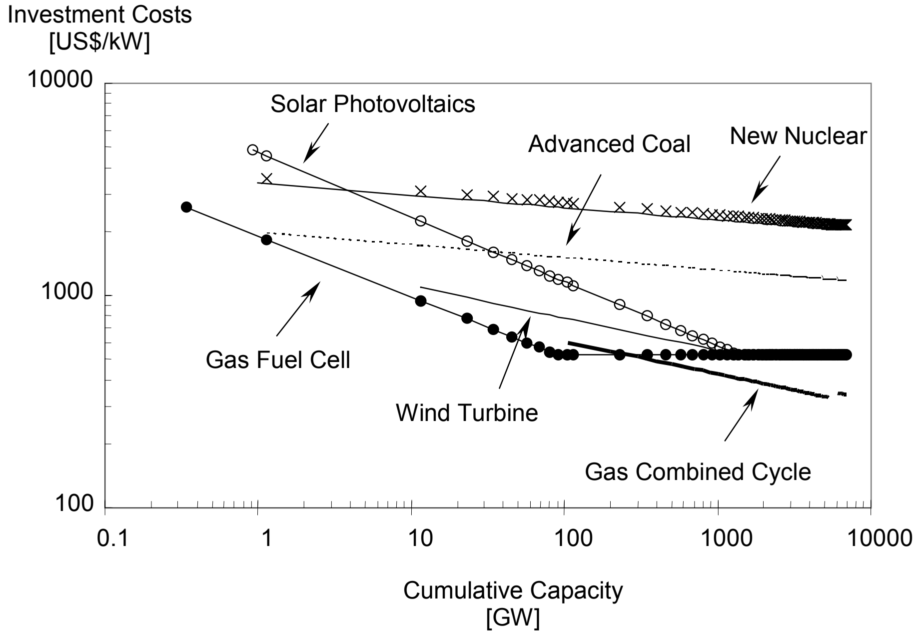

Figure 2.2 *Assumed learning curves for new electric generation technologies.*

The choice among these technologies was determined in twelve scenarios. In addition to business as usual, the scenarios examined included a Kyoto trend, that is, restrictions on carbon dioxide emissions according to the Kyoto Protocol through 2010, with a further reduction of 5 percent per decade to the end of the model horizon. Three different assumptions were made both as to the extent of international emissions trading and the extent to which technological learning is shared, as shown in Table 2.3.

Photovoltaic electric generation proves to be a marginal technology in this example, as shown in Table 2.3. Its dissemination depends upon the geographical limits within which learning is assumed to take place, and the extent of emissions trading. With business as usual - no restrictions on carbon dioxide emissions - photovoltaics are never selected by the model. With global learning, however, photovoltaics are always selected - in both Annex I and non-Annex I groups of countries - when emissions are restricted to the Kyoto trend. With full emissions trading, photovoltaics are also chosen when learning is assumed to spill over separately only among the Annex I countries, on the one hand, and among non-Annex I countries, on the other. If the economies of learning are restricted only to the individual nine world regions, however, photovoltaics are never selected.

Table 2.3 *Circumstances that favor the introduction of photovoltaics in the example.*

Learning boundaries	Business as usual	KYOTO TREND		
		No emissions trading	Trading only among Annex I regions by 2010	Full emissions trading by 2030
Global learning		x	x	x
Two learning regions: Annex I and non-Annex I				x
Single-region learning				

Some results for the choice of technologies are illustrated in Figure 2.3, in which business as usual is compared with the Kyoto trend scenario and emissions trading only among Annex I countries. With business as usual, shared learning beyond the single regions greatly benefits gas combined cycle at the expense of conventional coal (compare bars on the left). With single region learning, emissions trading also favors gas combined cycle, closely followed by nuclear power (compare black bars on the left and right).

With both global learning and emissions trading, the principal beneficiaries of the reduction in coal are gas combined cycle, nuclear power and photovoltaics (compare black bars on the left with light bars on the right).

The results highlight the importance of fostering international cooperation on energy development to stimulate the learning process in emerging energy technologies.

In their earlier experimentation, Kypreos and Barreto developed the prototype ERIS (Energy Research and Investment Strategies) model that included learning and the stochastic feature with risk aversion that identifies hedging against climate change. The model was solved using mixed integer programming and nonlinear programming. Two basic conclusions emerged from applications of the model at PSI as well as at the Energy research Center of the Netherlands (ECN):

- Significant policy implications can be expected from climate change analyses.
- The technology database is critical as well as the model and requires solid engineering justification.

In cooperation with ECN and Gary Goldstein, RMARKAL was extended to include stochastics and learning by technology clusters in a set of regions. Together with the Canadian ETSAP participants, common and simple databases were developed for electricity production, transportation, industry, and the residential and commercial sectors.

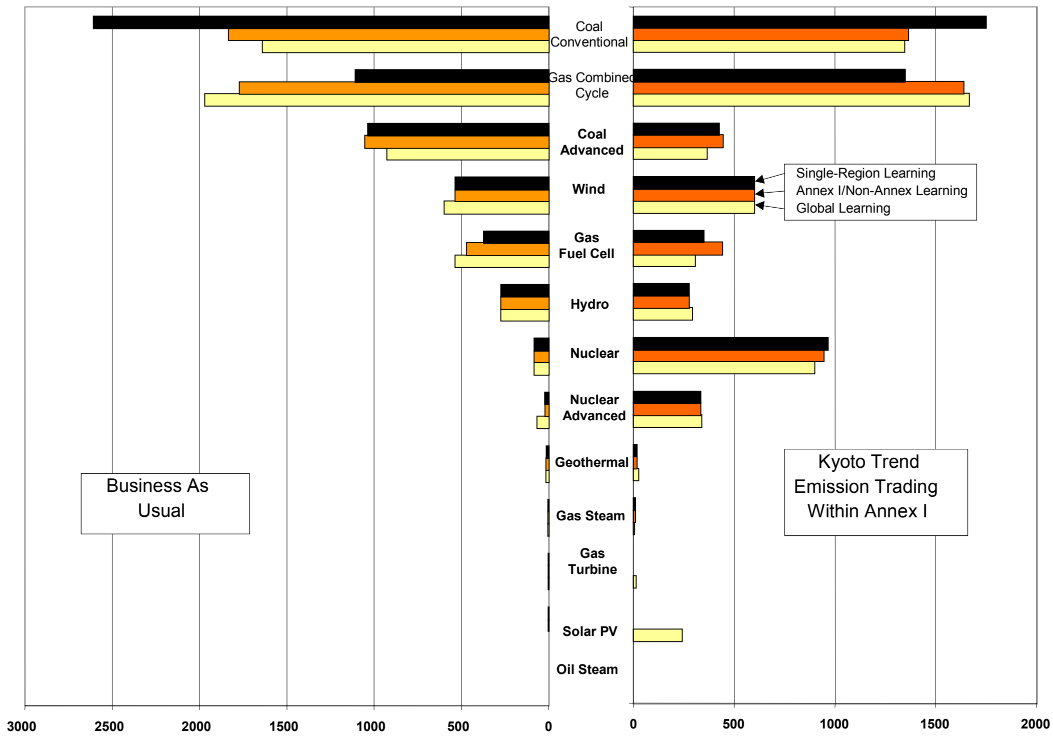

Figure 2.3 *Electricity generation in 2050 (gigawatt-hours), as affected by carbon dioxide emission restrictions and geographical sharing of learning. Technologies are ranked in decreasing order for business as usual with single-region learning.*

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L. Barreto. Technical Learning in Energy Optimization Models and Deployment of Emerging Technologies. Dissertation ETH-Zurich No. 14151, 2001, Switzerland.

2.3 Modeling clusters of learning technologies

Compared to earlier experiments with technology learning in the MARKAL model of Western Europe (as reported in Seebregts et al, 1998; 1999; Kypreos & Barreto, 1998; Barreto & Kypreos, 1999), a major advance in Annex VII was the implementation of the concept of clusters of technologies.

The first experiments with technology learning in MARKAL (Seebregts et al., 1998) and the synthesis of MARKAL, ERIS, and MESSAGE (Seebregts et al., 1999) made it clear that interdependent learning between technologies sharing common key components was an important issue, not yet addressed. Examples of interdependent learning issue are spillover and crossover[1] effects between technologies that are modeled separately.

A way to deal with these phenomena is to define and use the concept of clusters of technologies. A cluster of technologies is defined as a group of technologies sharing a common component. This component, which can be a technology in itself, is called the 'key technology' and is the selected learning component in each of the technologies in the cluster. Examples of key technologies are gas turbines, fuel cells, photovoltaic modules, wind turbines, burners and boilers. Most of the approximately 500 technologies defined in the MARKAL technology database for Western Europe are composed in part of about 20 such key technologies. The existing technologies need to be grouped into clusters that are similar in their learning behavior; i.e., the development of these technologies is in some way linked.

The Energy research Centre of the Netherlands (ECN) implemented this concept for five clusters of technologies covering about 30 technologies (Seebregts et al, 1999, 2000); see Table 2.4. These include not only power and supply-side technologies but also demand-side technologies such as fuel-cell vehicles.

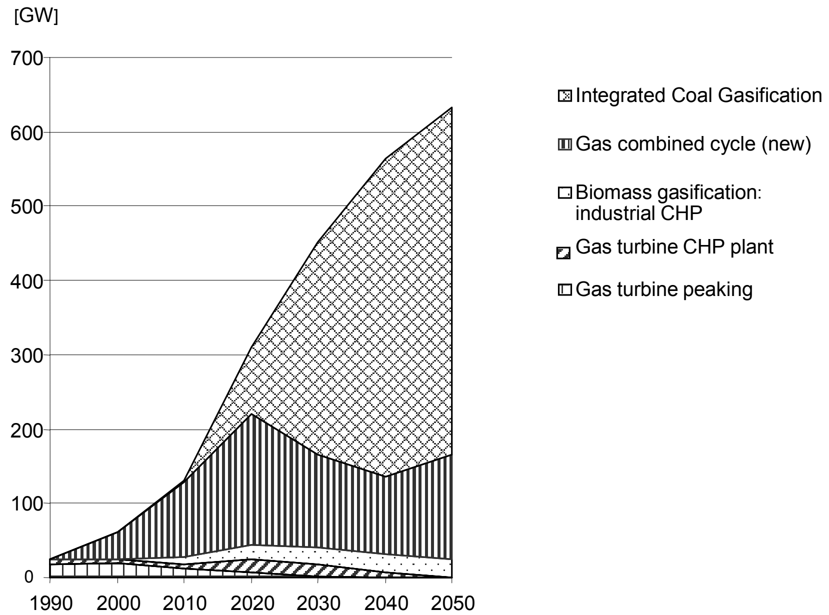
Table 2.4 *Clusters of learning technologies in the ECN MARKAL model of Western European (Seebregts et al., 2000).*

Description	Number of technologies in cluster
Photovoltaic modules	5 (complete systems including balance-of-system)
Wind turbine	4 (complete systems including tower, foundation, electrical infrastructure)
Fuel Cell	10 (7 in transport sector; 3 stationary in power sector)
Gasifier	5 (3 biomass; 2 coal)
Gas Turbine	11

[1] Spillover: Experience with a certain technology is relevant to the development of a quite similar technology. For example, photovoltaic technologies developed and used in a certain region of the world may or will have a positive effect on the development of such technology in another region.
Crossover: Experience with a technology is relevant for development of another quite different technology. For example, experience gained with gas turbines in airplanes may have a positive impact on gas turbines used in the power sector.

The interaction between different clusters in terms of lock-in, lock-out, path-dependency[2], and spillover is clearly observed in some cases. Such observations are now possible by including the concept of clusters of technologies as an integral part of the technology learning formulation. Compared to the first MARKAL models of the Western European energy system, this feature produces more consistent model results, assuming the data are available. Although this requires more data collection and longer solution times, these are both reasonable increases.

The analyst is forced to look at technology characterizations in more detail, which will improve the quality of the model's technology database. The use of clusters of technologies prevents underestimation of the technological progress from learning-by-doing. Coupling the experience of technologies that share important common learning components is prerequisite to obtaining consistent results. One of the specific advantages is that experience gained in rather different markets is combined, as was shown for fuel cell technologies, and for regional spillover as described in the previous section (Barreto & Kypreos, 2000).



.Figure 2.4.1 *Installed capacity of the gas turbine cluster of technologies, without CO_2 constraints.*

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2 Lock-in/out: Once a certain technology gains enough advantages over a competitor technology, it may take the entire or a large market share, while the competitor technology will never be able to catch up. The latter technology is then said to be 'locked out', while the former is said to be locked-in.
Path-dependency: Phenomena where the development of a certain technology is dependent on another. For example, wind energy may become very attractive in a particular (more renewable) scenario, making gas turbines less attractive. As a result, other technologies that compete with gas turbines are more attractive.

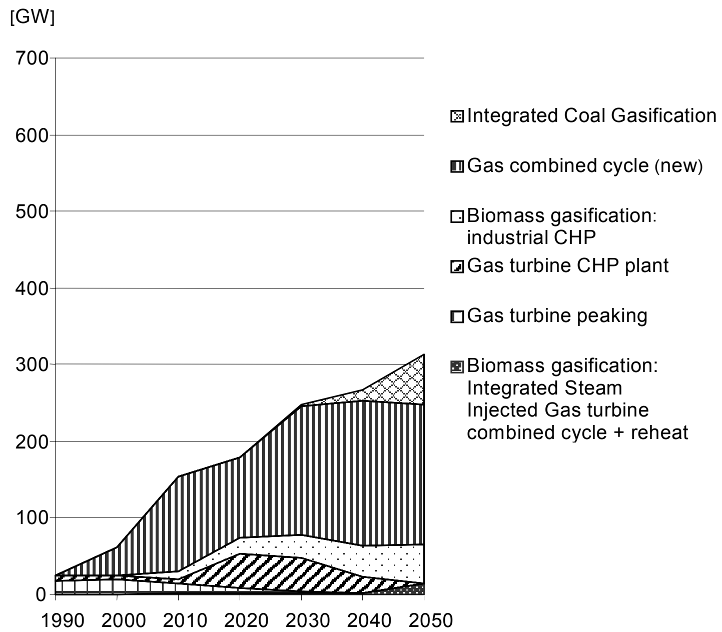

Figure 2.4.2 *Installed capacity of the gas turbine cluster of technologies, with CO_2 constraints.*

As part of the ongoing SAPIENT research project of the European Union, ECN increased the number of clusters to 10 covering more than 80 technologies. The concept of clustering is now also being used in the *Energy Technology Perspectives* project of the International Energy Agency.

Figures 2.4.1 and 2.4.2 show an example of results obtained with technology learning and clustering.

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2.4 Cooperation Among the Nordic Countries

In Scandinavia, the Nordleden project showed the value of grid-distributed energy trade and increased cooperation among the Nordic countries to reduce carbon dioxide emissions. Possible commitments by the stationary energy sectors of the countries were analyzed that would reduce emissions beyond the Kyoto Protocol requirements to about a 60 percent reduction by 2050. The regionalized MARKAL model was used by Swedish and Norwegian participants in ETSAP for the evaluation.

The measures considered included:

- Increased net electricity trade
- Common action rather than separate measures to reduce emissions
- Trans-Nordic natural gas transmission pipeline.

Each of these alternatives, implemented alone, was estimated to save from 10 to 50 billion Swedish crowns, depending upon future energy demand and technological developments. At least twice that amount would be saved if all three cooperative strategies were used at the same time.

The Nordic energy system displays a high degree of flexibility for meeting carbon dioxide reduction commitments, according to the model results. The many factors that can play an important part include hydroelectric and wind power, bio fuels, end-use conservation and efficiency measures, combined heat and power units, and increased use of natural gas. In the long term, solar power, fuel cells, and the sequestration and disposal of carbon dioxide will become more important, while the use of coal, oil and nuclear power will decrease drastically. By the year 2030, bio fuel might be the largest single type of energy carrier in the Nordic energy supply.

With this cooperation, according the model results, all three grid-distributed energy carriers - electricity, natural gas, and district heat - become more important. Electricity trade will increase among the Nordic countries. Sweden, due to its planned nuclear phase-out, will become a net importer of power, while Denmark and Norway are net power exporters. With low to modest carbon dioxide reductions required, natural gas traded through a Trans-Nordic pipeline will replace a considerable amount of coal and oil. With greater emission reduction requirements, however, the use of natural gas is somewhat attenuated by an increase in the use of bio fuels.

Trade in emission permits leads to further cost-efficient abatement. Generally, Danish and Finnish sectors using central combined heat and power production are net sellers of permits. Swedish and to some extent Norwegian end-users, particularly in industry, are the buyers.

The Nordleden project was financed by the Swedish National Energy Administration, Swedish Power Association, Swedish Gas Association, Swedish District Heating Association, and the Norwegian Electricity Federation.

Earlier studies of the benefits of cooperation in reducing carbon dioxide emissions among the Scandinavian countries were extended to include the Baltic countries. For this evaluation, the Nordic countries of Norway, Sweden, Finland and Denmark were merged into one large model. Using the regionalized MARKAL, this was linked with individual models of the Baltic countries: Estonia, Latvia and Lithuania.

For carbon dioxide emission reductions more severe than the requirements of the Kyoto Protocol, the analysis concluded that the cost of abatement can be reduced by 5% by the extension of electricity trading to the Baltic countries, and by 25% if both electricity and emission permits are traded.

The required carbon dioxide emission limits assumed for 2010 in this analysis were, in comparison to 1990, for Norway +1%, Sweden +4%, Denmark -21%, and Finland no change. For the Baltic countries, as much as an 8% reduction from the 1990 level was assumed, which is not as low as those countries expect to emit without further restrictions. Beyond 2010, there is an additional tightening of 5% per decade.

