NATIONAL ENERGY OPTIONS FOR REDUCING CO₂ EMISSIONS,
VOLUME I:
THE INTERNATIONAL CONNECTION


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NETHERLANDS ENERGY RESEARCH FOUNDATION ECN

DECEMBER 1993
ECN-C--93-101
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December 1993
This report was prepared by the Stichting Energieonderzoek Centrum Nederland (ECN), acting as Operating Agent for Annex IV of the Energy Technology Systems Analysis Programme (ETSAP), an Implementing Agreement of the International Energy Agency (IEA). As such, the material presented is the result of a collaborative research task, drawing upon studies performed by participants in IEA-ETSAP/Annex IV and guided by the ETSAP Executive Committee. The views and opinions expressed herein do not necessarily state or reflect those of Governments of any IEA member state, or any agency, contractor or subcontractor thereof; nor those of the International Energy Agency.
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VOLUME 2: COUNTRY STUDIES

(Separate Report ECN-C--94-024, Petten, March 1994)
INTRODUCTION

In recent years the long-standing scientific debate on the possibility that human activities may induce global climate changes has drawn widespread public attention. This so-called Greenhouse Issue, referring to rising global temperature levels following increased concentrations of certain gases in the atmosphere, has in fact become a main issue in international and national policy discussions. Assessments of causes for the observed rising concentration of greenhouse gases (GHGs) indicate that carbon dioxide (CO₂) released from burning of fossil fuels is a very important factor. Anticipating coordinated, international strategies, a wealth of national, regional and global studies is being carried out to investigate options, policies, instruments and consequences of more sustainable future energy systems.

The Energy Technology Systems Analysis Programme (ETSAP), a cooperative project of national expert groups under the aegis of the International Energy Agency (IEA), aims to contribute to the ongoing process by investigating emission control strategies for greenhouse gases. The methodology developed within ETSAP, in earlier stages used to address questions like long-term security of energy supply and acid emission abatement, is applied to calculate how CO₂ can best be reduced in the participating countries in the first decades of the next century. To this end (sub-)national scenario assessments are made, aiming at least-cost solutions to meet future energy demands at reduced CO₂ emission levels. The individual studies are compiled for aggregation and comparative assessment by the Operating Agent for ETSAP, the Policy Studies unit of the Netherlands Energy Research Foundation (ECN-Policy Studies).

This report contains the aggregate and comparative results, together with summaries of the individual studies in a common format. More detailed national reports are published separately in Volume 2: Country Studies (Report ECN-C--94-024).

The analysis presented here is inspired by the notion that country specific features will lead to differences in the ranking of CO₂ reduction options, both in terms of significance and cost. Physical (e.g. hydropower potential), socio-economic (GDP, economic structure, etc.) and technological (e.g. fine-meshed gas distribution systems) features, as well as policy guided features (e.g. nuclear power policies) shape both the reference or base case scenarios and the reduced emission cases. Maximum reductions achievable and costs incurred to reach pre-specified reduction levels thus differ considerably. Recognizing this, two alternative approaches towards reducing emissions from the group of countries are drafted.

The work benefited substantially from using a common methodology and tool, the MARKAL (acronym for MARKet ALlocation) model, developed within ETSAP. Recent development of versions running on personal computers (PC-MARKAL), and even more so of the user-friendly MARKAL Users Support System (MUSS), proved invaluable in conducting the analyses.
ACKNOWLEDGMENTS

The author would like to thank the experts of the national teams, not only for skilfully conducting the scenario studies that form the basis upon which the aggregation and comparison rests, but also for their support and critical comments throughout the study. Officers and other members of the Executive Committee for ETSAP are warmly thanked for their guidance, which helped to focus the analyses. Without forgetting other contributors, the following individuals are mentioned in particular:

Belgium: Denise van Regemorter (CES, KU Leuven)  
Jan van Rensbergen and Walter Debruyyn (VITO, Mol)

Canada: John Hollins, chairman (Environment Canada, Ottawa)  
Richard Loulou and Claude Berger (GERAD, Montreal)

Italy: Giancarlo Tosato (ENEA, Genova)

Japan: Takahashi Suzuki, vice chairman (STA, Tokyo)  
Shigeru Yasukawa and Osamu Sato (JAERI, Tokai)

Netherlands: Peter Okken, Remko Ybema, Paul Lako and Dirk Gerbers (ECN Policy Studies, Petten)

Norway: Fridtjof Unander and Arild Ek (IFE, Kjeller)

Sweden: Clas-Otto Wene and Thomas Larsson (Chalmers University of Technology, Gothenburg)

Switzerland: Socrates Kypreros (PSI, Villigen)

UK: Richard Kettle, vice-chairman (Dep. of Energy, London)  
David Swan (ETSU, Harwell)

USA: Leonard Hamilton, Sam Morris and Gary Goldstein (BNL, Upton, New York)

CEC: Frans van Scheepen and Pierre Valette (DG XII, Brussels)

Douglas Hill, former Project Head of ETSAP, must be mentioned for his extremely valuable contributions to this report. In particular by writing the Summary, major parts of Chapter 1 and Appendix A., and by providing innumerable editorial and linguistic suggestions. He also played a decisive role to promote ETSAP to a wider audience through his outstanding work as editor of ETSAP News, that is also gracefully acknowledged.

Gary Goldstein gets a special word of thanks for his enthusiasm and dedication in developing and championing PC-MARKAL and MUSS (including a special version for aggregation and comparison purposes at the OA’s office), and his highly appreciated support and advice to users of the software.

At ECN Policy Studies, the efficient and invaluable secretarial project support from Wilma Jansen and her successor Carla Roukema, is highly appreciated, as well as Ineke Wouts’ contributions to final editing.
SUMMARY

Under the aegis of the International Energy Agency (IEA), eleven nations and one international organization\(^1\) cooperated in a program to extend the application of methodology developed in the Energy Technology Systems Analysis Programme (ETSAP) to emission control of greenhouse gases. Representatives of nine of the nations -- Belgium, Canada, Italy, Japan, the Netherlands, Norway, Sweden, Switzerland, and the USA -- collaborated in calculating how countries can best reduce emissions of carbon dioxide and other greenhouse gases, especially from their energy systems. The countries used a common analytical methodology based on the MARKAL model to calculate how their national energy systems could best respond to possible future restrictions on carbon dioxide and other emissions.

The individual national analyses represent the specific situation unique to each country: the existing energy system, indigenous energy resources, national regulations such as those on the emission of acid rain precursors, and national policies such as those on the use of nuclear power. The common methodology, building on the previous work of the IEA Energy Technology Systems Analysis Programme over a decade and a half, makes a direct comparison of the individual national results possible.

Although the nine nations are all industrialized countries, the analysis reveals their diversity -- differences in their resources, their policies, their energy systems, and their ability to respond to possible future restrictions on carbon dioxide emissions -- even those that are geographically contiguous. This report is intended to provide information and insight into the strategies they would find most suitable to reduce future CO\(_2\) emissions.

Each country\(^2\) prepared a data base that describes the technologies that comprise its existing energy system and those that might come into use during the next 40 to 50 years. Each country formulated its own MARKAL model to represent the existing energy system by the set of technologies of which it is comprised and to allow for its evolution over the next 40 to 50 years. Consistent assumptions were made among the countries as to possible future courses of economic growth, energy prices, and energy demands.

Each country’s MARKAL model was then used to calculate the optimal evolution of its energy system over time, first, a baseline case without future restrictions on CO\(_2\) emissions, and then with a series of required future CO\(_2\) emission reductions up to the point of maximum feasible reductions. Note that MARKAL is a normative model that is used to design future energy systems in a parametric way, that is, by examining a range of possibilities. It is not a simulation model intended to predict the future.

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\(^1\) Belgium, Canada, Germany, Italy, Japan, the Netherlands, Norway, Sweden, Switzerland, United Kingdom, United States of America, and the Commission of the European Community.

\(^2\) For Canada separate analyses were made for two provinces, Quebec and Ontario. For reasons of simplicity, each of these is referred to as a “country study” like the others.
Five of the countries submitted results for two projections of future economic development: high growth and low growth. In this summary, the high-growth projections are compared with the central projections of the other countries in two cases: the baseline without future CO$_2$ restrictions, and one with maximum feasible CO$_2$ reductions in the year 2020. In the baseline, total CO$_2$ emissions from all the countries would rise by about 40 percent from the 1990 level (when they accounted for about one-third of global carbon dioxide emissions).

As "bottom-up" models, the MARKAL results provide a wealth of detail on the choice of technological measures. This is a summary of those choices, together with their implications on the use of fuels, the needed resources, and the emissions of CO$_2$.

**Steps to Reduce Carbon Dioxide Emissions**

Carbon dioxide emissions can be reduced by switching among fossil fuels, e.g., from coal to natural gas, or by reducing the use of fossil fuels. The use of fossil fuels can be reduced through energy conservation and efficiency improvements or by substituting other energy sources such as nuclear energy and renewables which are essentially carbon-free.

The optimal choices made by the individual country depend upon its circumstances, especially the resources available to it. For two extreme scenarios --one with no CO$_2$ emission restrictions and one with the maximum feasible CO$_2$ limitations in 2020-- the effect of these choices on the use of fossil fuel is summed up in figure 1. In the figure, each country is represented by a broken arrow. The circles show the situation in 1990. The break in the arrow shows the baseline projection for 2020 where the energy system is allowed to evolve without additional CO$_2$ emission restrictions. The arrowheads show the situation in 2020 with maximum CO$_2$ reduction.

Each of these points can be read by three measures in figure 1. The abscissa shows the CO$_2$ intensity of the fossil fuel mix, i.e., the amount of CO$_2$ that is emitted per unit of fossil primary energy consumption. With more coal in the mix, the CO$_2$ intensity is higher. With more natural gas, the CO$_2$ intensity is lower, both because of its chemical composition and because it is typically burned more efficiently. The ordinate shows the percentage share of primary energy that is fossil fuel. The diagonal dotted lines show the product of the abscissa and the ordinate: the carbon intensity of total primary energy.

In 1990, the Netherlands had the highest fossil fuel share, 97 percent, making use of its considerable gas reserves with almost all of its households connected to the gas grid and half of its electricity generated with gas. The lowest fossil fuel shares existed in Norway and Quebec, both making use of their hydroelectric resources, and Sweden. Sweden has already reduced its CO$_2$ emissions by 30 percent during the 1980s with nuclear power, biomass replacing oil in the pulp and paper industry, and aggressive energy conservation in the residential sector.