Three scenarios were considered:

- No net annual trading in electricity, but seasonal and diurnal trading allowed
- Electricity trading allowed among the Nordic and Baltic countries, but not between the two groups
- Full electricity trading within existing grid capacities, and unlimited trade in emission permits.

With trading, carbon dioxide emissions decline as required in the Nordic countries. In the Baltic countries, they increase, but not up to the limits allowed them.

The major exporter of electricity - and the largest buyer of emission permits - becomes Norway. Sweden becomes the major importer of electricity and a buyer of emission permits as its nuclear plants are phased out. Both Norway and Sweden face very tight emission targets, and could not be expected to meet their Kyoto targets on their own.

Finland becomes an importer of electricity, but gradually phases out its purchases of emission permits. Denmark increases its production of electricity slightly but phases out coal; over time, it ceases to sell emission permits.

The three Baltic countries all sell emission permits, and Estonia and Lithuania also become exporters of electricity.

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2.5 Managing Materials to Reduce Carbon Dioxide Emissions

Modeling studies of future requirements to reduce greenhouse gas emissions from Western Europe find that managing the flow of materials substantially increases the reductions that can achieved over managing the flow of energy alone. Nevertheless, the prospect of reducing greenhouse gas emissions by managing materials continues to be virtually ignored.

Culminating a four-year program, the Dutch National Institute of Public Health and the Environment published the comprehensive results of the MATTER project. An integrated systems engineering model, coupled with detailed studies of individual industrial sectors, was used to evaluate technologies for reducing future greenhouse gas emissions. To achieve the sharp reductions likely to be needed in the long run, changes in materials technology have the potential to reduce carbon dioxide emissions by another 50 percent over what can be achieved with only energy technologies.

To evaluate the potential contribution of changes in the management of materials to reduce emissions, the MATTER (MATerials Technologies for greenhouse gas Emission Reduction) model was created within ETSAP by extending the MARKAL model to include material flows as well as energy flows. As with the energy system, the materials system was characterized by the set of technologies that produce, convert, and use materials to satisfy a set of projected demands. The results suggest changes in industrial and governmental policies as well as the choice of technologies.

Emissions of greenhouse gases can be reduced significantly by measures related to the production and use of materials. In the model of Western Europe, emissions related to materials amount to 1,200 MtCO_2 equivalents of 5,100 MtCO_2 for the combined energy and materials system. With emission penalties of 100 Euro/tCO_2 this can be reduced by 800 MtCO_2 equivalents, a reduction of two-thirds.

A limited number of materials from natural resources produce most of the carbon dioxide due to materials production. These consist of three groups:

- Most important, bulk materials of two types: synthetic organic materials (plastics) produced with fossil fuel feedstocks, and materials that require a large amount of energy to be produced (e.g., steel and aluminum)
- Second, materials produced by chemical processes that emit large amounts of carbon dioxide, mainly cement
- Third, wood products from forests that are not as yet managed in a sustainable way, mainly timber from old-growth rainforests.

Steel, cement, and plastics produce most of the carbon dioxide emissions from Western European manufacturing.

The relationship between materials and greenhouse gas emissions is not yet widely considered in greenhouse gas policy-making, nor is the use of fossil fuels for non-energy uses, such as feedstocks. More attention should be given to substitute feedstocks in the petrochemical industry, and to reducing greenhouse gas emissions with substitute materials, improved material quality, the development of new materials, product redesign, and waste management strategies.

The case studies for buildings and infrastructure, steel and biomass provide examples of the potential for significant emission reductions. For *buildings and infrastructure*, these include:

- Replacement of non-renewable tropical timber with renewable substitutes
- Improved cement production, including the increased use of clinker substitutes such as slag, ashes, and geopolymeric cement
- Improved material quality for steel, cement, and wood products
- Redesign of buildings from the point of view of materials efficiency

- Improved building and construction waste recovery systems.

The *steel* industry may choose from a labyrinth of production possibilities, depending upon tax levels, energy prices, electricity emission factors, carbon dioxide storage capacity, the presence of excess energy markets, and the success of the cyclone converter furnace now in the pilot phase. Most of these routes would reduce carbon dioxide emissions considerably.

With more severe penalties on carbon dioxide emissions, the most important strategies for the use of *biomass* are energy (increasingly for transportation fuels), materials such as feedstocks for chemicals, and afforestation for carbon storage.

For newer materials and products, even greater potential for emission reductions can be expected.

Aside from carbon dioxide, the most important greenhouse gases resulting from materials are methane from landfill sites, nitrous oxide from the chemical industry and agriculture, and perfluorocarbons from aluminum smelting.

With stringent greenhouse gas emission reduction measures, emissions in many parts of the materials and energy systems will be reduced. It is necessary to use an integrated system model to consider the interaction among these measures to avoid overestimating the potential for emission reduction. These results in some cases offer striking differences from earlier partial assessments.

For example, if emissions are reduced in the production of materials - that is, if the materials themselves become less carbon-intensive - the benefit of reductions in the later use of those materials is reduced. Another example: If coal-fired power plants are phased out, the production of cement using fly ash will be affected. Again: the use of lightweight automobiles reduces the demand for transportation fuel. The selection of building materials affects the heating and cooling requirements of the buildings. Several industries compete for energy recovery from waste; if such interactions are not considered, potential emission reductions from waste recovery will be overestimated.

It is not possible to categorize ‘good’ and ‘bad’ materials from the point of view of greenhouse gas emissions, and no generic strategies can be recommended. The case studies show that each material must be analyzed within the context of a specific application. However, an integrated approach is required. It is of absolute importance to account for interactions on the level of the whole economy to avoid suboptimal emission reduction strategies. The output of the MATTER model, which can be found on the Internet, can be useful in developing materials strategies [http://www.ecn.nl/unit_bs/etsap/MARKAL/MATTER/main.html].

2.5.1 Effect of Emission Penalties

Greenhouse gas abatement measures are represented in the model as financial penalties on emissions. Such penalties will favor the use of certain materials, for example, aluminum in the transportation sector, and wood for building, paper production, and as a substitute for fossil fuel feedstocks. These penalties will have a far greater impact on materials production and waste handling than on the consumption of materials. The case studies for the building sector, iron and steel, and biomass offer clear examples of this.

Thus, for industries at the upstream and downstream ends of the materials system - such as materials producers and waste-handling companies - emission penalties will have a significant impact. Financial instruments are likely to affect their decision-making.

On the other hand, greenhouse gas emission reductions through changes within the materials system will have little impact on the price of consumer products, because the cost of materials is a small fraction of the price of the product. This suggests that pricing instruments alone will be insufficient to effect significant changes in the use of materials. Other policy instruments must be developed, such as legislation and covenants for industry, improved information for industrial designers, and R&D programs aimed at industries consuming materials, especially those with small and medium-sized enterprises. Nevertheless, rigorous pricing of greenhouse gas emissions remains an indispensable element to reveal the cost implications through the highly complex and interlinked systems of materials and energy flows.

2.5.2 Sustainable Development

The model calculations show that a long-term policy perspective must be provided to avoid short-term optimization with undesirable long-term consequences. Policy-makers have not yet provided emission reduction goals beyond the 2008-2012 Kyoto Protocol time horizon. Without such goals, industry is unlikely to take future emission reduction requirements into account in their current investment decisions. Because of the long-term consequences of investment decisions, this is a major barrier to moving in the direction of sustainable development.

To achieve the major reductions in carbon dioxide emissions that will ultimately be required, penalties on emissions will have to exceed 100 Euro/tCO_2. This is much higher than carbon tax levels presently under consideration. Industry should be given clear guidelines regarding future emission targets to inform decisions on investments with a life span of two, three or more decades.

Many of the measures that will reduce carbon dioxide emissions will also increase the sustainability of the economy. Thus, they can be viewed as the operationalization of the concept of sustainable development.

The report was published within the framework of the Dutch National Research Programme on Global Air Pollution and Climate Change. The participating organizations were the Energy research Centre of the Netherlands, Groningen University, Utrecht University, and the Free University of Amsterdam.

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2.6 Is the Kyoto Protocol Fatally Flawed?

A report, *Is Kyoto Fatally Flawed? - An Analysis with MacGEM*, was prepared by Johan Eyckmans and Denise Van Regemorter of the Center for Economic Studies (CES) at the Katholieke Universiteit of Leuven, and Vincent van Steenberghe of the Center for Operations Research and Econometrics at the Université Catholique de Louvain, Belgium.

Under the 1997 Kyoto Protocol, global emissions of carbon dioxide would rise by 15.6 percent, compared to a 30 percent rise under business as usual, according to the model results. With the USA out, the rise is expected to reach 25 percent. Under the Bonn agreement - depending upon the actions of the Eastern European countries and the former Soviet Union, and the possible use of carbon sinks - the rise may range between 23.8 and 26.4 percent.

The MacGEM model used for the projections consists of a set of marginal abatement cost functions for carbon emissions originating from fossil fuel use. The model aims to evaluate compliance costs and permit trading equilibria in the first commitment period of the UN Framework Convention on Climate Change. The marginal abatement cost functions were estimated from data generated for 15 regions or countries in the world by the GEM-E3-World general equilibrium model.

The USA is the major emitter of greenhouse gases among the industrialized countries that signed the Kyoto Protocol (Annex B countries), accounting for more than one-third of their total emissions. The nonparticipation of the USA therefore changes things significantly. The global emission reduction objective is drastically weakened.

Consequently, as summarized in Table 2.4, the price of the emission permits decreases by more than half (10 versus 22 US$1995ton/$CO_2$) because an important share of permit demand falls out. As the total emissions objective of the world falls, it is not surprising that the world's cost also falls, from 0.058 percent to 0.008 percent of 2010 GDP.

Compliance costs for most of the industrialized countries are also cut by more than half. However, the biggest losers are Eastern Europe and the former Soviet Union. By exactly the same amount as the drop in compliance costs in the other countries, their benefits drop from 2.1 percent to 0.8 percent of GDP in 2010 because of the sharp reduction in the permit price.

2.6.1 The Bonn Agreement

The Bonn agreement reached in July 2001 covers the use of flexible mechanisms and the use of carbon sinks, among other things.

Table 2.4 *Comparison of conditions under the Kyoto Protocol.*

Conditions	2010 World Emissions		Annex B* Emissions 2010	Carbon Permit Price	Compliance Cost [% GDP]	
	$GtonCO_2$	vs. 1990 [%]	[$GtonCO_2$]	[95$/$tonCO_2$]	World	Annex B*
Business As Usual	28.04	+30.1	10.28			
1997 Kyoto Protocol	24.91	+15.6	8.88	22	0.058	0.108
Without USA	26.94	+25.0	9.48	10	0.008	0.029
With CPR Flexible Mechanisms	26.94	+25.0	9.56	14	0.008	0.038
And with JI in CEU + 'hot air'	26.69	+23.8	9.36	17	0.014	0.058
Or with carbon sinks	27.24	+26.4	9.78	10	0.004	0.021

Notes: Annex B* = Annex B countries except the USA
GDP = Gross Domestic Product
CPR = Commitment Period Reserve
JI = Joint Implementation
CEU = Countries of Eastern Europe and the former Soviet Union

The Parties agreed to put no cap on the use of flexible mechanisms, but domestic actions should constitute ‘a significant element’ of the emission reductions. Under the Commitment Period Reserve, each party must keep some specified amount of Assigned Amount Units in its greenhouse gases account. The effect is similar to putting a ceiling on permit exports.

The goal of the Commitment Period Reserve is to prevent the risk of overselling emission permits by Parties by requiring them to maintain a certain amount of permits in their account. This must be at least (a) 90 percent of the Party’s assigned amount, or (b) five times its most recently reviewed inventory, whichever is lower.

In a scenario without the USA, the countries of Eastern Europe and the former Soviet Union would wish to export 26 percent of its permits. Therefore, they are constrained by the Commitment Period Reserve in the amount of permits they may sell.

The total compliance costs for the countries of Eastern Europe and the former Soviet Union are lower under the Commitment Period Reserve regime. This is because the supply of permits is limited, and their price rises about 30 percent. Likewise, the total cost to the Annex B countries other than the USA (hereinafter Annex B*) rises by about 30 percent.

Thus, the Commitment Period Reserve benefits the countries of Eastern Europe and the former Soviet Union. But they can do even better if they exert their considerable market power by restricting their exports of permits.

In the prior analysis, it was assumed that emission reductions in the countries of Eastern Europe and the former Soviet Union are due to domestic measures, such as a cap-and-trade system or a general carbon tax. However, they may make only those reductions through Joint Implementation projects financed by other Annex B countries. These emission credits would be used by the sponsoring countries to meet their reduction requirements, and would be automatically deducted from the accounts of the countries of Eastern Europe and the former Soviet Union. (For the calculations, it was assumed that only 60 percent of feasible Joint Implementation are implemented.) This behavior can be considered as choosing the amount of ‘hot air’ to be sold.

‘Hot air,’ the difference in emissions from the assigned amount under the Kyoto Protocol and that projected for business as usual, amounts to 0.68 $GtCO_2$, or 15.3 percent of the assigned amount of these countries.

Under these circumstances, the Commitment Period Reserve is not binding. The countries of Eastern Europe and the former Soviet Union export only 18.5 percent of its Authorized Amount Units, about half from Joint Implementation Projects and half from hot air. As the countries sell only 62.5 percent of their hot air, world emissions increase by 23.8 percent over 1990, compared to 25 percent otherwise.

World total costs are higher. The increase is due not only to the market power of the countries of Eastern Europe and the former Soviet Union, but mainly to the restricted accessibility to Joint Implementation.

2.6.2 Carbon Sinks

The Bonn agreement included definitions of such concepts as afforestation, reforestation, etc. Reforestation and afforestation projects under the Clean Development Mechanism (CDM) are capped at a maximum of one percent of the donor country's base year emissions. Caps are set on the use of carbon absorption from forestry management and agriculture. Limits have also been set upon the use of certain land use, land use changes, and forestry activities.

Carbon sinks are much debated because there is no easy way to measure the carbon sequestered by changes in vegetation. The modelers assumed that land use changes and forestry activities constitute free abatement options and that countries will try as much as possible to use existing projects without additional costs to meet their emission reduction obligation.

Although activities that enhance carbon sinks should in principle not modify world carbon dioxide emissions, introducing them into the agreement is likely to reduce carbon emission reduction efforts. This will erode the global emission target even further, and will lead to a further decrease in total world costs by half. Annex B* countries' cost would also be reduced.

As a result of the use of carbon sinks as well as the flexible mechanisms under the Commitment Period Reserve, world emissions would increase by 26.4 percent by 2010.

The report concluded that the US withdrawal and the Bonn Agreement have completely eroded the greenhouse gas emission targets for the first commitment period as they were laid down in the 1997 Kyoto Protocol. However, the Bonn Agreement has the merit of saving the international negotiation framework of the UNFCCC so that more stringent objectives can be envisaged for subsequent commitment periods, and conditions can be created for developing countries to commit to quantified greenhouse gas emission reduction targets and for a possible reconsideration of the USA position.

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3. NATIONAL STUDIES

3.1 Linking Local Actions with Global Consequences

Reducing greenhouse gases will also reduce local air pollution, and thus the corollary benefits should be counted in evaluating the cost of reducing greenhouse gas emissions. Reducing local air pollution also reduces greenhouse gas emissions, and therefore reduces the cost of reaching a greenhouse gas reduction target. Belgian analysts have calculated that combining the two emission reduction policies would achieve the same benefits at lower cost.

Stef Proost and Denise Van Regemorter of Center for Economic Studies at the Catholic University of Leuven used the MARKAL model of the Belgian energy system to compare the benefits of a combined policy of reducing local air pollution and reducing greenhouse gas emissions with doing each alone.

For this purpose, a damage function was added to the MARKAL objective function that takes into account the environmental cost of local air pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOC), and particulate matter (PM). The local environmental problems considered were those due to acid deposition, and ambient air quality linked to acidifying emissions and ozone concentration.

The MARKAL database was extended in three ways:

- emission coefficients for the local air pollutants from each technology, together with emission abatement technologies
- coefficients for the translation of emissions into concentrations, including the transportation mechanism
- environmental impacts due to local air pollution, and their monetary evaluation.

The monetary cost of emissions of greenhouse gases was not estimated in the manner of the local air pollutants. However, in the policy simulations, greenhouse gas emissions are implicitly monetized through the shadow price associated with the constraint on greenhouse gas emissions.

Emission coefficients for the four pollutants vary with the individual energy technologies, unlike carbon dioxide which depends only upon the fuel consumed. This requires a major extension of the database. The total damage due to emission of these pollutants in Belgium is estimated to go far beyond the country itself, and is principally due to particulate matter, as shown in Table 3.1.

The translation of emissions into atmospheric concentrations must take into account their dispersion and transport as well as prior background concentrations. The photochemical reaction of NO_x and VOC in the atmosphere to produce ozone must be considered. The results of the complex meteorological and chemical models used to make these calculations were made static and linear as coefficients for MARKAL, a linear model.

Table 3.1 *Damage of emissions from Belgium (millions of Belgian francs per kiloton of pollutant).*

	Damage in Belgium	Total damage in Belgium and abroad
Nitrogen oxides	9.51	99.11
Sulfur dioxide	27.30	96.44
Volatile organic compounds	0.77	7.52
Particulates	102.89	317.17

The approach to estimating damage from these atmospheric concentrations and its monetary valuation were based on the ExternE project of the European Commission (1995). The damage occurs when primary (e.g., sulfur dioxide) or secondary (e.g., sulfates) pollutants are deposited on a receptor (e.g., in the lungs or on a building). Ideally, one should relate this deposition per receptor to physical damage per receptor. In practice, dose/exposure response functions are related to:

- ambient concentrations to which a receptor is exposed,
- wet or dry deposition on a receptor,
- ‘after deposition’ parameters, such as the pH level of a lake due to acid rain.