With growing economies, however, each of these three countries would require a larger share of fossil fuel. This indicates that it is more difficult to maintain high nonfossil fuel levels than to use more fossil fuel to meet grow-
ing energy demands, because of availability and cost of resources or because of disproportionate growth of demands most conveniently served by fossil fuels, e.g., transportation. Ontario also would increase its share of fossil fuel; Ontario expects a relatively high economic growth, relatively modest improvement in energy intensity (total primary energy requirements per unit of GDP), and the opportunity to use more coal.

![Figure 1 Comparative use of Fossil Fuels among Countries](image)

Figure 1 Comparative use of Fossil Fuels among Countries

The remaining countries show little change in their fossil fuel shares with the exception of Japan. Japan would triple its nuclear energy production and double its renewable energy supply in the baseline, reducing the need for fossil fuel. However, growing use of coal and a decline in oil would raise the \(\text{CO}_2\) intensity of fossil fuel use.

The use of more coal in the baseline also raises the \(\text{CO}_2\) intensity of the fossil fuel mix in the Netherlands, Ontario, and Sweden. Only Quebec significantly decreases the \(\text{CO}_2\) intensity of its fossil fuel mix under these circumstances because of a marked increase in its use of natural gas to reduce acid gas emissions.

Fossil Fuel Changes with Maximum Reduction of \(\text{CO}_2\)

The changes in fossil fuel use with maximum reduction of \(\text{CO}_2\) reveal the differences in the alternatives available to the countries, shown by the direction of the arrowheads in figure 1. At one extreme, Belgium and the Netherlands depend primarily upon switching among fossil fuels to reduce \(\text{CO}_2\) emissions, indicated by the arrows pointing to the left, in both cases due to greater use of natural gas.

In Belgium, coal disappears entirely as a power station fuel as \(\text{CO}_2\) is progressively constrained, and more and more electricity is generated by combined heat-and-power (CHP) plants fueled by gaseous energy carriers. With
maximum CO₂ reduction shown by the arrowhead, electricity is generated by fuel cells using hydrogen in part produced from natural gas. Hydrogen is also used as a transport fuel under these circumstances.

The Netherlands, with little potential for energy supply from renewables and no new nuclear power plants, must continue to rely on fossil fuels. A complex pattern of substitution takes place as CO₂ emissions are successively reduced. The energy system shifts from gas to coal with medium emission restrictions. The increased use of coal is made possible by the removal of CO₂ from exhaust gases and its disposal in aquifers and depleted gas fields. However, more drastic emission reductions result in a shift back from coal to gas. With more than a 50 percent reduction in CO₂ emissions, hydrogen becomes a prominent energy carrier, with the hydrogen produced by steam reforming from natural gas.

At the other extreme are Norway and Quebec, each of which depends entirely on reducing the share of fossil fuel, as indicated by the arrows pointing straight down. Both places have the potential for further developing their hydroelectric resources under extreme restrictions on CO₂ emissions. In addition to another 70 TWh of hydropower, Norway can develop potential wind and wave power.

Sweden, Switzerland, and Ontario would also depend more upon reducing fossil fuel share rather than changing the fossil fuel mix to reduce CO₂ emissions.

In Ontario, the role of coal would expand in the baseline by up to one-third of total primary energy, but it becomes negligible with just a stabilization of CO₂ emissions required. CANDU nuclear reactors first replace coal-fired electric generating plants, and as the use of electricity grows they then reduce oil and gas.

In Switzerland, there is a slight increase in hydropower in the baseline. The nuclear moratorium in Switzerland restricts nuclear capacity to its present level, but due to technical improvements and enhanced utilization of capacity, nuclear electric generation can still increase by 25 percent. Further CO₂ reductions depend upon introducing wind and solar power for generating electricity.

In Sweden, the carbon intensity of total primary energy is already about as low as hydroelectric-rich Norway and Quebec due to the technological changes of the past decade, as indicated in figure 1 by the diagonal dotted lines. For further CO₂ reductions, the existing 10 GWe of nuclear power is retained, contrary to the current policy of phasing out nuclear reactors at the end of their lifetimes. In addition, expensive wind and wave power are introduced to replace fossil-based electricity, and biomass substitutes for fossil fuels to produce industrial process heat.

---

3 Large-scale disposal of CO₂ is yet to proved as a technically feasible, and acceptable with regard to potential risks and environmental impacts, option. Research programmes are initiated to assess the various aspects.
Japan and the USA depend more upon a mix of the two types of measures, not depending primarily on substitution for fossil fuel. This is indicated in figure 1 by the arrows pointing more to the "southwest." This may be explained by the fact that their energy systems are large and heterogeneous, offering many different possibilities for both switching among and substituting for fossil fuels. The fact that the arrows are roughly parallel for the two indicates that the mix of the two types of measures is about the same in the two energy systems.

In Japan, nuclear power further increases up to a 20 percent reduction in CO\textsubscript{2} emissions in 2020 when it reaches the maximum feasible rate of market penetration. Coal is first replaced by oil and LNG for electric generation, and then by LNG alone. Finally, more hydropower and other renewables are brought in.