The incremental physical damage to a country is given as a function of the change in deposition or concentration, such as the acidifying components or ozone concentrations in the model. Two types of damage are considered in the model:

- damage to public health: acute morbidity and mortality, and chronic morbidity (but not occupational health),
- damage to the ecosystem (agriculture and forests) and to materials, the latter in a very aggregated way.

Economic evaluation of the damage can be based on either willingness to pay, or willingness to accept. For market goods, this valuation is determined by the market price. For non-market goods, there are three approaches to value the damages:

- contingent valuation method (CVM), in which people are asked their willingness to pay in hypothetical scenarios,
- hedonic price method, which seeks to discover values for non-market goods by examining the market for substitutes or complements,
- travel cost method, particularly useful for evaluating recreational impacts, determined by willingness to pay.

Estimating environmental costs on the global level raises different problems, such as the transferability of results from specific studies, time and space limits, uncertainty, the discounting factor, the use of average estimates rather than marginal estimates, and aggregation.

3.1.1 Impacts on Public Health

In evaluating impacts on public health, a distinction is made between morbidity - the amount of sickness - and mortality - the death rate. The valuation of morbidity is based on willingness to pay. The willingness to pay for an illness is composed of three parts:

- Value of time lost because of the illness
- Value of the lost utility because of pain and suffering
- Expenditure on averting or mitigating the effects of illness.

3.1.2 Impacts on Terrestrial Ecosystems

In addition to their effect on human health, pollutants may damage terrestrial ecosystems, such as agriculture and forests.

Damage to agriculture and forests is due to foliar uptake or to acid deposition on the soil. Often, multiple stresses - climate, pests, pathogens - are involved, and it is not possible to attribute damage to a specific cause. Damage due to chronic exposure is usually different from acute injury. A given dose of a pollutant will produce a variable response depending upon a wide range of factors: species affected, age of the organism, other pollutants, time of day or season, water status, light conditions, soil and nutrient status, heavy metals in the soil, etc. On agricultural land, actions may be taken to counteract the effect of pollution. These different elements make it very difficult to assess the impact of incremental air pollution.

At this stage of research, the estimated effects on agriculture are thought to be small. There are no models both widely applicable and well accepted by which to estimate forest damage.

3.1.3 Impacts on Materials

Discoloration, material loss and structural failure are the main damages to materials from pollutants, resulting from acidifying substances like sulfur dioxide and nitrogen oxides, particulates, and ozone. Damage is mostly from acidic deposition. The materials considered are calcareous stone, mortar, paint, concrete, aluminum, and galvanized steel in houses, shops, factories, offices and schools, not buildings of aesthetic or cultural merit. The valuation was considered very preliminary.

The impacts on biodiversity, noise and water were not considered, either for lack of data or because air pollution is only a minor source of damage. Damage to materials and ecosystems combined was estimated to be less important than to human health.

3.1.4 Scenario Analysis

Three policy scenarios were simulated with MARKAL:

- *Local air pollution control.* An environmental tax was imposed on SO_2, NO_x, VOC, and PM equal to the total damage (in Belgium and abroad) due to the pollutant emitted in Belgium.
- *Greenhouse gas emission reduction.* By 2010, greenhouse gases must be reduced by 7.5 percent below the 1990 level, following the burden sharing agreement in the European Union to comply with the Kyoto Protocol. Greenhouse gas emissions are assumed to decline at the same rate after 2010 to a reduction of 15 percent by 2030. This target must be met in Belgium with no tradable permits or other flexible mechanisms to be used.
- *Both local air pollution control and greenhouse gas emission reduction.*

These were compared to a reference scenario in which neither type of emission reduction is required.

The comparison among scenarios is focused on cost differences, and not on the technological options to reach the environmental targets or the distribution of cost among sectors. The principal results are illustrated in Figure 3.1.

Local air pollution control. Imposing a tax on local pollutants equal to the damage they would otherwise generate reduces both local air pollution and greenhouse gas emissions. The reduction occurs through investment in abatement technologies and a decrease in the demand for energy services because of the increase in price. Investment in abatement technologies has an impact on local pollution, whereas the decrease in demand reduces both local pollution and greenhouse gas emissions. Welfare is reduced, but the total welfare change remains positive when environmental benefits are included. Environmental benefits are measured by the monetary value of the reduction in local environmental damage.

Greenhouse gas emission reduction. With the imposition of a constraint on greenhouse gas emissions, local pollutants as well as greenhouse gases are reduced. The emission reductions result from improvements in energy efficiency and a decrease in the demand for energy services. The reduction in welfare that accompanies the reduction in greenhouse gas emissions is partially offset by the gain in welfare due to local environmental benefits.

Both local air pollution control and greenhouse gas emission reduction. With the combination of emission controls, the interactions among pollutants are taken into account. The environmental benefits of the two combined policies (labeled ‘Both’ in the figure) are greater than with local air pollution control alone, and much greater than with greenhouse gas emission reduction alone.

The analysis will continue in two directions. The definition of local air pollution policy will be related to the different agreements Belgium has signed for this type of pollution. The implications for the choice of policy instruments will be further examined as it is a crucial element for a full explanation of the interaction between pollutants.

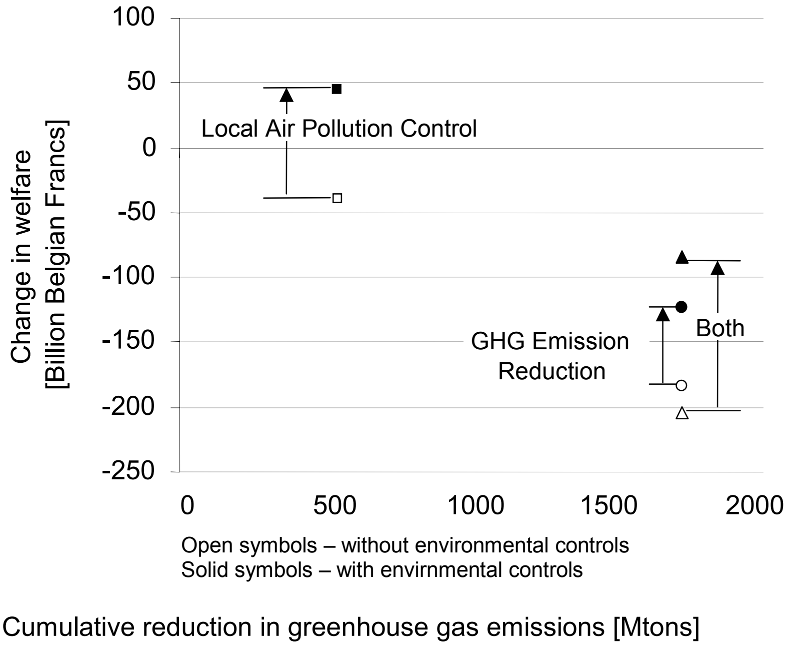

Figure 3.1 *Differences from the reference scenario in welfare and environmental damage from 1990 to 2030. The global environmental benefits of reduced emissions of greenhouse gases are not monetized.*

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3.2 Sharing Emission Reductions Domestically

The Kyoto Protocol specifies how greenhouse gas emission reductions will be shared among the industrialized countries. But how will these reductions be distributed within each country, and who will bear the costs?

The government of Canada addressed these questions in a comprehensive analysis of alternative ways to comply with the Kyoto Protocol. MARKAL was used to compare various schemes for domestic emission trading. An innovative use of the model is to show how incremental costs of emission reductions will be distributed among energy sectors either through demand or price effects.

In April 1998, the Canadian government initiated the National Climate Change Implementation Process (NCIP) to provide 'a thorough understanding of the impact, the cost and the benefits of the Kyoto Protocol's implementation and of the various implementation options open to Canada.' More than a dozen 'Issue Tables' were formed under the NCIP. Some were concerned with emission reduction policy in specific sectors. Others were tasked with economy-wide emission reduction policy or with other aspects of climate change, such as adaptation.

An Analysis and Modeling Group (AMG) was set up to assure consistency and comparability of the results coming from the individual analytical elements. AMG directed the 'roll-up' or whole-economy analysis of the Sector Tables' work. For one of two studies using different whole-economy models, AMG retained HALOA Inc. to use its multiregional and multisectoral MARKAL model of the Canadian energy system. Two of the principals in HALOA are Richard Loulou and Amit Kanudia who regularly represent Canada in ETSAP.

Several different paths were defined by which Canada could meet the Kyoto requirement to reduce its greenhouse gas emissions to 94 percent of the 1990 level by the 2010 time period. These consist of proposed measures grouped as:

- Transportation
- Industry/upstream
- Electricity
- Residential/commercial/institutional/municipal
- Other.

The paths differ in the extent to which individual sectors must reduce emissions and the role of the sectors in domestic emission trading:

- *Path 1*: Each sector is required to reduce its emissions to 95.67 percent of its 1990 level. The remaining reduction is assumed to be met by growth in the forest sink.
- *Path 2*: All sectors, including the forest sink, are *collectively* constrained to reach 94 percent of their aggregate 1990 emission levels. Path 2 represents the least-cost solution to meeting the national cap, but the precise control measures are not predefined. This path is a benchmark to which other paths may be compared.
- *Path 3*: Large final emitters are subject to a collective cap, and may trade permits among themselves. These emitters consist of power generation, petroleum refining, pulp and paper, iron and steel, chemicals, smelting

and refining, cement, and most ‘upstream’ oil and gas. These sectors produced about 35 percent of Canada’s 1990 emissions.
- *Path 4*: The cap-and-trade system is extended to include industries producing fossil fuels. The difference from Path 3 is that the energy producing sectors (oil refining, gas production, coal) are responsible for the end-use emissions embodied in the fuel produced. Effectively, this brings the end-users of fossil fuels into the cap-and-trade regime. Only about 20 percent of Canada’s 1990 sources are not covered, including upstream oil, methane from upstream gas, agriculture and landfill gas.

A preliminary set of results indicated the total costs of greenhouse gas reductions by sector and path as shown in Table 3.2, compared to the theoretical minimum calculated for Path 2.

Table 3.2 *Total national abatement costs relative to business as usual, normalized to the theoretical minimum (Path 2).*

	Upstream	Electricity	Refining	Industry	RCM	Transport	TOTAL
Path 1	+0.23	-1.12	-0.33	+1.00	+1.50	+0.77	+2.56
Path 2	**+0.21**	**-1.58**	**-0.10**	**+0.80**	**+1.10**	**+0.12**	**+1.00**
Path 3	-0.12	-1.33	+0.05	+0.74	+1.65	+0.44	+1.93
Path 4	+0.14	-1.50	-0.09	+0.77	+1.32	+0.14	+1.20

Notes: Upstream = fuel sources prior to processing
RCM = residential, commercial and municipal

It is apparent in Table 3.2 that the pro rata caps in Path 1 are inefficient, with the total cost more than double the theoretical optimum of Path 2. The comparatively low total cost of Path 4 recommends an approach that includes as broad as practical a cap-and-trade system coupled with additional local measures for subsectors not included in the trading system.

Each entry in the table is the sum of two types of cost:
- Investment and operations & maintenance (O&M)
- Fuel costs (fuel purchases minus fuel sales).

These sums may be positive or negative, because they are incremental costs compared to business-as-usual without greenhouse gas emission reductions.

Contrary to sectoral costs, the whole economy costs do not depend upon what economic instrument is used to effect the reductions, such as, for example, an emission permit system with a particular allocation scheme. However, the total national cost is dependent upon two key assumption which, if relaxed, would probably change the cost values significantly:
- *No leakage.* It was assumed that Canadian consumers do not have the option of purchasing electricity or refined products from a country not subject to greenhouse gas pricing.

- *Constant output.* Economic output is generally assumed to be unaffected by greenhouse gas pricing.

3.2.1 Sectoral Costs

The total economy-wide costs are unambiguously defined by the model, but the distribution of costs among the various sectors depends upon the policy instrument used and the pricing mechanism in the model. To make sectoral cost comparisons, certain assumptions must be made about the allocation of permits to the capped sectors.

Regarding permit allocation, the sectoral costs are based on the assumption that the actions taken in a particular sector are paid for by the same sector. Or equivalently, each sector is assumed to be allocated an amount of free emission permits exactly equal to the sector's emissions in that path. Thus, the sectors do not trade emissions among themselves or with the government.

Turning to pricing, the MARKAL model uses marginal cost pricing for all commodities. This means that a sector that incurs additional costs as a result of reducing greenhouse gas emissions will increase its output to reflect the marginal cost of the last unit of output. Thus, sectors may increase both costs and revenues. The revenues may increase more than the total cost incurred, because pricing is at marginal cost, not at average cost. Hence, some sectors (for example, electricity) may show a surplus.

Compared to business as usual, therefore, net costs are sometimes positive and sometime negative. Considering the oil refinery sector, for example, in a transition from business as usual to Path 1:

- Refining *cost* is pushed *up* due to in-plant investment and operation expenditures to reduce emission in response to the emission constraint.
- Refining *cost* is pushed *up* because of the higher price of electricity used by refiners.
- Refining *cost* is pushed *down* because of variable cost savings from processing less capacity, or from avoiding investment in new capacity
- *Revenues* are pulled *down* due to lower sales volume from demand reductions induced by the sales tax.
- *Revenues* are pushed *up* due to higher plant gate prices.

Tables 3.3 and 3.4 separate the effects of these various elements for two sectors: electricity generation and petroleum refining. Incremental sectoral cost is broken down into two components: investment and O&M, and fuel costs. Fuel cost is further broken down into four components, as follows:

- Incremental cost of fuel purchase - price effect: the incremental cost of the Path's *total* fuel purchases times the *price increase* from business as usual to Path.
- Incremental cost of fuel purchase - demand effect: the incremental cost of the Path's *additional* fuel purchases, priced at the *business-as-usual price*.
- Incremental loss of revenue - price effect: the incremental loss of revenue of Path's *total* fuel sales times the *price increase* from business-as-usual to Path.
- Incremental loss of revenue - demand effect; the incremental loss of revenue of the Path's *additional* fuel sales, priced at *the business-as-usual price*.

Using the model results, the difference in cost by sector between business as usual and a Path can be calculated as:

$$P_{path} * Q_{path} - P_{bau} * Q_{bau}$$

where P = price, Q = quantity, and the subscripts refer to the individual Path and business as usual. This amount can be decomposed into the sum of the price effect and the demand effect as follows:

- Price effect: $(P_{path} - P_{bau}) * Q_{path}$
- Demand effect: $(Q_{path} - Q_{bau}) * P_{bau}$.

In the petroleum refining sector, shown in Table 3.3, the variation among Paths is the result of two opposing forces. On the one hand, the production volume decreases due to less demand in transportation and residential/commercial, resulting in less investment and operating costs, but also less output in physical units. On the other hand, the marginal production costs of refined products increase - due to greenhouse gas abatement actions - and therefore so do refinery-gate prices.

Table 3.3 *Incremental cost breakdown for the petroleum refining sector, relative to business as usual, normalized to the theoretical optimum. (Path 2)*

	Path 1	**Path 2**	Path 3	Path 4
	Each sector capped	**Theoretical optimum**	Large fuel emitters capped	Path 3 + energy producers capped
Fuel cost	-0.18	**-0.038**	+0.19	-2.21
Purchase: price effect	-0.02	**-0.01**	-0.02	-0.01
Purchase: demand effect	-1.23	**-0.75**	-1.14	-0.49
Sales: price effect	-0.55	**-0.11**	+0.07	-2.25
Sales: demand effect	+1.61	**+0.84**	+1.27	+0.54
Investment + O&M	-0.15	**-0.067**	-0.14	-0.07
TOTAL	-0.33	**-0.105**	+0.05	-2.27

In Paths 1, 2 and 3, the price effect is small compared to the demand effect, because refined product prices vary only slightly from business as usual. Path 4, on the other hand, is quite different. Path 4 puts the onus of end-use reductions on the fuel producers. Oil producers will bear the cost of buying permits and will pass on these costs to fuel consumers. This is apparent in Table 3.3 where the price effect of fuel sales is very large, and it generates a surplus for the industry. A large portion of this surplus will be spent to buy permits in the first place.

The electricity sector shown in Table 3.4 is somewhat different. Revenue increases far exceed the gross costs of abatement, yielding large surpluses for the sector. Contrary to the oil refining sector, the price effect is the principal cause of the surplus in all Paths.

These MARKAL results are likely to be very different from those obtained with a model that assumes average cost pricing (as opposed to marginal cost pricing). In that type of model, no price effect would be observed.

Table 3.4 *Incremental cost breakdown for the electricity sector, relative to business as usual, normalized to the theoretical optimum. (Path 2)*

	Path 1	**Path 2**	Path 3	Path 4
	Each sector capped	**Theoretical optimum**	Large fuel emitters capped	Path 3 + energy producers capped
Fuel cost	-1.27	**-1.66**	-1.24	-1.55
Purchase: price effect	+0.05	**+0.19**	+0.09	+0.18
Purchase: demand effect	+0.28	**+0.19**	+0.17	+0.20
Sales: price effect	-1.32	**-2.40**	-1.81	-2.28
Sales: demand effect	-0.29	**+0.37**	+0.31	+0.35
Investment + O&M	+0.15	**+0.07**	-0.09	+0.05
TOTAL	-1.12	**-1.58**	-1.33	-1.50

In both cases, the extra greenhouse gas premium collected by fuel producers through fuel sales will be spent buying permits if permits are auctioned. If permits are distributed gratis, the question of what to do with the large surplus is unresolved. In all cases, it is essential that the price consumers pay should reflect the full greenhouse gas price of the final combustion of fuels.

In the model runs, the end-use sectors in most Paths bear the brunt of the abatement costs, since they pay high prices for final energy, and they must also achieve greenhouse gas reductions in their own sectors. This need not be the case in the real economy, if redistribution policies are set up to equalize the burden of greenhouse gas reductions.