In the USA, nuclear energy is reintroduced in the CO\textsubscript{2} reduction cases. Renewables, which contribute substantially to electricity generation in the baseline, grow further, eventually supplying one-third or more of all primary energy. Renewables include various geothermal, wind, wave, OTEC, biomass, and solar technologies. With the most severe CO\textsubscript{2} reductions, the use of coal almost disappears; fossil fuel use is about equally divided between oil and natural gas.

The effectiveness of the various measures to reduce CO\textsubscript{2} emissions from the use of fossil fuel is shown in figure 1 by the location of the arrowheads on the diagonal grid for carbon intensity of total primary energy. Quebec achieves the lowest intensity of about 10 tCO\textsubscript{2}/PJ, followed by Sweden (16.6), Ontario (18.6), and Norway (20.2). The highest intensity is in Italy (53.2), followed by the USA (40.9) and Japan (36.9).

The use of fossil fuel, however, is only part of the story. To examine the effectiveness of the CO\textsubscript{2} reduction strategies of the various countries, their use of fossil fuel has to be placed in a larger perspective.
CO₂ Reduction Strategies

The total amount of CO₂ emissions from a national energy system is determined by social, economic, technological and energy/environmental policy-related factors. The calculation of this amount can be broken down as shown in Diagram 1.

Diagram 1  Representation of CO₂ Emission Components

\[
\text{CO₂} - \text{CAP} \times \left( \frac{\text{GDP}}{\text{CAP}} \right) \times \left( \frac{\text{TPER}}{\text{GDP}} \right) \times \left( \frac{\text{TFOS}}{\text{TPER}} \right) \times \left( \frac{\text{CO₂}}{\text{TFOS}} \right)
\]

\[
\frac{\text{CO₂}}{\text{CAP}} = \left( \frac{\text{TPER}}{\text{CAP}} \right) \times \left( \frac{\text{CO₂}}{\text{TPER}} \right)
\]

with:  
\text{CO₂} = \text{Total CO₂ Emissions}  
\text{CAP} = \text{Population}  
\text{GDP} = \text{Gross Domestic Product}  
\text{TPER} = \text{Total Primary Energy Requirements}  
\text{TFOS} = \text{Fossil Primary Energy Requirements}

Projected energy demands are an input to the MARKAL models based on forecasts of population and Gross Domestic Product that are external to the model. The factor (GDP/CAP) is therefore entirely independent of the model. Total Primary Energy Requirements are calculated by the MARKAL models; therefore the factor (TPER/GDP) is determined by the model, as are the terms CO₂ and TFOS.

The comparison of CO₂ emissions from national energy systems can therefore be shown with three graphs, as indicated in diagram 1.

In each of the three graphs, three elements of the calculation are compared. Those dealing with the fossil energy results have already been shown in figure 1. Those elements dealing with energy use will be shown in figure 2. Finally, the CO₂ emissions per capita will shown as a function of the combined elements in the figures 1 and 2 in figure 3.
Comparative Energy Use Among Countries

Figure 2 compares the countries on the basis of their use of energy, measured by Total Primary Energy Requirements (TPER). Primary Energy Intensity, or the Total Primary Energy Requirements per unit of Gross Domestic Product (GDP), is shown on the abscissa. GDP per capita, estimated outside the model, is shown on the ordinate. The product of these two terms, TPER per capita, is shown on the diagonal grids.

*Caveat: The absolute dollar figures should be treated as approximate. The model calculations were made in the currency units of the individual countries. These were converted to US dollars using the 1990 exchange rate. However, purchasing power can differ significantly among countries, and the U.S. exchange rate of national currencies is subject to large fluctuations.*

The actual 1990 figures are shown by the solid circles. Gross domestic product per capita, measured on the ordinate, was highest for Switzerland and Sweden. It was lowest for Italy and the Netherlands. Primary energy intensity, measured on the abscissa, was highest for Quebec, USA, Norway and Ontario.

*Caveat: nonfossil energy sources are accounted for as "fossil fuel equivalents", implying that primary energy consumption in cases where there is a large share of nonfossil energy supply tends to be overestimated; see also the box "Accounting of Energy Consumption" on page XXII.*

The 2020 baseline projection for Total Primary Energy Requirements obtained from the MARKAL models, divided by the projected GDP in each country is shown as the break in the arrows. Unlike figure 1 where there were decided differences in the baseline trajectories of the countries, these are much alike.

![Figure 2 Comparative Primary Energy Requirements among Countries](image.png)
Primary energy intensity—the ratio of total primary energy requirements per capita to GDP—has decreased over time in industrialized countries. The MARKAL projections indicate that they would continue to do so. An increase in GDP—which all the countries anticipate through 2020—would move the points directly "northwest" in figure 2 if everything else were held equal. This accounts for the first leg of the arrows pointing in that general direction.

Given a specified set of useful energy demands, the primary energy requirements are determined both by efficiency in end use and by efficiency in conversion, transportation or transmission, and distribution. These two effects can be distinguished by considering figure 2a in which Final Energy Use has been substituted for Primary Energy Requirements, compare figure 2.

(Caveat: The share of electricity in final energy consumption plays an important role here. Generally, the more energy services are met by electricity, the smaller are the losses at the end-use level. So, besides "real" savings and efficiency improvements, the share of electricity is to be taken into account when comparing final energy use between countries and cases, see also the box "Accounting of Energy Consumption" on page XXII.)

Typically, many energy conservation measures are found to be cost-effective by MARKAL models, so that most efficiency improvements would occur in the baseline case. The horizontal arrowheads pointing "west" in figure 2a indicate that Final Energy Use is further reduced by additional end-use efficiency or conservation measures in all countries when CO₂ emission reduction measures are introduced.

![Diagram](image)

Figure 2a Comparative Final Energy Use among Countries

The changes that take place in the rest of the energy system may reinforce or reverse these savings, however. Where the remainder of the energy system becomes more efficient when CO₂ emission restrictions are applied (Japan, USA, Italy), there is a proportionately greater reduction in Primary Energy
Intensity, seen by the longer arrowheads pointing west in figure 2. In all the other countries (except Switzerland where the change is insignificant), the remainder of the energy system becomes less "efficient" (by the usual accounting convention) when CO₂ emission restrictions are applied, and the reduction in Primary Energy Intensity seen in figure 2 is either less (Belgium, Netherlands) or actually increases, i.e., points east (Norway, Ontario, Quebec, Sweden). Compared to the change in the baseline scenario from 1990 to 2020, however, the net change in Final Energy Intensity due to CO₂ emission reductions is in any case comparatively small.

The arrowheads are all horizontal because, in the absence of a better estimate, the Gross Domestic Product per Capita in 2020 is assumed to be the same with maximum CO₂ reduction as in the baseline. This is clearly unlikely. Severe CO₂ restrictions would undoubtedly reduce GDP, and this would in turn affect the energy demand projections on which the MARKAL results are based. It is here that the limits of the stand-alone MARKAL become apparent. A linkage of MARKAL with an economic model is needed to close this loop for a better estimate of the economic consequences of CO₂ restrictions.

The Total Primary Energy Requirements per Capita are measured on the diagonal dotted grids in figure 2. With the assumption of unchanged GDP in 2020, the highest values occur in Quebec, Ontario, USA, and Norway. (Again recall the caveat on nonfossil energy accounting above). The lowest are for Switzerland, Japan, Belgium, and the Netherlands.

**Carbon Dioxide Emissions per Capita**

Carbon dioxide emissions per capita are calculated as the product of Carbon Intensity of Total Primary Energy and Total Primary Energy Requirements per Capita, the results of figures 1 and 2 shown in figure 3.

In the baseline without CO₂ restrictions, CO₂ per capita would increase from 1990 to 2020 in all cases, although very little in Switzerland. Following the pattern of figure 1, maximum reduction of CO₂ from the baseline in 2020 results in proportionately large reductions in Carbon Intensity of Total Primary Energy in Ontario, Quebec, the Netherlands, and Sweden. (This is due in part to the large increases that would occur in 2020 without CO₂ reduction). Following the pattern of figure 2, Total Primary Energy Requirements per Capita with CO₂ reduction generally increase. The resulting CO₂ per Capita with maximum reduction in CO₂ by 2020, measured by the dotted diagonal grid in figure 3, is least for Sweden, Switzerland, Quebec, and the Netherlands.
Figure 3  Comparative CO₂ Emissions per Capita among Countries

With log-log grids, figure 3 compares the proportional changes from 1990 to maximum CO₂ reduction in 2020 by way of the 2020 baseline. From another perspective, the absolute changes from 1990 to the maximum reduction in 2020 are shown in Table 1.

Table 1  CO₂ Emissions per Capita

<table>
<thead>
<tr>
<th>Country</th>
<th>1990</th>
<th>Maximum Reduction in 2020</th>
<th>Difference</th>
<th>(Percent Reduction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>19.5</td>
<td>15.3</td>
<td>4.2</td>
<td>(22%)</td>
</tr>
<tr>
<td>Ontario</td>
<td>14.3</td>
<td>8.7</td>
<td>5.6</td>
<td>(39%)</td>
</tr>
<tr>
<td>Netherlands</td>
<td>10.8</td>
<td>5.1</td>
<td>5.7</td>
<td>(53%)</td>
</tr>
<tr>
<td>Belgium</td>
<td>10.5</td>
<td>5.8</td>
<td>4.7</td>
<td>(45%)</td>
</tr>
<tr>
<td>Quebec</td>
<td>9.7</td>
<td>4.9</td>
<td>4.8</td>
<td>(49%)</td>
</tr>
<tr>
<td>Japan</td>
<td>9.1</td>
<td>7.1</td>
<td>2.0</td>
<td>(22%)</td>
</tr>
<tr>
<td>Norway</td>
<td>8.3</td>
<td>7.5</td>
<td>0.8</td>
<td>(10%)</td>
</tr>
<tr>
<td>Italy</td>
<td>7.2</td>
<td>6.5</td>
<td>0.7</td>
<td>(10%)</td>
</tr>
<tr>
<td>Switzerland</td>
<td>6.4</td>
<td>4.9</td>
<td>1.5</td>
<td>(23%)</td>
</tr>
<tr>
<td>Sweden</td>
<td>6.3</td>
<td>4.6</td>
<td>1.7</td>
<td>(27%)</td>
</tr>
</tbody>
</table>

The two countries with the largest energy systems --the USA and Japan-- achieve maximum per capita reductions of carbon dioxide emissions in 2020 of about 22 percent, compared with the 1990 level. In addition to the conservation measures introduced by all countries, the reductions are achieved in the USA and Japan in part by replacing fossil fuels with nuclear or renewable energy and in part by substituting natural gas for coal and oil.
The largest percentage reductions --on the order of 40 to 50 percent-- are achieved by smaller countries that take advantage of local resources (hydroelectricity in Quebec, aquifers and depleted gas fields for the disposal of carbon dioxide in the Netherlands) or nuclear energy (Ontario) or both (aquifers and nuclear energy in Belgium).