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3.3 National Scenario Analysis

Finnish participation in the ETSAP work is coordinated by the Energy Institute of the Technical Research Center of Finland (VTT). VTT Energy carries out development and research on energy, economy and emissions models, and uses these models in scenario analyses for the Government of Finland and other contractors. In model development and scenario analysis work, VTT Energy cooperates on an equal basis with Helsinki University of Technology (TKK), with the Government Institute for Economic Research (VATT), and with the private Research Institute of the Finnish Economy (ETLA).

During Annex VII, VTT, VATT and ETLA carried out a series of extensive scenario analyses of the costs and effects on the national economy of various policies proposed to meet the targets of the Kyoto Protocol, extended to the year 2020. The analyses were prepared for an official national working group, consisting of representatives of the Ministries of Finance, Environment, and Trade and Industry.

Two different approaches were taken: VTT and VATT linked together the EFOM/ENV energy and emissions model of VTT and the econometric model (KESSU) of the Finnish economy developed by VATT. EFOM/ENV gave immediate effects and costs of the scenarios, and KESSU shows impacts on the whole national economy.

To analyze the same scenarios, ETLA and VTT developed a stationary computable general equilibrium model of the Finnish economy, which has a very detailed representation of the energy sector based on individual technologies, not on the usual smooth production functions. The results computed by the two approaches are in reasonable accord with each other.

VTT and TKK have begun to develop and install a Finnish TIMES model. A prototype was developed by TKK in cooperation with IER Stuttgart, and a full-scale version is now under way.

3.4 Consequences of a Nuclear Phase-out

German modelers analyzed the technological, economic and environmental effects of a planned phase-out of nuclear energy in Germany. Eleven models - including both bottom-up and top-down models - were used to examine the consequences of eight scenarios differing in power plant lifetimes, carbon dioxide emission restrictions, and future energy prices. Qualitatively similar results were obtained with the bottom-up models, but the top-down models projected higher phase-out costs. The study concluded that both types of models are needed.

An agreement between the German government and the electric utilities, which was reached on 14 June 2000 and signed on 11 June 2001, capped the total lifetime output of each nuclear plant, leading to an average operating time of 32 years from the beginning of commercial operation. Coincidentally, the results of Model Experiment II (MEX II) of the Forum for Energy Models and Energy-Economic Analysis (FEES) were announced on the same day as the agreement was reached. FEES is sponsored by the German Federal Ministry of Economics and Technology, which was also responsible for recommending a policy for the future of nuclear power in Germany.

The objective of MEX II was to evaluate the structural, economic and environmental effects of phasing out nuclear power. These included impacts on electric generation costs, electricity prices, the technology mix in the electric sector, generation structure including electricity imports, and the rest of the energy sector. Economic effects on GDP growth, employment, and the competitiveness of industry were quantified. The environmental focus was especially on energy-related greenhouse gas emissions.

Among the MEX II conclusions:

- Nuclear energy will be replaced by hard coal or, especially with future restrictions on carbon dioxide emissions, natural gas.
- In the absence of emission restrictions, the carbon dioxide produced will increase by an amount about equal to one year's emissions from Germany by 2030.
- Electricity production will drop by 4 percent, and electricity prices will rise from 8 to 12 percent, according to the top-down models. Growth in GDP will be 0.2 to 0.6 percent lower.
- There would be a slight increase in renewable energy, in the form of wind and biomass, only in a scenario with Kyoto restrictions extrapolated to 2030.

The eleven models included four top-down models and seven bottom-up models, of which three were energy system models and four were restricted to the electricity sector. The German ETSAP representative, IER, University of Stuttgart, provided three of the models: the general equilibrium model NEWAGE, the energy system model E3NET, and the electricity sector model TIMES-GES, an application of the TIMES model developed by ETSAP. The Programme Group Systems Analysis and Technology Evaluation (STE) at Research Center Jülich ran the energy system model IKARUS-MARKAL.

A business-as-usual scenario, with nuclear power plants assumed to have a 40-year life after being connected to the electric grid, was taken as a reference. In three phase-out scenarios, nuclear power plants were assumed to be limited to a 25-year life. The phase-out scenarios were:

- no emission restrictions,
- emissions the same as the business-as-usual scenario,
- emissions reduced by 21 percent by 2010, following the Kyoto Protocol burden-sharing agreement within the European Union, extrapolated to a 43 percent reduction by 2030.

Each of these four scenarios was run with two different energy price projections.

3.4.1 Bottom-up Model Results

If carbon dioxide emissions were not restricted, the differences from the business-as-usual case would increase by up to 100 million metric tons of carbon dioxide in 2015, according to the bottom-up models, as shown in Figure 3.2. Differences decline after 2015, because the nuclear plants would also be replaced then in the business-as-usual scenario.

With the same level of carbon dioxide emissions maintained, nuclear power is replaced primarily by hard coal and natural gas, according to the four electricity sector models. With the Kyoto restrictions of carbon dioxide emissions, highly efficient natural gas combined cycle plants predominate.

The bottom-up models gave similar results for the cost of a nuclear phase-out, which increases when there are also emission reductions. With no emission reduction, the additional costs range from 23 to 63 billion DM_{98} undiscounted (or 17 to 39 billion DM_{98}, discounted at 5 percent to the year 2000). With the Kyoto restrictions, the additional costs range from 53 to 111 billion DM98 undiscounted (or 24 to 69 billion DM_{98}, discounted to 2000).

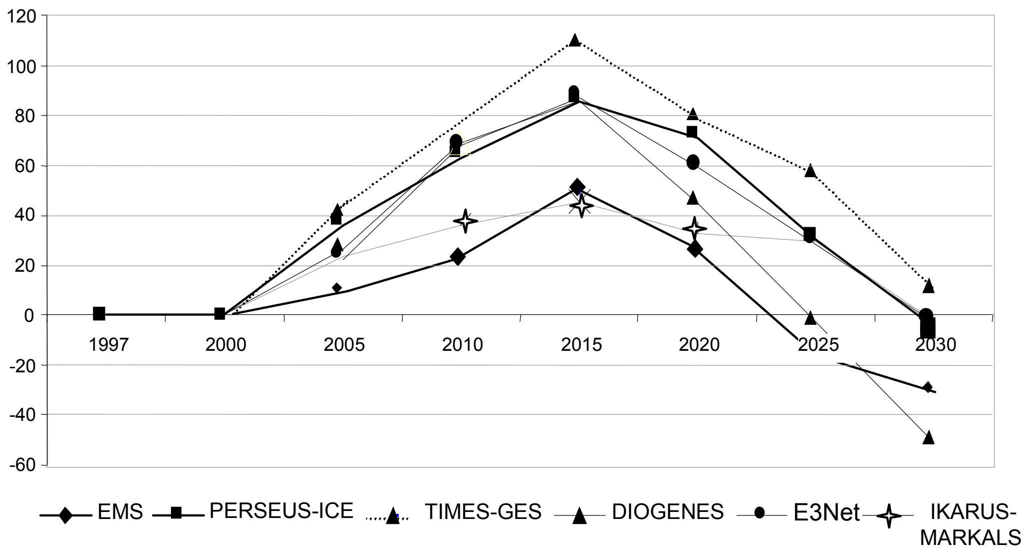

Figure 3.2 *Difference in carbon dioxide emissions with a nuclear phase-out, absent emission restrictions (millions of metric tons).*

Sensitivity analyses of the bottom-up models revealed that:

- Shorter nuclear lifetimes increase costs.
- Fuel prices, especially of natural gas, have a strong influence on costs and emissions.
- Costs decline when nuclear-generated electricity can be shifted among generators, from older to newer, and smaller to larger plants.
- Variation in electricity demand among the electricity models does not affect phase-out costs

- Free trade in electricity leads to more imports when nuclear power is phased out.

3.4.2 Top-down Model Results

The top-down models generally indicated more severe effects from a nuclear phase-out. While the bottom-up models indicated little effect on the level of electricity consumption, the top-down models showed a decrease of 4 percent, with 8 to 12 percent higher electricity prices. German GDP would continue to grow, but at a 0.2 to 0.6 percent lower rate. These effects were amplified when carbon dioxide emissions must also be reduced. The four top-down models differed somewhat in their results for the effect of a phase-out on employment and imports and exports.

However, the top-down results were robust. Only slight changes in the electricity sector and negligible changes in the entire economy resulted from variations in fuel substitution elasticities, use of renewables, electricity price levels, or import possibilities. Only the lifetimes of nuclear power plants influenced the results substantially.

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3.5 Coordinated Local Energy Planning

The MARKAL model played a key role in planning waste management for the Basilicata region of southern Italy. Decisions had to take into account the complex of laws, land use, air quality standards, anticipated greenhouse gas emission limits, energy resources, social restrictions, waste characteristics, and available technology in minimizing the cost of waste disposal. The results contributed to regional plans for waste management, air quality, and energy use.

The Basilicata region, about 10,000 square kilometers in area, is at the ‘ankle’ of the Italian ‘boot’ bordered on the west by the Tyrrhenian Sea and on the southeast by the Gulf of Taranto. Its dry climate is poor for agriculture, but olives, plums and cereals are grown, and sheep and goats are raised. There are many newly built industrial areas: the Vulture-Melfese zone in which the FIAT-SATA automotive plant is located, the neighborhood of Potenza and Matera where many furniture companies are located, and the Agri

Valley where mining has been developed recently. The chief town is Potenza, a city of 67,000 inhabitants, in the center of the region that is home to about 610,000.

For the Basilicata region, the *Institute for Advanced Methodologies of Environmental Analysis (IMAAA)* of the *National Research Council (CNR)* is developing an integrated energy-environment system that includes both the production of goods and services and the waste treatment system. The group is led by Vincenzo Cuomo and Maria Macchiato, and consists of Carmelina Cosmi, Monica Salvia, Filomena Pietrapertosa and Gerardo Marmo. The analyses were made within the framework of the Regional Air Quality Recovery and Protection Plan and the Regional Waste Management Plan. Stakeholders supporting the work are the National Council of Research, University of Basilicata, University of Naples, *National Institute for Physics of Matter (INFM)*, and the Basilicata Region as local authority. Financing is provided by the INFM and the Basilicata Region authority.

The main objectives were to:

- reduce emissions of pollutants,
- assess energy resources,
- define optimized strategies for energy use,
- facilitate technology substitution and technological innovation,
- support decision-makers with recommended policy measures.

Pollutants such as nitrogen oxides (NO_x) and sulfur dioxide (SO_2) are important at the local and regional levels, and carbon dioxide is important to meet national commitments under the international Kyoto Protocol. Some regional actions may lead to emission reductions elsewhere in the country; the models must therefore be able to represent energy and emissions trading. Furthermore, a global optimization system is required that takes into account the entire system of goods and services, including waste treatment and the full life cycle of products. The optimizing models must include both energy and material flows. Moreover, different spatial scales must be considered.

In this framework, a preliminary analysis carried out only on the regional energy system pointed out the possibility of reducing emissions by a better market allocation of fuels and technologies, and by implementing energy savings. The trade-off between increases in total system cost and reduction of the emissions of the principal pollutants is shown in Figure 3.3. Sulfur dioxide (SO_2) was reduced most, nitrogen oxides (NO_x) next, and carbon dioxide (CO_2) least. The cost of reducing sulfur dioxide rises rapidly after about a 60 percent reduction, nitrogen oxides after about a 30 percent reduction, and carbon dioxide emissions after about a 10 percent reduction.

For the Basilicata region as a whole, the waste treatment system was analyzed within the context of local production of goods and services and national requirements for waste treatment, using the standard MARKAL model. National legislation requires separate collection of recoverable materials up to 35 percent of waste, and that landfill be the technology of last resort.

For optimal waste treatment, decisions had to be made on:
- the extent of separate collection of recoverable material,
- the size of the grid for screening the remaining waste into dry and biodegradable fractions,
- landfill fees for the waste that is not composted or incinerated.

The model was run for a series of scenarios in which a range of these choices was varied parametrically. The waste components that can be recovered vary according to the percentage of the waste that is collected separately. The composition of the individual components of the remaining waste - fermentable material, paper, plastics, glass, metal, wood and textiles - varies after screening according to the wire mesh size. Landfill fees of 40,000, 60,000, 80,000, and 160,000 lire per cubic meter (Italian lire '98/m^3) were tested.

With screening, the volume of the landfill is reduced to less than half of what it would be otherwise. Although the total system cost jumps by almost half, it may vary little with different mesh sizes. An example of the results of the model runs is illustrated in Figure 3.4 for a landfill fee of 60,000 Italian lire/m^3. The figure shows the reduction in greenhouse gas emissions that can be achieved by a larger percentage of separate collection and finer screening. Both carbon dioxide and methane emissions are taken into account, assuming that methane has a global warming potential 21 times larger than carbon dioxide.

At the urban scale, the regionalized MARKAL is being used for the municipality of Potenza to emphasize the role of renewable resources, particularly in the residential sector. Planners in Italy are facing a new phase in planning because of trends in deregulation and privatization. It is impossible to separate local and national strategies. The study concluded that energy and technology systems analysis play a crucial role in advanced local energy and environmental planning. Such planning is a process that requires both the development and integration of planning tools, among which optimizing models are essential.

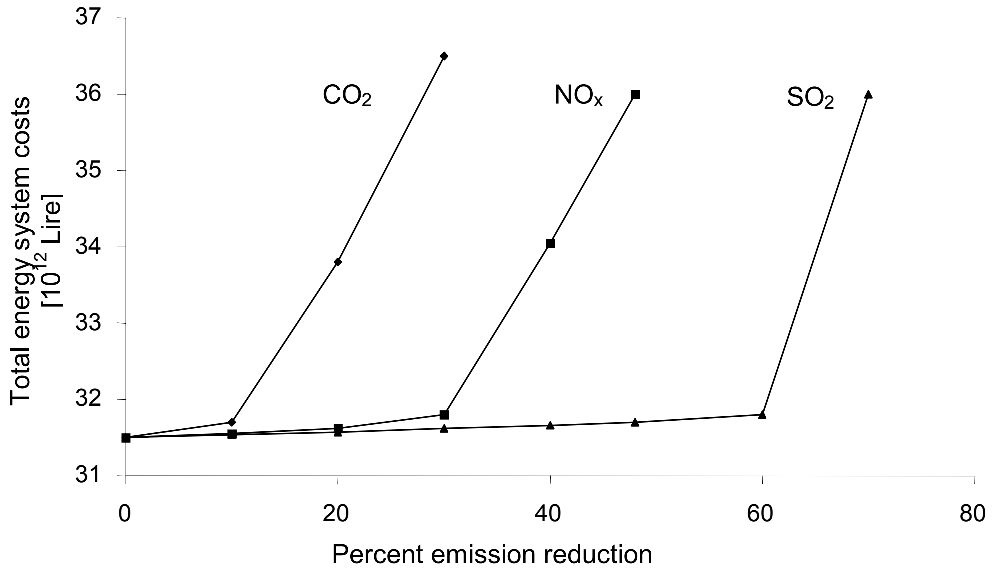

Figure 3.3 *The trade-off between emission reduction and total system cost (Italian lire '94). Carbon dioxide is more expensive to reduce than sulfur dioxide or nitrogen oxides.*

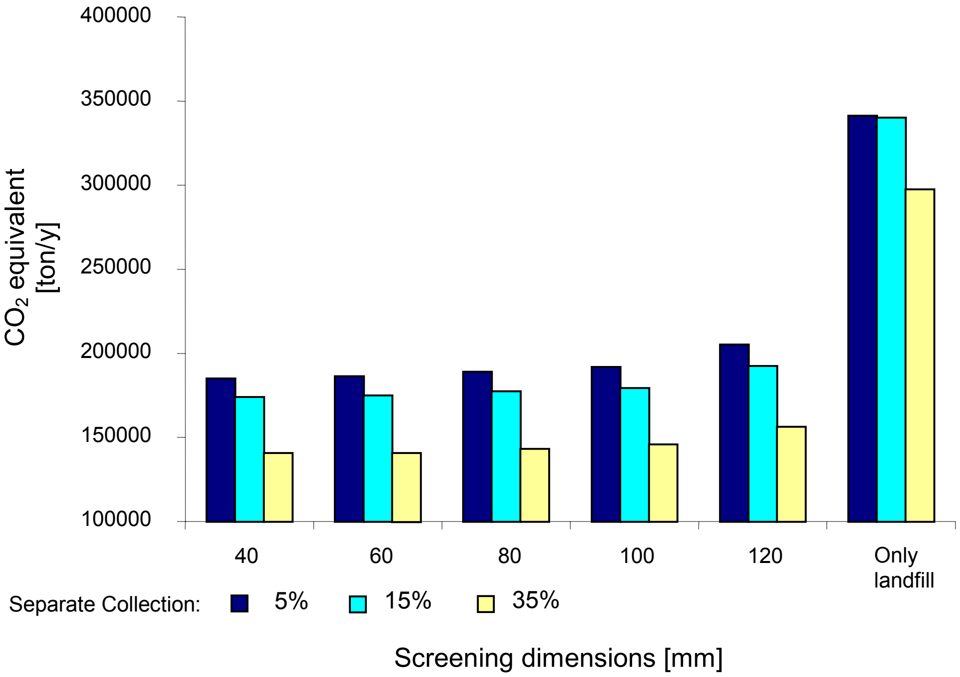

Figure 3.4 *Taking into account both carbon dioxide and methane, the emission of greenhouse gases is reduced with a higher percentage of separate collection and finer screening.*

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3.6 Updating Estimates of Elasticity

To analyze the interaction of energy and the economy, it is important to know how energy consumption will respond to changes in income and energy prices. In the past, particularly after the oil crisis of the 1970s, many studies were made of this issue. There is now more extensive and reliable statistical data. To take advantage of the more recent information, the Japan Atomic Energy Research Institute analyzed the income and price elasticity of final energy consumption in Japan. These are used to estimate future energy demand and provide input data needed for energy- economy interaction models.