The two countries with the lowest carbon dioxide emissions per capita in 1990 (Sweden and Switzerland) would still lead the others in 2020. Primarily by reducing the percentage of fossil fuel used, depending upon nuclear power, hydroelectricity or biomass. Norway and Italy are least able to reduce their carbon dioxide emissions. Norway because its overwhelming reliance upon hydroelectricity will be diluted by a greater need for fossil fuels for transport. Italy because nuclear and renewable resources are assumed to make small contributions only to the already modest energy consumption.

The total national CO$_2$ emissions, taking into account both the size of the population and the per capita emissions, are compared in figure 4.

![Graph comparing total CO$_2$ emissions for various countries](image)

**Figure 4** Total National CO$_2$ Emissions

If all the countries were to reduce carbon dioxide emissions to the maximum, there would be little change in their ranking by total carbon dioxide emissions. In absolute terms, even the most extreme measures taken by small countries would be dwarfed by moderate changes in the USA and, secondarily, Japan.
The Choice of Technologies

The choice of technologies is at the heart of the MARKAL modeling process. To define the evolving energy system, the model chooses from a menu of technologies those that minimize total energy system cost while meeting the projected energy demands and satisfying other constraints such as the limitation on carbon dioxide emissions. In aggregate, the choice of technologies determines the needs for primary energy sources and the use of electricity. In this section, the modeling of technologies and some results are summarized. In the following sections, the effect of the models’ choice of technologies on primary energy and electricity are described.

Among the eight countries, more than seventy types of technologies are candidates; more than thirty supply technologies and more than forty demand technologies, as listed in Appendix C.

Power and Heat Production

With carbon dioxide emission restrictions, power sources that are essentially carbon-free are preferred where they are available. Nuclear power--where it is allowed--is almost always expanded to meet CO₂ requirements. In Japan, this includes advanced reactors such as Very High Temperature Reactors and fast breeders. Hydroelectricity is developed wherever the potential exists, with CO₂ restrictions justifying higher cost development. Solar electricity (photovoltaics, solar thermal) is developed in the US even in the base case. Elsewhere, it only enters with relatively severe CO₂ restrictions when other CO₂-free options are exhausted. Other renewables--wind, geothermal, wave, etc.--are expanded to a limited extent with modest carbon dioxide reductions, and further with more stringent CO₂ constraints.

Next, combined heat-and-power generation increases with CO₂ restrictions. The tendency is toward technology with higher electricity-to-heat ratios, so that back-pressure turbines are replaced with combined cycle plants and even with fuel cells (the latter especially with hydrogen available). Combined generation of heat and power promises CO₂ reductions of 20 to 30 percent, but mismatches in supply and demand and institutional barriers limit its application. Heat pumps can be used in conjunction with combined heat-and-power plants to raise to a useful temperature the heat from some low temperature sources such as waste heat in sewage water.

Fossil power (integrated gasification with combined-cycle plants or molten carbonate fuel cells, and natural gas combined-cycle plants) with CO₂ removal are important in Belgium and the Netherlands to the extent that carbon dioxide storage is available in aquifers or depleted gas fields.

Other Supply Options

The circumstances specific to certain countries provide other options for reducing carbon dioxide emissions in the supply of energy.

Except for gas produced from organic wastes, which is a universal energy source, synthetic fuels from biomass are only competitive in the USA where the production of synthetic gaseous and liquid fuel from wood, herbaceous crops, and other sources is estimated to be relatively efficient and inexpensive.
With the most severe carbon dioxide restrictions in Japan, the Integrated Energy System is introduced. This consists of a set of interlinked conversion processes integrated with Very High Temperature Reactors to produce electricity, heat at various temperatures, hydrogen and synthetic gas and liquid fuels.

Hydrogen and methanol can be produced from coal and natural gas with the removal of some carbon. These processes are used to reduce carbon dioxide emissions in Belgium and the Netherlands to the extent that carbon dioxide storage reservoirs are available. With carbon dioxide storage capacity constrained, production of hydrogen from natural gas is preferred; the hydrogen is used for fuel cells in combined heat-and-power generation and vehicles.

As a "backstop" technology called upon only under the most severe restrictions on carbon dioxide emissions, Belgium and the Netherlands considered import hydrogen by pipeline from the Sahara where it is produced by electrolysis using photovoltaic power.

**Energy Savings in End Use**

Many end-use energy conservation options are cost-effective in the base cases, leaving limited potential for additional demand reductions with carbon dioxide restrictions.

The industrial sector is modeled by individual sectors in some countries so that alternative industrial processes can be evaluated. In others, industry is aggregated, but choices can be made among industry-wide processes such as more efficient steam boilers, furnaces and electric motors, heat pumps, waste heat recovery, and cogeneration of heat and electric power.

In the residential and commercial sectors, space heating is the largest energy demand; space cooling is important only in a few countries. Distinctions are made between new and existing buildings of different types. Energy conservation options include improved insulation, more efficient boilers and furnaces, and heat pumps. Water heating is also evaluated, considering fuel shifts and various types of heat pumps. Electric appliances and lighting are a sizeable and growing share of residential and commercial demand. Conservation opportunities are modeled by individual options or as conservation "supply curves" that yield energy savings at increasing costs.

For cars, trucks and other vehicles, autonomous efficiency improvements are assumed in most country models. In the US model, more efficient private cars running on oil products are evaluated by individual types. In Switzerland and the Netherlands, more efficient cars are cost-effective in the base case, and thus do not contribute any more with carbon dioxide reductions. Diesel cars are generally more efficient than gasoline cars, but their market share is mostly limited exogenously in the models to reflect market behavior. Modal shifts, such as from automobiles to mass transport, have not been modeled.

Some alternative transportation fuels like alcohols and hydrogen emit less carbon dioxide than oil products, depending upon the source material and the processes by which they are produced. Compressed natural gas (CNG) cars emit less carbon dioxide. Gaseous fuels for cars are inefficient and expensive and would only be justified with extreme emission restrictions.
Electric cars appear attractive, primarily for urban use, only with extreme carbon dioxide restrictions, and then only assuming that improved batteries and low carbon dioxide electricity are available.

Cost of CO₂ Emission Reduction

The monetary cost to the energy system of these comparisons have not been mentioned, but it is implicit in each case because these are least-cost solutions to the MARKAL linear program. The maximum CO₂ reduction in 2020 calculated by the MARKAL model of each country represents a configuration of its energy system that is both feasible and optimal. Feasible in the sense that the energy system could evolve in such a way, meeting all the constraints; in the model, all the numbers must add up. Optimal in the sense that no other configuration of the energy system could achieve the same reduction in CO₂ emissions at less cost.

Whether the cost is bearable is another question. Indeed, the maximum CO₂ reduction in 2020 is an extreme scenario intended to define the limits of technical feasibility.

MARKAL calculates direct costs: the capital cost of manufacturing or building each new technology, its operating and maintenance costs, and the cost of fuel consumed. The total of these direct costs of the energy system is large enough to be sometimes compared with Gross Domestic Product --a small percentage of GDP-- but it should not be confused with costs determined by changes in GDP as in the case of macroeconomic models; see also sections 1.4.3 and 3.6.3.

The direct costs can be calculated for a series of configurations of the energy system as CO₂ emissions become more severe. The increasing cost of the energy system can be shown on a graph as a function of amount of CO₂ reductions achieved. At each successive solution, MARKAL also calculates the marginal cost of CO₂ reduction.

The marginal cost is the cost of the last unit of CO₂ reduced. In an optimization model like MARKAL, it is necessarily the most expensive unit to remove. With more severe CO₂ restrictions, the marginal cost in each case becomes successively more expensive.

Figure 5 illustrates the differences in marginal cost found among the various counties. The maximum reductions of CO₂ in 2020 can be read at the end points of the curves.
The uncertainties in converting national currencies into US dollars noted above should be recalled. Nevertheless, it is clear that there are wide variations among the countries. Norway, Sweden, and Switzerland—which now emit the least CO2 per capita—would be among those suffering the highest costs in achieving a specified further reduction in CO2 emissions. Norway, indeed, can do little more than achieve stabilization at zero percent reduction. Quebec’s costs are relatively high at stabilization, but its vast hydroelectric potential would make it possible to achieve substantial CO2 reductions without a great increase in its marginal cost. The Netherlands, with the assumed availability of CO2 removal and storage options, appears able to make the greatest reductions at the least cost.

The two largest energy systems—Japan and USA—are in different halves of the distribution. Japan, we have seen in figure 1, reduces fossil energy use by increasing nuclear power even without CO2 emission restrictions. The further reductions that are possible before reaching the maximum are therefore among the lowest shown in table 1. The marginal cost of these further reductions is comparatively low.

The USA, on the other hand, would continue the high carbon intensity of its fossil fuel mix, as seen in figure 1, by exploiting its inexpensive domestic coal resources. From that baseline, the reduction in CO2 emissions before the maximum is reached is therefore among the larger differences shown in in table 1. Starting with a low cost, high CO2 emission baseline, the opportunity cost of CO2 emission reductions is therefore high.

The most cost-efficient way to allocate CO2 emission reductions among the countries is to limit their emissions at a point where their marginal costs are equal. In total, it would be more costly for one country to pay higher marginal costs to reduce CO2 emissions when lower-cost opportunities exist elsewhere. The allocation of emission restrictions on the basis of equal marginal costs is the basis for schemes to establish this allocation through tradeable
emission permits or through CO₂ or carbon taxes. To specify in this way how much emission reduction should take place in each country, however, is different from the question of how much each country should pay toward this common expense. It must be noted that establishing common basic assumptions for reduction options—in practice difficult to achieve as e.g. this study showed—is of key importance to derive marginal reduction costs that may serve as yardstick for actual strategies.