Regression analysis was used to express final energy consumption as a function of average energy price and income, measured by Gross Domestic Product (GDP) or other indices. Data on energy consumption during the 1969-1996 time period was classified by sector:

- Industry (iron and steel, chemicals, cement and glass, pulp and paper, and others)
- Commercial

- Residential
- Transportation (passengers and freight).

Within that time period, the data were segregated into periods when prices were rising, declining, or changing only moderately. The periods in which plausible results were successfully achieved is shown in Table 3.5. The results are summarized in Table 3.6.

3.6.1 Income Elasticity of Energy Consumption

A strong correlation with income was observed for energy consumption in the residential and commercial sectors, the transportation sector, and ‘other industries.’ Negative elasticities were derived for iron and steel, cement and glass industries. That is, there were decreases in energy consumption in spite of increases in the monetary value of production. This is because substantial energy conservation was achieved during the time period through the mid 1980s.

3.6.2 Price elasticity of energy consumption

Contrary to the income effect, almost no correlation with prices was observed for energy consumption in the residential and commercial sectors, the transportation sectors, and ‘other industries.’ Elasticities were very small even for short-term changes in energy prices. Significant correlation with prices was observed, more or less, for energy consumption in the raw material production industries.

As an index of ‘income’ in addition to GDP, domestic production in individual industries was used in the relevant sectors, and passenger-kilometers and ton-kilometers were used for transportation. However, no significant differences from using GDP were observed in the results of the regression analysis.

Table 3.5 *Results of regression analysis of elasticities of energy consumption.*

Sector	Index of Income / Period	GDP Entire Period	GDP Partial Period A	GDP Partial Period B	GDP Partial Period C	GDP Partial Period D	Industrial Prod./Transportation Entire Period	Industrial Prod./Transportation Partial Period A	Industrial Prod./Transportation Partial Period B	Industrial Prod./Transportation Partial Period C	Industrial Prod./Transportation Partial Period D
Industry	Iron & Steel	Negative or Extreme Income Elasticities	Negative or Extreme Income Elasticities	Negative or Extreme Income Elasticities	Negative or Extreme Income Elasticities	Negative or Extreme Income Elasticities	Negative or Extreme Income Elasticities	Positive Price Elasticities	Positive Price Elasticities	Successful	Successful
	Chemicals	Successful	Successful (Regression with 3 Years Time Period)	Successful (Regression with 3 Years Time Period)	Successful	Successful	Successful	Successful (Regression with 3 Years Time Period)	Positive Price Elasticities	Negative or Extreme Income Elasticities	Successful
	Cement, etc.	Negative or Extreme Income Elasticities	Successful (Regression with 3 Years Time Period)	Successful (Regression with 3 Years Time Period)	Positive Price Elasticities	Successful	Negative or Extreme Income Elasticities	Positive Price Elasticities	Positive Price Elasticities	Negative or Extreme Income Elasticities	Successful
	Pulp, Paper	Successful	Positive Price Elasticities	Negative or Extreme Income Elasticities	Negative or Extreme Income Elasticities	Successful	Successful	Positive Price Elasticities	Negative or Extreme Income Elasticities	Positive Price Elasticities	Successful
	Others	Successful	Positive Price Elasticities	Negative or Extreme Income Elasticities	Positive Price Elasticities	Successful	Successful	Positive Price Elasticities	Negative or Extreme Income Elasticities	Positive Price Elasticities	Successful
	Total	Successful	Positive Price Elasticities	Negative or Extreme Income Elasticities	Positive Price Elasticities	Successful	Successful	Positive Price Elasticities	Positive Price Elasticities	Negative or Extreme Income Elasticities	Successful
Resid. & Comm.	Commercial	Successful	Successful	Successful (Regression with 3 Years Time Period)	Negative or Extreme Income Elasticities	Positive Price Elasticities					
	Residential	Almost Successful (Slightly Positive Price Elasticities)	Successful (Regression with 3 Years Time Period)	Positive Price Elasticities	Negative or Extreme Income Elasticities	Almost Successful (Slightly Positive Price Elasticities)					
Transport	Passenger	Almost Successful (Slightly Positive Price Elasticities)	Successful	Positive Price Elasticities	Successful	Successful	Almost Successful (Slightly Positive Price Elasticities)	Successful	Negative or Extreme Income Elasticities	Successful	Almost Successful (Slightly Positive Price Elasticities)
	Freight	Almost Successful (Slightly Positive Price Elasticities)	Successful	Positive Price Elasticities	Negative or Extreme Income Elasticities	Successful	Almost Successful (Slightly Positive Price Elasticities)	Successful	Positive Price Elasticities	Successful	Successful
Total Final Energy		Successful	Positive Price Elasticities	Negative or Extreme Income Elasticities	Negative or Extreme Income Elasticities	Successful					

Partial Period:
- A (Prices Down) : 1971-1973 for Industry, Residential Sector; 1970-1973 for Other Sectors
- B (Prices Up) : 1973-1975
- C (Prices Up) : 1979-1982 for Industry, Residential Sector, Transport; 1979-1981 for Commercial Sector
- D (Moderate Change) : 1986-1996

Status:
- Successful
- Successful (Regression with 3 Years Time Period)
- Almost Successful (Slightly Positive Price Elasticities)
- Negative or Extreme Income Elasticities
- Positive Price Elasticities

Table 3.6 *Income and price elasticities by sector in Japan, 1969-1996.*

Sector	Income Elasticity (I.E.) and Price Elasticity (P.E.)
Industry	
• Iron & Steel	I.E.: Inverse correlation (about -0.2) with GDP and production. P.E.: Small in long-term. Around -0.4 in short term
• Chemicals	I.E.: Very small in long term. Around 0.5 after 1986. P.E.: About -.03 in long term. -0.4 or higher in short term.
• Cement, etc.	I.E.: Inverse correlation with GDP and production (-0.1). P.E.: Very small in long term. Less than -0.4 in short term.
• Pulp, paper	I.E.: About 0.3 in long term. Unstable in short term. P.E. About -0.3 in long term. -0.5 or higher in short term.
• Others	I.E.: About 0.5 in long term. Unstable in short term. P.E.: Very small both in long term and short term.
• Total	I.E.: About 0.2 in long term. Larger in short term (unstable). P.E.: -0.15 in long term. A little higher in short term.
Residential & Commercial	
• Commercial	I.E.: About 1.0 in long term. Possibly larger in short term. P.E.: -0.1 in long term. Unstable in short term.
• Residential	I.E.: About 1.0 in long term. Similar results in short term. P.E.: No correlation observed.
Transport	
• Passenger	I.E.: 1.6 (pass*km), 1.2 (GDP) in long term. P.E.: No correlation observed.
• Freight	I.E.: 1.0 (ton*km), 0.6 (GDP) in long term. Both 0.6 after 1986. P.E. No correlations observed.
Total Final Energy	I.E.: About 0.5 in long term. About 0.9 after 1986. P.E.: Very small (-0.1) in long term. A little higher in short term.

Reference

O. Sato, K. Kunii, K. Tatematsu, Y. Gotoh, and Y. Tadokoro. Progress report on the ETSAP studies at JAERI. I. Income and price elasticity of final energy consumption. Japan Atomic Energy Research Institute. April 30, 1999.

3.7 Hedging Against Uncertain Long-term Emission Reduction Requirements

Although greenhouse gas emission targets have been set by the Kyoto Protocol for the period around 2010, the long-term need to reduce carbon dioxide emissions in particular remains uncertain. In the face of this uncertainty, the Japan Atomic Energy Research Institute (JAERI) used the stochastic version of the MARKAL model to calculate a near-term hedging strategy for the electric power generation and low temperature heat system of Japan.

The range of uncertainty in the average annual reduction of carbon dioxide emissions through 2030 was taken as plus or minus 15 percent of the 1990 emission level. Two possible probability distributions were examined for three possible future states, as shown in Table 3.7.

Table 3.7 *Assumed probability of occurrence of change in average annual carbon dioxide emissions from 1990 through 2030.*

Case	Average annual CO_2 emission change from 1990 level		
	+15%	0%	-15%
A. Pessimistic	0.333	0.333	0.333
B. Optimistic	0.98	0.01	0.01

In the Pessimistic Case, the three alternatives are considered equally likely. In the Optimistic Case, an allowable increase in average annual carbon dioxide emissions is considered highly probable with only a one percent chance of either of the other two states. The uncertainty is assumed to be resolved by 2015 when average annual emissions can then diverge from the interim hedging path.

The interim hedging path in each case is calculated using the stochastic MARKAL with the cumulative emissions through 2030 set to result in average annual emissions of +15 percent, no change, or -15 percent of the 1990 level. For comparison, three deterministic solutions were calculated with the same limits on cumulative emissions.

In the interim period through 2010, the resulting annual emissions in the Optimistic Case were as high as in the 0% deterministic case. In the Pessimistic Case, they were slightly lower. This implies that carbon dioxide emission reductions should begin early, even if there is only a slight chance that very stringent reductions will be required later on.

The most striking departure from the deterministic trends occurs in the annual energy system costs that will be incurred in later years if the optimistic assumption is made but the stringent reduction of -15% is required after 2010. This can be seen by comparing the results of the stochastic and deterministic solutions in Figure 3.5. The additional costs in the Pessimistic Case are about double those of the Optimistic Case if a -15% average reduction becomes required.

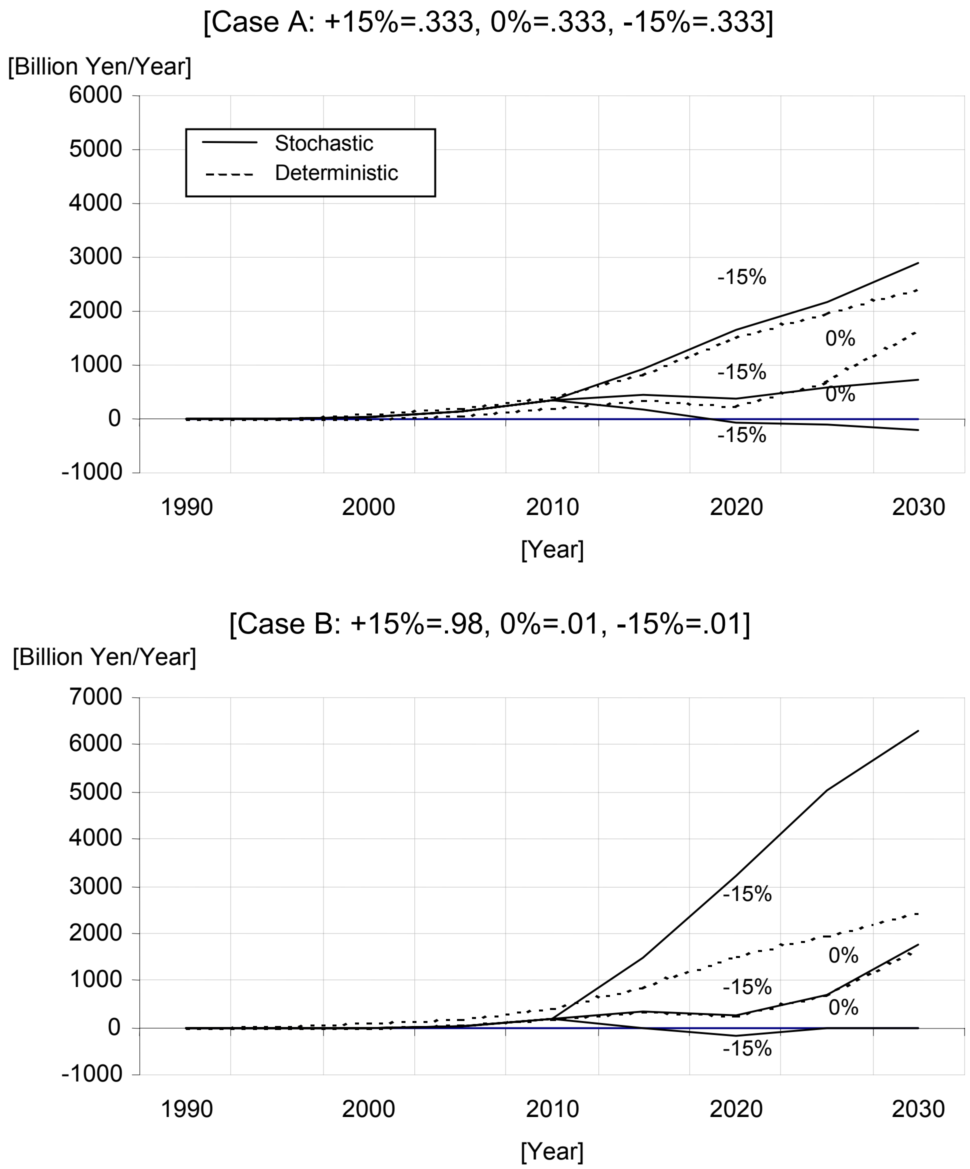

Figure 3.5 *Cost of carbon dioxide emission reduction.*

As a practical matter, the probability distributions of future states are unknown. In the case of the long-term electric power systems in Japan, however, JAERI reached conclusions that are independent of specific assumptions as to probability, namely:

- If there is even a slight chance that stringent carbon dioxide emission reductions will be required in the long term, measures should be taken early to prepare for them.

- The additional costs will be very large if an optimistic assumption is made but stringent reductions are eventually required, but not large if a pessimistic assumption is made and only small reductions are eventually required.

Reference

O. Sato, K. Kunii, K. Tatematsu, Y. Gotoh, and Y. Tadokoro. Progress report on the ETSAP studies at JAERI. II. CO_2 emission reduction strategy under uncertainty. Japan Atomic Energy Research Institute. April 30, 1999.

3.8 Nuclear Energy for High-Temperature Process Heat

Nuclear energy is already used extensively for generating electricity in Japan. However, a large amount of fossil energy is still used for non-electric energy demand such as industrial heating and transportation. High temperature gas-cooled reactors (HTGR), which can provide high temperature industrial process heat and other heating services, have been developed by the Japan Atomic Energy Research Institute (JAERI).

JAERI has examined the evolution of Japan's energy system over the very long term to evaluate the possible role of HTGRs and their use to provide heating services, especially from the viewpoints of economics and reduction of carbon dioxide emissions. The Japanese mainframe version of MARKAL was used to project four scenarios. In the scenarios, either carbon dioxide emissions are maintained at the 1990 level, or reduced by 40 percent by 2050 and 70 percent by 2100. HTGRs either are, or are not, used.

The scenarios are predicated on a number of assumptions about Japan's demographic, economic, and technological future. Although population is expected to peak about 2010, gross domestic product (GDP) is projected to continue its growth well into the 21st Century, albeit at a declining rate. The annual production of raw materials such as crude steel and cement is expected to peak early in the century, although production of paper and board is anticipated to continue its growth until late in the century. Useful energy demand in industry and the commercial and residential sectors is projected to continue rising until mid-century when it begins a gradual decline. Domestic passenger and freight transportation is expected to continue rising rapidly, leveling off at mid-century.

Imported fossil fuel prices are projected to rise gradually, with coal rising by about 25 percent by mid-century, and crude oil approximately doubling. Natural uranium is assumed to rise from the 2000 level to return to the 1990 level by mid-century.

More than twenty different types of technology are candidates for future electric power generation in these scenarios, including those fueled by coal, oil, liquefied natural gas, and renewable energy such as hydroelectric, geothermal, solar and wind. Other technologies include fuel cells, light-water and fast breeder nuclear reactors as well as HTGRs. Realistic upper limits are placed on the future capacity of technologies for electricity and heat.

In each of the four scenarios, total energy system cost is minimized. The resources used for electric power generation in the four scenarios vary with required reduction in future carbon dioxide emissions and the availability of HTGRs. With carbon dioxide emissions maintained at the 1990 level and without HTGRs, the use of natural gas expands until about 2030 when it begins a decline to be phased out by 2090. It is replaced primarily by coal, but nuclear and a small amount of renewable energy continue to expand through the century. With HTGRs introduced, more nuclear power is used, with slight reductions in natural gas, coal and renewables after about 2030.

The changes are more pronounced in the two cases with carbon dioxide sharply reduced beginning in 2010. Without HTGRs, coal is rapidly phased out principally in favor of natural gas and with some growth in renewables, but little effect on the use of nuclear power. With HTGRs, the role of nuclear is greater, principally at the expense of natural gas. In all four cases, hydroelectric power is unchanged, and the use of oil for power generation declines from its level in 2000 to become very minor throughout the century.

In the two scenarios that include HTGRs, they are installed up to the allowed capacity for combined heat and power production throughout the century. For production of synthetic fuel, they are installed up to their allowed capacity throughout the century with carbon dioxide emission reduction, and until 2080 with level emissions. While the total amount of industrial energy provided by the HTGRs is small, their effect on marginal cost of carbon dioxide emission reduction is appreciable, as shown in Figure 3.6. In both sets of scenarios, introducing HTGRs reduces the marginal cost after about 2030. Figure 3.7 shows the amount of carbon dioxide that needs to be recovered and disposed of, which in the case of the emission reduction scenarios, is markedly reduced with the presence of HTGRs.

Reference

O. Sato. A study on nuclear process heat application in Japan’s future energy systems: assumptions and preliminary results. Japan Atomic Energy Research Institute. May 18, 2000.

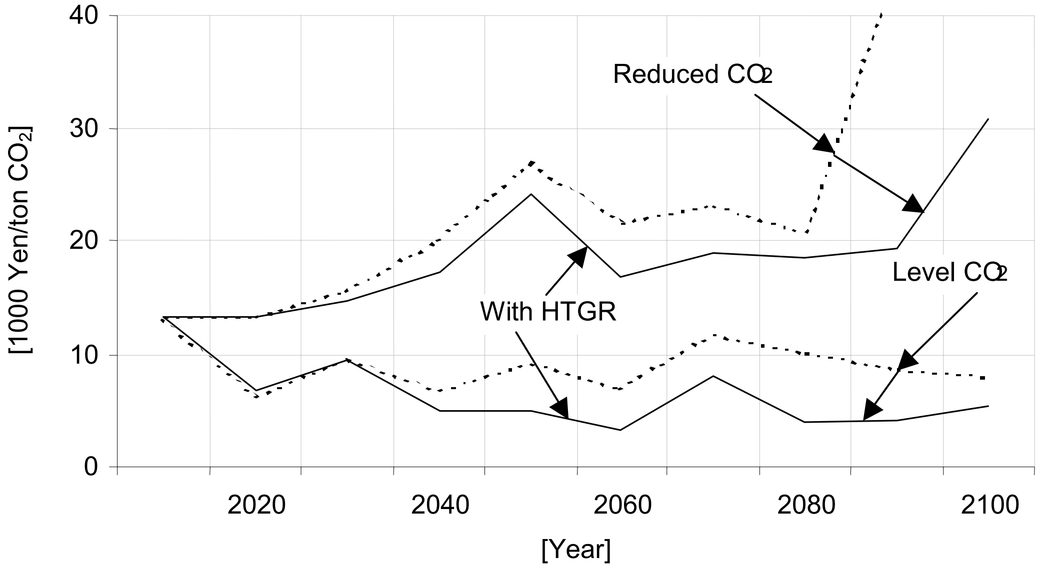

Figure 3.6 *Marginal costs of CO_2 emission reduction.*

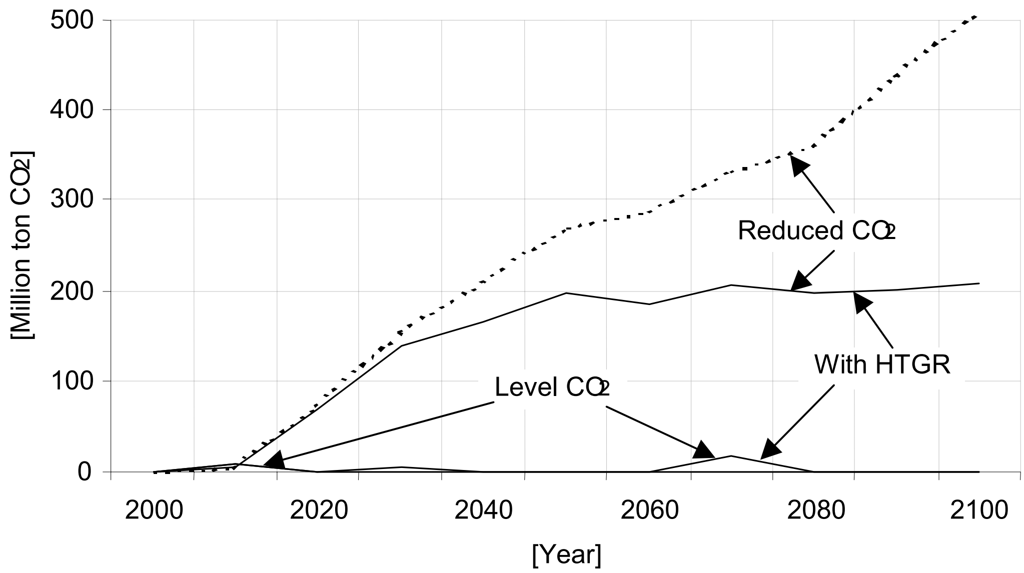

Figure 3.7 *Amount of CO_2 recovery and disposal.*

3.9 An Advanced Automobile Concept for Reducing Carbon Dioxide Emissions

In Japan as in other countries, automobiles are the source of a large and growing proportion of carbon dioxide emissions. For large emission reductions in the long term, major changes will be needed. To this end, a team from Kanazawa Institute of Technology (KIT) and the Japan Atomic Energy Research Institute (JAERI) evaluated a novel concept for recycling carbon dioxide emissions from vehicles.

The thermal energy produced in an internal combustion engine cannot be fully converted to mechanical work. To reach higher efficiencies, auto and bus designers have turned to fuel cells, which generate electricity without combustion.

Hydrogen is the ideal fuel for a fuel cell. However, hydrogen presents problems for on-board storage, one of which is safety. Such an inflammable fuel could be a safety hazard, for example, in the event of an accident in a densely populated area.

The Japanese team therefore proposes to use methanol as the on-board fuel. Methanol is more chemically stable, and can be safely stored in a fuel tank. Each vehicle would be equipped with a mini steam reformer that produces hydrogen for the fuel cell from methanol as it is needed. Carbon dioxide, which is a by-product of the reforming process, is liquefied in the vehicle using off-duty power. The liquefied carbon dioxide is then returned to the fuel station, where it is transformed to dry ice and shipped back to a methanol production plant. This plant can be at a high-temperature nuclear reactor also used to produce hydrogen. Here, the dry ice is used to cool turbine outlet gas or wet steam, and the carbon dioxide is recovered and re-used to produce methanol.

To analyze the potential of this concept in the context of a future national energy system, the MARKAL model of Japan was used. The model contains about 300 kinds of technologies and 110 different energy carriers, and it tracks ten kinds of environmental emissions including carbon dioxide. Each technology is characterized by its performance characteristics, including efficiency, and the cost of investment, operations and maintenance, and fuel. The transportation sector includes both freight and passenger vehicles. Alternative vehicle fuels include gasoline, diesel oil, methanol, and electricity.

In the model, the system for using motor vehicles with recyclable carbon dioxide consists of a set of technologies. Each automobile is equipped with a hydrogen fuel cell, mini methanol steam reformer, and carbon dioxide recovery unit. The infrastructure consists of fuel stations that collect liquid carbon dioxide and convert it to dry ice, trucks to transport dry ice from the stations, and high-temperature nuclear reactors where the plants for the production of methanol and hydrogen are located.

To simulate increasingly stringent restrictions on the emissions of carbon dioxide, a surcharge to penalize carbon dioxide emissions was assumed to increase linearly from zero in 2000 to $250 per ton of carbon dioxide in 2080.
In the modeling results, the automobile with recoverable carbon dioxide begins to be used when the surcharge rises above $60 per ton - about 2020 - leading to an annual reduction in carbon dioxide emissions that rises to about 35 million tons per year in 2080.

With this system, 95 percent exergy efficiency is attained. Compared to direct use of hydrogen as a fuel, the concept offers safety and security.

Reference
S. Yasukawa, K. Kato, O. Sato, and K. Tatematu. Greenhouse gas emission reduction by CO_2 returnable motor vehicle. Presented to ETSAP Workshop, Venice, Italy, 17 May 2001.

3.10 Modeling the Pulp and Paper Industry

A model of the Norwegian paper and pulp industry was developed by the Institute for Energy Technology of Norway using MARKAL. The purpose of the model is create a data set, using different prices for electricity, oil and biomass, to calculate pseudo price elasticities. The model can also be used to analyze various energy efficiency measures, such as environmental taxes, energy efficiency grants, and other policy measures.

The industry is modeled as 14 units: 12 individual mills and two groups of minor mills. Energy demand is specified, divided into steam, electricity and direct use of oil. There are five production processes: chemical pulp, ground wood pulp, thermomechanical pulping, paper and board.

Energy conversion equipment in the base year, 1996, is specified in the model as the actual installed equipment in that year. It is specified as to type, size, age, costs, and efficiency. For the remainder of the nine 4-year periods, each mill is allowed to invest in any type of energy conversion equipment, except those restricted to certain production processes, and to choose among energy carriers appropriate to the selected equipment. All mills may produce electricity from their own steam in back pressure turbines, and one mill is also allowed to use condensing turbines. Production of electricity from water turbines is restricted to a fixed value based on the 1994-1998 time period. Additional electricity is purchased from the grid.

More than 99 percent of electricity in Norway is produced from hydropower. However, precipitation can vary from year to year thereby affecting the supply and price of electricity. Therefore, energy flexibility - the ability to change from one energy carrier to another - is a prerequisite to make the energy markets function smoothly.

Steam can be produced from boilers using oil, electricity, biomass or coal. Steam can also be recovered from thermomechanical pulping, although this cannot be used to produce electricity because of its low pressure. Some mills may buy steam, and some sell steam or electricity outside the pulp and paper sector.

Biomass used for energy may be internal to the individual plants or purchased from outside. Black liquor, the most important source, is restricted by the production of chemical pulp through a fixed ratio for each mill. Internal production of energy from biomass - black liquor, bark, thermomechanical pulping vapor, sludge, etc. - is restricted to a maximum based on actual use in the 1994-1998 time period. Purchased biomass is restricted by cost classes determined by the cost of harvesting and transportation.

The model was calibrated for the years 1995 and 1996. In 1995 electricity prices were low due to high precipitation, and 1996 prices were extremely high due to a cold winter and almost no precipitation. Short term results were evaluated for the year 2000, and long term effects for 2020. The short-term results were in good agreement with actual conditions.

Reference
E. Rosenberg and L.K. Alm. A bottom-up model for energy use in the Norwegian pulp and paper industry. Institute for Energy Technology, Norway, October 1999.

3.11 Energy Planning in China

ABB, the Swedish-Swiss industrial giant, hosted a joint seminar of ETSAP and the China Energy Technology Program (CETP) in Baden-Dätwill, Switzerland, in October 2000. CETP is an international project run by ABB's Energy and Global Change Department in conjunction with the Alliance for Global Sustainability, a collaboration of three universities. Eleven organizations participate in the project: five in China, four in Switzerland, and one each in Japan and the USA.

The CETP program had three objectives:

- to develop a globally applicable cradle-to-grave methodology to analyze the true impact of electric power generation on the environment, using the Shandong Province of China as a case study,

- to develop a new and effective cooperative research mechanism between academia and industry,
- to engage the active participation of stakeholders to ensure application of research results toward the ultimate goal of sustainable development in China.

The two-year program, started in May 1999, involved a team of 75 scientists, academics and engineers in four countries on three continents, from business, universities, and research institutions. Prominent among the latter was the Paul Scherrer Institute (PSI) which also represents Switzerland in ETSAP. PSI was charged with leading the efforts in life-cycle assessment, environmental impact assessment, risk analysis, and energy/economy system modeling.

The energy/economy modeling work was the responsibility of the Energy Economics group of PSI, headed by Socrates Kypreos, in cooperation with the Global Climate Change Institute of Tsinghua University. An important tool used in the study was the MARKAL model developed by ETSAP. PSI also developed and applied other models like the China Regional Energy Trade Model (CRETM) that is based on partial equilibrium and endogenous learning options, both incorporated in optimization models by the ETSAP project.

Kypreos presented some insights from the CRETM. Energy intensity – that is, energy consumption per unit of economic activity - has been declining rapidly in China, but it remains two or three times higher than in the USA. Coal will continue to be the dominant fuel in China, causing sulfur dioxide air pollution and high emissions of carbon dioxide. Moderate investments in scrubbers or advanced coal technology can reduce sulfur dioxide pollution. Transmitting electricity between regions could be another economic option to reduce local pollution.

If you can control carbon dioxide emissions, sulfur dioxide is automatically reduced. However, this is expensive. Advanced coal technologies, at $1,200 per kilowatt, are about twice as expensive the present inefficient coal technologies. Also, fuel diversification options based on gas infrastructure are quite expensive in China. The cumulative and discounted cost of power production for a more sustainable path for China would be increased by 2 to 4 percent. The cost of reducing only sulfur dioxide emission is modest, however, and the Chinese are primarily concerned with sulfur dioxide, not global warming.

3.12 A Project for the Clean Development Mechanism in Taiwan

Under the Kyoto Protocol, a 'Clean Development Mechanism' was established which authorizes emissions trading with a developing country as a means by which an industrialized country can meet its obligation to reduce greenhouse gases. To qualify for credit, projects under the CDM must result in an emissions reduction 'additional to any that would occur in the absence of the certified project activity.' Much remains to be defined and agreed upon before the CDM is implemented. Key issues are how 'additionality' is determined, and how emission reductions are to be reported, verified, and certified.

Before a CDM project can start, the participants - the host country and the investor in an industrialized country - must set and define baselines and criteria for quantification of emission reduction. Equally important is an agreement on how the accrued emission credits should be shared between the host and the investors: the question of equity.

Under an agreement between the U.S. Environmental Protection Agency and the government of Taiwan, a study was made by Brookhaven National Laboratory to demonstrate that these issues can be addressed within a single modeling framework. The MARKAL-MACRO model was used to evaluate the costs and benefits of what a CDM project might be, together with its impact on economic development.

The project to be evaluated was the transfer of technologies that are being promoted by the USEPA Energy Star Buildings program. In the U.S., this is a voluntary, market-based program in which commercial building owners and operators agree to make a series of energy-efficient improvements. The USEPA provides tools and technical support in the areas of energy-efficient technology, pollution prevention, and upgrade strategies to assist in planning and implementation.

MARKAL-MACRO is a well-established E^3 (energy-environment-economy) systems model. It is an integration of a 'bottom-up' technological model and a 'top-down' macroeconomic growth model. In a dynamic structure, the model captures the system-wide impact of adjustments to the future development of an energy system. For this project, the model calculated the impact of more efficient technologies on energy supply-demand balances, environmental emissions, and growth in the overall economy, based on an efficient allocation of resources.

The case study started with the MARKAL-MACRO model of Taiwan and a database that already includes many conservation measures and efficient technologies currently available in the market. The database also included some advanced technologies that are likely to enter the market in the near future. With no constraint on carbon dioxide emissions, a business-as-usual scenario was calculated. This provides a plausible baseline from which to measure 'additionality.'

Next, phased sets of Energy Star Buildings technologies were introduced into the database. It was assumed that the maximum rate at which these technologies can be retrofitted in existing buildings is 5 percent per year, and that all new commercial buildings have the option to use these technologies.

To evaluate these changes as a CDM project, another case was run with the model. The CDM case was then compared to the business-as-usual case to determine the impact of the Energy Star Buildings technologies. This is the situation when Taiwan itself is subject to no requirement to reduce its own greenhouse gas emissions.

To represent the possibility that Taiwan also is subject to greenhouse gas emission restrictions, a second set of model runs was made assuming that there is a limit on carbon dioxide emissions of 10 tons per capita by the year 2025. Again, the comparison with business as usual shows the impact of the Energy Star technologies.

The analysis focused on three kinds of results:
- sectoral impact of the Energy Star program on commercial buildings,
- impact on the entire energy system and the overall economy,
- implications for investment, economic benefits, and total carbon emissions from the energy sector.

3.12.1 Impact on Commercial Buildings

In each CDM case, the model chose to implement the Energy Star Buildings technologies in commercial buildings. In Stage 1, incandescent bulbs are rapidly replaced by compact fluorescent tubes as bulbs burn out and as new lighting is provided. Next steps are:
- Stage 2. Building tune-up
- Stage 3. Other load reductions
- Stage 4. Fan system upgrades
- Stage 5. Heating and cooling system upgrades.

In the scenario with carbon dioxide emissions from Taiwan limited, the future demand for lighting and air-conditioning is reduced somewhat, but the replacement pattern was much the same.

MARKAL-MACRO also calculates the marginal cost of providing the new technology as the incremental change in national welfare when the technology is provided. With future carbon dioxide emissions restricted, the marginal cost is higher than in the base scenario. In both scenarios, however, the improved technology reduces this marginal cost. The projected demands for lighting and air conditioning increase as a result, due to the rebound effect induced by the lower costs.

3.12.2 Impact on the Energy System and the Economy

Total energy system costs are lower when the Energy Star Buildings measures are introduced in both scenarios. These costs include energy resource and fuel costs, investment in supply and demand technologies, and operating and maintenance costs. Restricting future carbon dioxide emissions makes a pronounced reduction in these energy costs. This is the result of the substantial reduction in the use of fossil energy, especially coal.

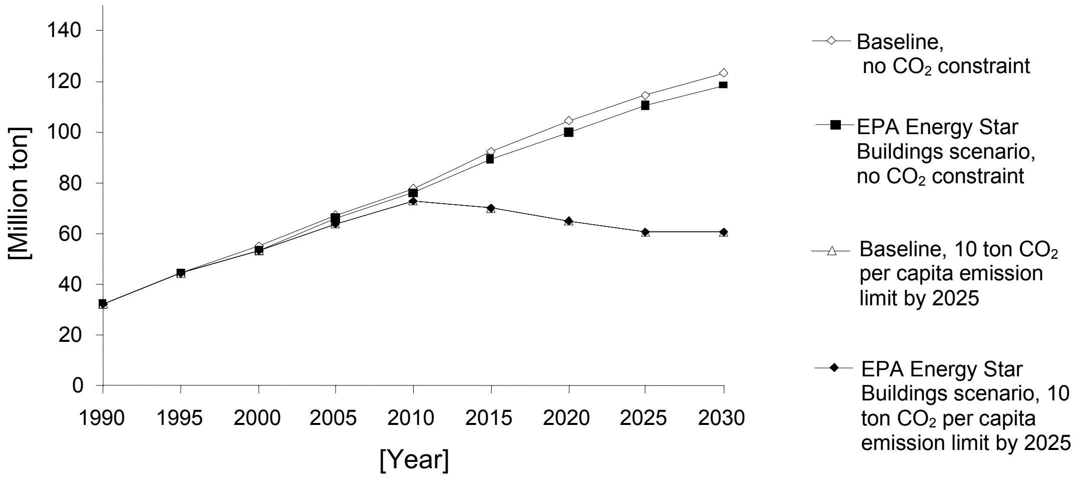

Figure 3.8 *The cumulative reduction in carbon emissions over the planning horizon due to the Energy Star Buildings measures amounts to 3 percent of total carbon emitted in the business-as-usual scenario.*

The pattern of annual carbon emissions is shown in Figure 3.8. The cumulative reduction in carbon emissions over the planning horizon due to the Energy Star Buildings measures amounts to 3 percent of the total carbon emitted in the business-as-usual scenario.

The introduction of the Energy Star program has a positive impact on the growth in gross domestic product (GDP). Since this incremental growth stems from reduced fossil energy, it can fairly be considered an increase in the direction of sustainable development.

3.12.3 Financial Impacts

The incremental investment necessary to pay for the higher capital cost of the Energy Star Buildings measures amounts to less than half the benefit generated in the commercial sector, as shown in Figure 3.9. The benefit is measured by the increased consumer surplus calculated by the model.

Assuming that the incremental investment is financed interest-free by the investors, the average cost of carbon reduction based on the investors' cost of capital ranges from US$7 to US$11 per ton of carbon. If the prevailing carbon credit price is assumed to be US$20 per ton, the fair share of the investors initially amounts to about half the total carbon reduced through the Energy Star Buildings program, as seen in Figure 3.10.

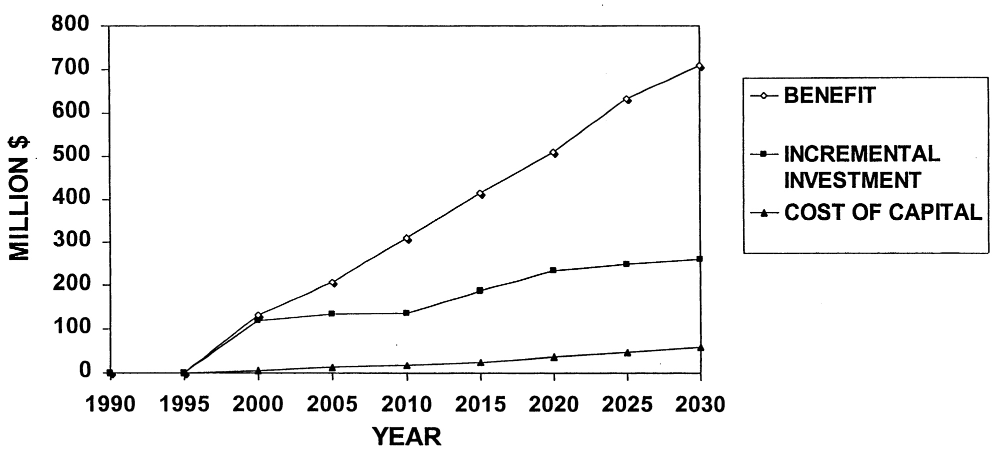

Figure 3.9 *The incremental investment needed to pay for the higher capital cost of the Energy Star Buildings measures is less than half the benefit generated in the commercial sector.*

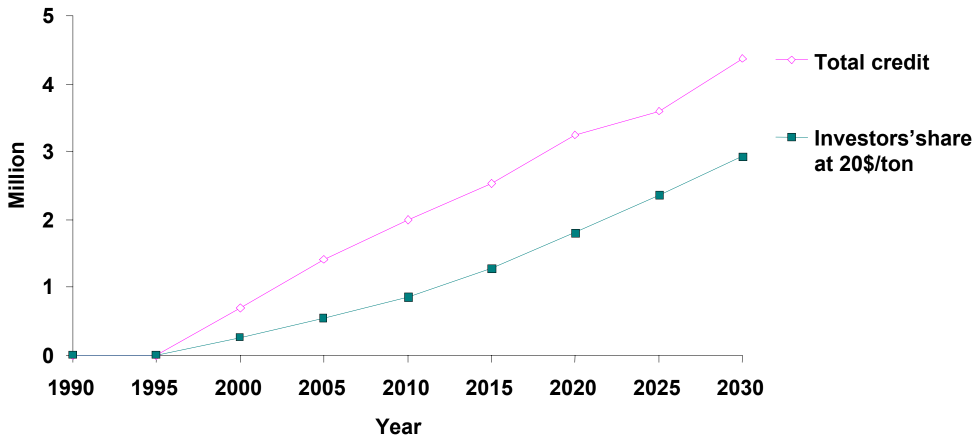

Figure 3.10 *The income from carbon credits is estimated to be distributed initially about evenly between investors and the host country.*

3.12.4 Advantages of Using MARKAL-MACRO for CDM Program Evaluation

Based on this case study, Lee and Linky concluded that MARKAL-MACRO offers a number of advantages for evaluating future programs under the Clean Development Mechanism:

- comprehensive and consistent baseline from which to measure 'additionality',
- explicit representation of the new technologies, their market potentials, and investment costs,
- calculation of real and verifiable energy and emission reductions premised on an efficient allocation of resources,
- dynamic structure that allows for the analysis of long-term mitigation strategies that have great potential for greenhouse gas reduction,
- measure of improved sustainable development seen in the incremental change to gross domestic product,
- basis for emission credit distribution.

Reference

J.C. Lee and E.J. Linky. MARKAL-MACRO: an integrated approach for the evaluation of Clean Development Mechanism programs: the case of Taiwan. Proceedings of the International Energy Agency Energy Technology Systems Analysis Programme, Annex VII, 1st workshop.

4. RESEARCH AND DEVELOPMENT PROGRAM

4.1 Development of TIMES, the Successor to MARKAL

Conceived in Annex VI of ETSAP, the TIMES model has been substantially completed, validated, and begun to be applied in Annex VII. With the experience gained over two decades applying MARKAL to real world problems, with the many fresh ideas arising from this experience, and with the expanding need for a detailed technology-oriented model that can be scaled from the municipal level up to a multi-regional global model, ETSAP decided to take on the development of the new model.

TIMES builds on the best features of MARKAL and the Energy Flow Optimization Model (EFOM), a sister model to MARKAL that was widely used in Europe, hence the acronym TIMES (The Integrated MARKAL-EFOM System).

The group that has developed the model is led by Gary Goldstein, the ETSAP primary systems coordinator. Those principally involved during Annex VII have been Amit Kanudia and Richard Loulou of Canada's *Groupe d'études et de recherche en analyse des décisions* (GERAD), Uwe Remme of the Institute of Energy Economics and the Rational Use of Energy (IER) at the University of Stuttgart, Tom Kram of the Energy research Centre of the Netherlands, Ken Noble of the Australian Bureau of Agricultural and Resource Economics (ABARE), GianCarlo Tosato of the Italian Agency for New Technologies, Energy and the Environment (ENEA), Mario Contaldi, National Agency for the Protection of the Environment (ANPA), Italy, and Denise van Regemorter of the Catholic University of Leuven, Belgium.

4.1.1 Features of TIMES

TIMES will greatly expand upon MARKAL's traditional strengths and inherent flexibility, building on the advanced features added to MARKAL over time. For example, the TIMES model:

- represents emissions, and material and financial flows as well as energy,
- facilitates the linkage of individual national models to examine trade in fuels, money, emission rights, and other commodities,
- can be scaled to model energy systems from the level of a local community up to global regions,
- can alter the product mix from refineries in response to needs,
- allows for separate discount rates for different technologies and energy demand sectors,
- supports the modeling of endogenous technology learning,
- can be linked with economic models for E^3 (energy, economy, environment) optimization.

4.1.2 What's new in TIMES

New features in TIMES include:

- A regional index to allow examination of trade issues and mapping to geographic information systems. This can be used to evaluate the effects of carbon emissions trading, carbon 'leakage' from one country to another, and the implementation of the Clean Development Mechanism. The same feature makes it possible to evaluate infrastructure needs for electrical grid and gas transportation facilities.
- Vintaging of technologies, which allows for the analysis of early reduction credits and subsidies for less carbon-intensive or energy-intensive technologies.
- Time slices to any level of detail down to the hour of the day, not simply season and day/night. With this feature, for example, TIMES may be used to model the effects of time-of-use electrical rates on load curves.
- Variable time period lengths, which allow for the evaluation of the annual effects of carbon mitigation policies in the short term, together with five-year, ten-year, or even 50-year increments for evaluations in the intermediate and long term.
- Intertemporal equations to permit examination of retrofitting and life extensions options.
- Representation of the intensity of attributes, such as sulfur content of fuel when representing refiner blending criteria.
- A distinction between service life and economic life of technologies, along with construction lead times
- Processes can be depicted using flexible input relationships and approaches to emissions accounting
- Independence of model year data from source year data, permitting data to be entered as obtained but analyzed for other years.

TIMES adopts a generic concept to describe the components (commodities and processes) of an RES and its interconnections.

- *Commodities* are defined as the energy carriers, energy demands, materials, money, and emissions, which flow through the RES network.
- *Processes* are the means of transforming commodities from one form to another. A process is described by its capacity and activity, with the units of each explicitly defined by the user.

The flexible representation of processes in TIMES allows the relationship between individual flows to be depicted in a natural way to describe even the most complex processes. Furthermore, a consistent approach is used for depicting all technologies in the energy system, with special additional information required only for interregional exchanges, storage technologies, and combined heat-and-power plants.

The process box will allow inputs and outputs to be described in a flexible manner so that almost any (linear, for now) relationship may be depicted. This includes, but is not limited to:

- Tying input or output flows directly to either the capacity or overall activity of the process
- Establishing fixed proportions for various inputs or outputs, including tying emission levels to individual commodity flows (e.g., consumption of different energy carriers)
- Allowing minimum and/or maximum allocation levels to be specified for all inputs or outputs to/from a process that will then be optimized by the model, and
- Allowing an input in one time-slice to control output in another.

Data are organized by *attributes* that are either global to the model or provide knowledge of the nature of a piece, or time-series, of information to be associated with a process or commodity. An *attribute qualifier*, or index, provides further knowledge of the specific nature or particular instance of an attribute. Primary attribute qualifiers are:

- Region
- Time indexes that distinguish the years for a particular model run
- Time-slices that divide one year
- Boundary types: upper, lower, fixed, none
- Monetary units
- Process name
- Commodity (energy, material, emissions, demand service)
- Commodity groups, to relate commodities by type (energy, material, financial) or to identify commodities that determine the nature of the process (e.g., mix of crude oils to a refinery), and
- Characteristic or indicator, to distinguish properties of a commodity for blending (e.g., sulfur content, octane level) or a source or price indicator for an import or export.

4.1.3 Vintaging

In traditional systems engineering models, attributes usually have one time index, and the data generally relate to one specific future year. Without vintaging, the characteristics of any modeled technology are independent of the age structure of the stock of installations. However, the technical characteristics of an installation often change with aging. For example, the availability of power plants may increase at first as initial problems are overcome, and later decline due to more outages as parts wear out. Some changes over time may be independent of the technology itself, such as a rise in 'fixed' operating and maintenance expense due to higher wages.

By vintaging installations, their technical characteristics depend upon the year of installation and the age structure of the stock. The change of attribute values over the lifetime of a vintage process can be specified in TIMES.

4.1.4 The objective function

The objective function of TIMES, which is minimized by the solution to the program, includes a number of innovations. The objective function is expressed as the discounted sum of annual costs minus revenues, so as to provide year-by-year reporting of net costs. Some features embodied in the objective function include:

- The model accepts technology-specific discount rates as well as a general discount rate. This is used for discounting the yearly payments of investment costs over the economic life of a technology.
- The model can represent sunk costs of materials and energy carriers, that is, those embedded in a technology at its inception. Examples are the uranium core of a nuclear reactor, or the steel embedded in an automobile. Unless these are represented in the RES, their cost should be included in the investment cost.
- The investments in new technology do not occur in a single year, but are represented as a series of annual increments.
- Fixed and variable operating and maintenance costs.
- Decommissioning or dismantling costs are accepted, with an optional time lag that, for example, may be required for radioactive material to cool down.
- The recuperation of sunk materials can be credited when a facility is decommissioned.
- Any taxes or subsidies on investment, decommissioning, and fixed annual costs are accepted by the model.
- Payments made beyond the model's horizon, for decommissioning or recuperation, are reported separately.
- Salvage costs are reported as a single lump sum at the end of the horizon.
- When elastic demands are used in the model, the objective function includes the loss of welfare due to the reduction or increase in demands.
- Learning curves for investment costs are represented when endogenous technology learning is requested.

When the validation and testing phase is completed, the formulation of TIMES will be expanded to include enhanced quality control, stochastics, and a linkage with the economic model MACRO, as well as other advanced features such as grouping technologies and sectors for selective representation.

4.1.5 TIMES Validation and Applications

The first full conversion of a national MARKAL model to TIMES was made by Denise van Regemorter for Belgium, with the assistance of a MARKAL-to-TIMES (M2T) conversion utility. Amit Kanudia in Canada, Mario Contaldi in Italy, Anjana Das and Uwe Remme in Germany, and John Lee and Gary Goldstein in the USA are in the process of integrating and validating their national models.

Early application of TIMES has ranged from the local public transportation system in Turin, Italy, to the initiation of an IEA-sponsored global *Energy Technology Perspectives* undertaking. In this program, Kanudia is validating regional ETP models against their MARKAL counterparts. In addition:
- Anjana Das of IER and Koen Smekens are converting the ECN MARKAL model of Western Europe to TIMES,
- Anti Lehtilae and Jussi Maekelae of Finland are transferring the Finnish national EFOM model to TIMES,
- Leif Alm of Norway, Anna Entek of Sweden, and Lehtilae and Maekelae of Finland are planning to build a multiregional TIMES model for the Nordic countries,
- IER has built an electricity sector model for Germany. An energy model of Bavaria has been used to support a dialogue of the local ministry of economics and technology. Currently, IER is converting their national E3Net model to TIMES.

4.1.6 TIMES for Local Public Transportation

The objective of the TIMES model in Turin was to provide the local transportation utility with insights and suggestions as to:
- Investment opportunities
- Policies and measures to request from the local authorities
- Optimal emission reduction targets
- Cost of compliance with emission reduction targets
- Evaluation of externalities.

TIMES was selected because of the detail in provides in modeling, such as:
- Flexibility in subdivisions of the year provides a precise description of mobility over time and during different seasons of the year
- ‘Time slices’ in the description of processes facilitate precise characterizations of efficiency and demand
- Peak equations enable mobility peaks to be examined

- User constraints can define capacity depending upon demand
- Flexibility in specifying the time horizon permits different time horizons to be examined.

The results showed year-by-year mobility (measured in passenger-kilometers), and emissions of carbon dioxide and nitrogen oxides for eighteen different types of buses and trams. Next steps using the model will include new technologies, competition between the public and private sectors, and details on costs such as for public space and from congestion.

4.1.7 TIMES for Global Coverage

TIMES was chosen by ETSAP to model the global energy system, a project speadheaded by Richard Loulou and Amit Kanudia of HALOA, Canada. This effort has been expanded for the new IEA initiative *Energy Technology Perspectives*.

Analysis of global issues needs a bottom-up technology oriented perspective, for example, to approach coordinated greenhouse gas emission abatement. National policy makers require region-specific detail that is only available in such technological models. These are complementary with top-down economic models, but advanced bottom-up models such as MARKAL and TIMES extend far into the macroeconomic aspects in dealing with endogenous demands, international trade and welfare losses.

The GLOBAL TIMES will start with the databases of existing MARKAL models of the USA, Europe, Japan, Canada, Australia, and India. New databases will need to be developed for the countries in Eastern Europe and the former Soviet Union and Yugoslavia. The model will eventually consist of about twelve regions of the world which trade in energy, emission permits, capital, and some commodities.

New databases are to be created and maintained by individual country on spreadsheets. Regional databases will be created from the individual national spreadsheets. TIMES regional databases will be imported into the computer shell from the regional spreadsheets. These will be merged into a multiregional TIMES model where multiregional constraints will be added or modified as appropriate.

A number of conceptual issues need to be faced to bring GLOBAL TIMES about, such as how to aggregate cost functions of many countries with different development levels to compute a meaningful equilibrium.

4.1.8 TIMES Shells

During the development of TIMES, parallel efforts have been made to develop the ‘shell’ that provides the interface between TIMES and the user: ANSWER-TIMES by Noble of Australia, TIMESAP by a group at IER led by Christoph Schlenzig, and VEDA by Kanudia of Canada.
ANSWER is the shell currently used for MARKAL. It has been continually expanded and improved during Annex VII, with the revisions routinely tested by the ETSAP primary systems coordinator and participants. The latest version includes application to the new MARKAL variant for environmental damages. Its adaptation for TIMES was requested by ETSAP as an interim solution to managing the TIMES data. It has served well in this purpose, but will be superseded by the TIMESAP and/or VEDA endeavors.

TIMESAP is a layer, or ‘dashboard,’ built upon MESAP4, an established databank and data management system designed to serve many models. At present, it is in a development stage; different modules, which will be part of TIMESAP, are being tested. The MESAP4 components consist of the reference energy system editor, data sheets, scenario manager, and ANALYST. The TIMES shell consists of the TIMES-specific user interface layer, the extractor link to GAMS, and a bulk load importer for data and results.

VEDA was newly developed during Annex VII. The VEDA (analyst) has been used successfully for two reports, and links to MARKAL and TIMES have been established and tested. It is extremely strong. VEDA and VEDA-Front End (VEDA-FE, the TIMES data-handling component) are ready for use by experienced MARKAL/TIMES modelers. VEDA-FE features a set of spreadsheet templates that are expressed as MARKAL data sets and attributes that are converted for TIMES. For World TIMES, VEDA has been run successfully with single and multi-region models.

References

M. Contaldi. Validation of TIMES: Lessons learned by converting the MARKAL-ITALY model (draft). Presented to the ETSAP workshop, Baden, Switzerland, 16-19 October 2000.
A. Das and U. Remme. Experimenting with TIMES. Presented to the ETSAP workshop, Venice, Italy. 14-17 May 2001.
G. Goldstein. Update on ETSAP tools. International Resources Group. Presented to the ETSAP workshop, Venice, Italy. 14-17 May 2001.
R. Loulou and A. Kanudia. Development of MARKAL and TIMES toward global coverage. Presented to the ETSAP workshop, Paris, France. 17-19 May 2000.
D. Scaramuccia. Modeling in TIMES: Case study: Transport system analysis. Presented to the ETSAP workshop, Baden, Switzerland, 16-19 October 2000.

4.2 Goal Programming with MARKAL

A new variant, goal programming, has been proposed for addition to the MARKAL family of models. Like the majority of other mathematical programming models, MARKAL normally optimizes a single objective function, usually minimizing the expected cost of an energy system over a period of time. Restrictions on the energy system, such as the maximum allowable emissions of pollutants, are represented by ‘hard’ constraints that must be satisfied.

Goal programming is a more flexible approach where reductions in pollutant emissions are set as targets and included in the objective function. These targets may be met, exceeded, or not met, depending upon the specification of other targets, such as total energy system cost, and the set of options available to meet the targets. As a result, multiple goals can be represented in the planning problem.

Policy formulation involves numerous stakeholders with different values and perceptions of risk. For such a group, no single purpose exists that can be described by a single mathematical function that is optimized. The group decision process consists of an examination of trade-offs between alternatives in light of different values and criteria for acceptance of an alternative. For the electrical sector in particular, many factors such as dispatchability, availability, fuel choice, and environmental emissions of various pollutants, must be included in the decision process.

Goal programming can be used to screen alternatives with different technical attributes. A set of feasible alternatives can be divided into a subset of Pareto-efficient (or non-dominated) and Pareto-inefficient solutions. A Pareto-efficient set of solutions includes all alternatives that approach the goals more closely, but no one alternative is better in all respects than another. As a result, goal programming can be used to identify co-benefits from reducing multiple pollutants, and compromise solutions to complex policy and planning problems.

To represent this mathematically, a set of target values can be defined that represent the goals of the parties. For example, these may represent desired reductions in emissions of various pollutants. To obtain the Pareto-efficient set of alternatives for the development of an energy system, the sum of the deviations from these targets is then minimized. In addition to target levels, the decision-makers must agree on a set of weights to be assigned to the importance of deviations above and below each goal.

To illustrate the results, Figure 4.1 shows the trade-offs between two goals: total energy system cost and emissions of three pollutants between 1995 and 2030. The three pollutants were sulfur dioxide, nitrogen oxides, and carbon dioxide. The figure maps the results of a set of alternative goal programming solutions or alternatives. Although this graph shows tons of emissions without differentiating among the pollutants, the goal programming formulation actually minimizes the percentage deviation from each pollutant goal.

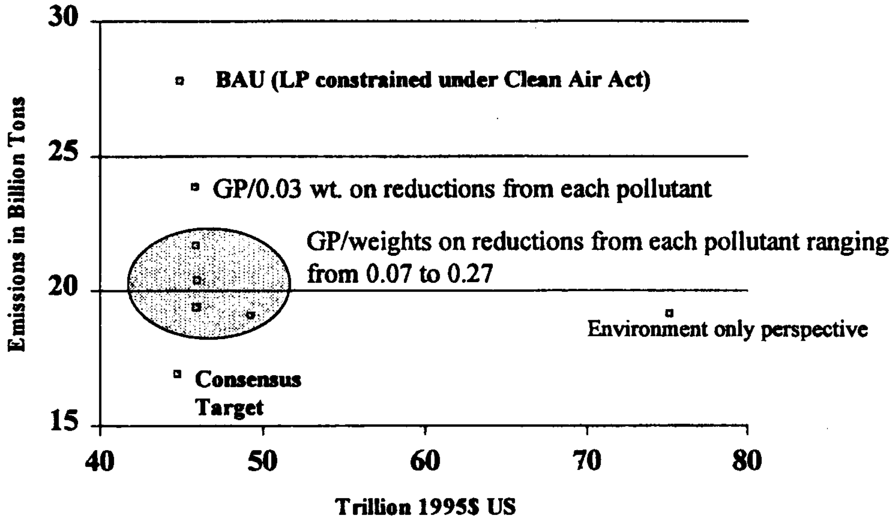

Figure 4.1 *Trade-offs between costs and emission levels.*

The consensus target is a ‘dream point’ with a lower assumed energy system cost than the business-as-usual scenario, and emission levels desired by one set of decision makers.

The goal programming scenarios depicted in the figure attempted to reach those targets. However, each alternative solution used different preference weights between total energy system cost and emission reductions. For comparison, the business-as-usual result and a point representing a total commitment to emissions reduction at any cost are shown. These represent end-points of a continuum of solutions.

The solutions for a wide range of preference weights cluster relatively tightly within this continuum, as shown within the ellipse. This suggests that groups with highly divergent views can reach a consensus on alternatives for future energy system development, and still substantially reduce emissions from that source.

Further, this diagram indicates that greater reductions in the emissions of three pollutants can be achieved using more flexible approaches than mandating fixed reductions for two pollutants. Goal programming identifies the most economically efficient reductions with optimal timing for all targeted pollutants. In contrast, both the amount and timing of emission reductions must be specified exogenously with a standard linear program.

Although none of the identified solutions achieved the desired targets, the results suggest points for further consideration by decision-makers. For example, they might reconsider the emission reduction and cost targets and agree on less ambitious goals. Or they might consider promoting more costly technologies with lower emissions, or conservation measures that use less energy. The use of goal programming therefore provides a tool for evaluating many potential strategies, and leads to the exploration of new options that might not ordinarily be examined.

The goal programming application of MARKAL was developed by Lorna A. Greening, with assistance by Gary Goldstein,. The work was supported by the Office of Atmospheric Research Programs, U.S. Environmental Protection Agency, and was performed in collaboration with John A. ('Skip') Laitner of that office.

Reference

L.A. Greening. *Design of Coordinated Energy and Environmental Policies Using Multicriteria Decision Making, and Harmonizing U.S. Energy and Environmental Policies Using Goal Programming*. (LGDoone@aol.com)

APPENDIX A THE MARKAL FAMILY OF MODELS

MARKAL is a family of models that represent energy systems by the set of technologies used to extract, transport or transmit, convert, and use energy to meet projected future energy service demands. The basic MARKAL is a bottom-up linear programming model, but its variants include coupling with top-down economic models and nonlinear solution algorithms. The solution to a MARKAL model represents the optimum set of technologies that, with perfect foresight, meet the projected energy demands within the constraints that are specified, for example, the maximum level of carbon dioxide emissions permitted.

The various versions of MARKAL have generally been developed by individual participants in ETSAP to meet their specific needs. However, with the exceptions noted below by an asterisk, they are now incorporated in a common model. The user activates these features by providing the appropriate data and/or switches. Most of the MARKAL versions can be coupled to combine desired features.

MARKAL-ED: MARKAL with elastic demands. In this ‘partial equilibrium’ approach, the projected energy demands, rather than being fixed for future years, are modified as part of the solution of the program in response to the changing cost of energy. The energy demands are represented with a stepwise linear approximation, where the user provides own-price elasticities for each ‘flexible’ demand sector. There is also an extension to MARKAL-ED that permits income elasticities (MEDI) also to be provided by sector.

MARKAL-ETL: A nonlinear version of MARKAL in which the unit costs of technologies may decline with increasing total capacity as a result of endogenous technological learning, that is, down the learning curve.

MARKAL-EV: A version that includes environmental damage calculations, or nonlinear optimization of an objective function that includes the damage calculation.

MARKAL-GP*: A variant of MARKAL used for goal programming. Rather than ‘hard’ constraints, such as maximum allowable emissions of pollutants, target values are specified. With different weights given to their importance, a set of Pareto-efficient solutions can be found to enable decision-makers to examine a range of solutions representing different goals.

MARKAL-MACRO: A nonlinear, dynamic optimization model that links MARKAL with MACRO, a top-down macroeconomic growth model. Multiple MARKAL-MACRO models may be linked to represent trade among countries in energy and emission permits.

MARKAL-MACRO-MERGE*: An integration of MARKAL-MACRO with MERGE, a global trade model.

MARKAL-MICRO: Like MARKAL-ED, a partial equilibrium approach. In this case, projected energy demands are represented as nonlinear functions, and the solution is obtained using nonlinear programming techniques.

MARKAL-Stochastics: A version that allows for uncertainty in such input values as the permitted future level of carbon dioxide emissions, prices of energy and technologies, and levels of demand. Probabilities are assigned to alternative future scenarios. The model calculates the hedging strategy: the singular optimal mix of technologies for the near term until the uncertainty is resolved at an assumed future date.

MATTER: An extension of MARKAL that includes the flow of materials as well as the flow of energy.

RMARKAL: Regionalized MARKAL in which a set of MARKAL models may be linked by flows of energy, materials, and emission permits.

SAGE: System to Analyze Global Energy, a version of MARKAL that permits stepped (or 'myopic') solutions in successive time periods to the model horizon.

TIMES: The Integrated MARKAL-EFOM System, which is the evolutionary replacement of MARKAL. It offers the analyst greater flexibility and additional features.

Reference

Energy planning and the development of carbon mitigation strategies: Using the MARKAL family of models. International Resources Group. 1999. <ggoldstein@irgltd.com> and <http://www.ecn.nl/unit_bs/etsap>

APPENDIX B EXECUTIVE COMMITTEE AND PROJECT HEADS

Members of the Executive Committee, Annex VII

Chairs:	J.G. Hollins (1999), P. Tseng (1999-2002)
Vice-Chairs:	M. Ishigami (1999-2001), G-C. Tosato, T. Yano (2001-2002)

Australia:	R. Stuart, K. Noble
Belgium:	A. Fierens
Canada:	H. Labib
European Union:	D. Rosetti
Finland:	P. Pirilä
Germany:	A. Voss
Greece:	G. Giannakidis
Italy:	G.-C. Tosato
Japan:	M. Ishigami, T. Yano
Korea:	H. Shin
The Netherlands:	A.J. Seebregts, K. Smekens
Norway:	L.K. Alm
Switzerland:	S. Kypreos
Sweden:	U. Wallin
Turkey:	T.S. Uyar
U.S.A.	P. Tseng

Project Heads

T. Kram (1999-2001), K. Smekens (2001-2002)

APPENDIX C SCHEDULE OF WORKSHOPS

May 1999	Washington, DC
Host:	U.S. Department of Energy and Brookhaven National Laboratory
September 1999	Bergen, The Netherlands
Host:	Energy research Centre of the Netherlands
May 2000	Paris, France
Host:	International Energy Agency
October 2000	Baden, Switzerland
Host:	Paul Scherrer Institute/ABB Corporate Research Joint meeting with China Energy Technology Program of ABB Corporate Research with Alliance for Global Sustainability, universities, and Chinese organizations Topic: 'Regional and Global Climate Change Concerns and Policy Options'
May 2001	Venice, Italy
Host:	Agency for New Technologies, Energy and the Environment (ENEA) Joint meeting with the Kyoto Club Topic: 'Climate Change: An Experts' Update and Markets' Response'
October 2001	Paris, France
Host:	International Energy Agency

APPENDIX D WORLD WIDE WEB PAGE

During Annex VII, the ETSAP World Wide Web page has undergone major restyling and has attracted more and more visitors. The current home page is shown in Figure D.1.

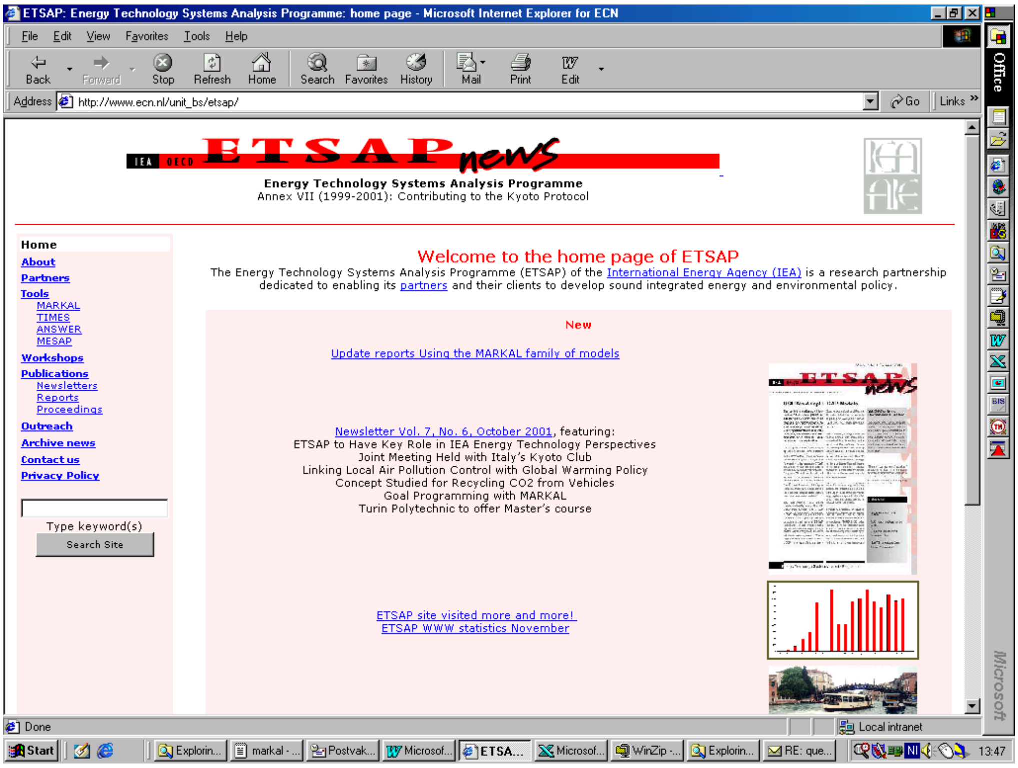

Figure D.1 *ETSAP Home Page on the World Wide Web.*

Since it was launched in September 1996, the ETSAP Web site has received more and more attention. The number of monthly page hits has grown from about 30 in 1996, through about 1,000 in 1998, to almost 1,500 in 2000. The average through November 2001 was more than 3,500 page hit per month (Figure 17). Currently, the ETSAP newsletter and the proceedings of the semiannual workshops can be downloaded as PDF files from the Internet. The WWW update service was also implemented during Annex VII.

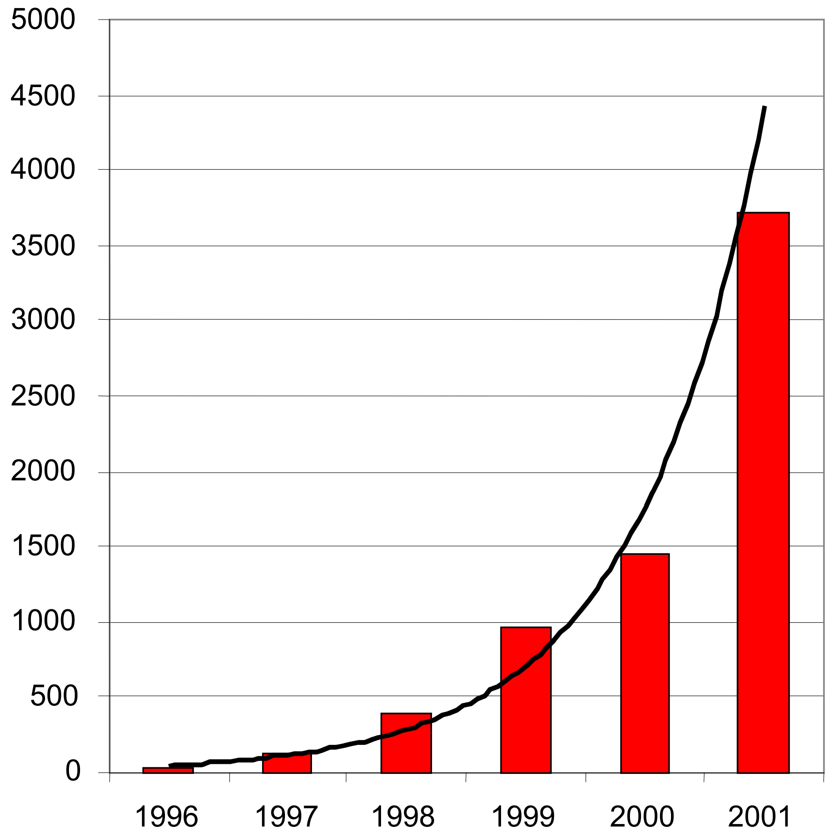

Figure D.2 *Number of hits per month on ETSAP World Wide Web home page.*

APPENDIX E CONTENTS OF ETSAP NEWSLETTER IN ANNEX VII

Number 1, January 2000

The new TIMES: a model for the millenium
Around the world
Annex VII to stress international cooperation
Summary of Annex VI published
ETSAP members in Third IPCC Assessment
Wene writes on experience curves
IEA cites ETSAP as 'success story'

Number 2, May 2000

Regional environmental planning in Italy
Building upgrades in Taiwan as an example for CDM
Calculating environmental benefits with MARKAL

Number 3, September 2000

Report roundup!
- Emissions trading
- Joint Implementation
- Kyoto Protocol
- Learning curves
- Local energy planning
- Materials management
- Methodology
- Policy analysis
- Technology assessment
- Report sources

Number 4, December 2000

USEIA to adopt ETSAP models
ABB hosts joint seminar on China
CO_2 emission reduction: sooner or later?
How will greenhouse gas emission reductions be shared domestically?

Number 5, April 2001

German modelers look at nuclear phase-out
Multi-regional technological learning with MARKAL
Around the world
Correction

Number 6, October 2001

ETSAP to have key role in IEA Energy Technology Perspectives
Joint meeting held with Italy's Kyoto Club
Linking local air pollution control with global warming policy
Concept studied for recycling CO_2 from vehicles
Goal programming with MARKAL
Turin Polytechnic to offer master's course

Number 7, January 2002

Is Kyoto fatally flawed? - An analysis with MacGEM
The MARKAL family of models
Managing materials to reduce carbon dioxide
Progress on IEA Energy Technology Perspectives
Tom Kram departs