Effect of CO₂ Emission Reduction on Primary Energy Consumption

With increasingly stringent restrictions on CO₂ emissions, the countries must use less fossil fuel or switch to fuel producing less carbon dioxide. As a result, more renewable energy is developed in those places where it is available, and more nuclear power is put in service in those countries that permit it. The use of coal is substantially curtailed, usually to be replaced by natural gas. The use of oil declines but because of its essential role in transportation it is the fossil fuel least affected.

Coal
Without CO₂ restrictions, the use of coal would come to provide from 10 to 30 percent of primary energy in most countries without very substantial hydroelectric resources, and up to 45 percent in Japan. With CO₂ restrictions, the use of coal virtually ends in several countries: with CO₂ stabilization in Ontario, with CO₂ reductions in 2020-2030 of 20 to 30 percent in Sweden and Switzerland, and of 40 percent in Belgium. Even with maximum CO₂ reductions, coal continues to provide as much as 5 to 25 percent of primary energy in Japan, the Netherlands, and the USA.

That technology may salvage the use of some coal is suggested by an anomaly in the Netherlands case. The downward trend in the use of coal in 2030 is reversed with CO₂ emission reductions of 40 to 50 percent when advanced coal power plants (integrated gasification combined-cycle plants and integrated gasification molten carbonate fuel cells) are used in combination with CO₂ removal and disposal in aquifers and spent gas fields. With further CO₂ emission restrictions, however, the decrease in the use of coal resumes as coal-fired power plants are replaced with hydrogen-fueled cogeneration and photovoltaic cells.

Natural Gas
Without CO₂ emission restrictions, natural gas would provide from 10 to 35 percent of primary energy in 2020-2030 in all the countries except Sweden. Where the possibility of replacing natural gas with hydroelectric or nuclear power exists, as in Norway, Ontario, Quebec, and Switzerland, its use may decline with CO₂ emission restrictions, but it is never fully replaced. In Belgium and Sweden, the percentage of natural gas in the primary energy mix initially rises with CO₂ restrictions but declines with maximum restrictions. In Japan, the Netherlands, and the USA, more natural gas is used as CO₂ emission reductions become more stringent.
Oil
Although its share declines with more stringent CO₂ emissions in almost all places, oil continues to account for one-tenth to one-third of primary energy in all countries because it is needed for transportation.

Nuclear Energy
In the 2020-2030 time period, nuclear energy increases with more stringent CO₂ emissions to provide as much as one-tenth of primary energy in the USA, one-third in Japan, and two-thirds in Ontario, although in Ontario and the USA there would be little or no nuclear used without CO₂ restrictions. Nuclear energy continues to provide about the same share of primary energy in Belgium, Sweden, and Switzerland. It is absent or insignificant in the Netherlands, Norway, and Quebec.

Renewables
With greater CO₂ emission restrictions, renewables provide the largest share of primary energy in places with remaining hydroelectric potential: up to 50 percent in Switzerland and as much as 80-85 percent in Norway and Quebec. Up to half of Sweden’s primary energy in 2030 may come from renewables, consisting of wind, wave, and biomass. One-third of the primary energy in the USA in 2030 with maximum CO₂ reductions would come from a variety of renewables: geothermal, wind, wave, OTEC, and solar technologies. Renewables would provide no more than 15 percent of primary energy in the remaining countries although with maximum CO₂ reduction Belgian renewables would reach a level of 20 percent of primary energy by importing “CO₂-free” hydrogen produced in the Sahara using photovoltaic cells and electrolysis.

Effect of CO₂ Emission Reductions on Electricity
In most countries, electricity takes a larger share of final energy as CO₂ emission restrictions become more severe. There are often two countervailing trends. On the one hand, more efficient electric appliances reduce electricity demand. On the other, new electricity-using devices such as electric heat pumps and electric cars may be introduced. New conversion technology, such as combined heat-and-power plants and fuel cells, may make electricity less expensive to generate. The trend toward more electricity depends largely upon the primary energy sources available in the individual country.

The possibility of increasing nuclear power encourages the use of electricity in Belgium, Japan, Ontario, and to some extent in Switzerland where additional technical improvements may increase production. Similarly, the availability of additional hydroelectric resources may foster electricity use in Norway, Quebec, and Switzerland. In most countries, other renewables such as wind, wave, photovoltaic and biomass electric come into play only with extreme reductions in CO₂ emissions.

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4 In the analyses, indirect CO₂ emissions associated with producing equipment is not included. So-called Life Cycle Analysis studies of e.g. photovoltaics sometimes suggest these may be significant.
In Japan and the USA, coal would become a growing source of electricity in the absence of CO₂ constraints, but with restrictions on CO₂ emissions, coal-fired power plants are severely reduced, to the point of extinction with severe CO₂ restrictions.

A more complex pattern in the use of coal to generate electricity is seen in the Netherlands, as described above, culminating under extreme CO₂ restrictions with coal-fired power plants being replaced with hydrogen-fueled cogeneration and photovoltaic cells. The hydrogen is produced from natural gas in combination with fuel cells. With severe CO₂ restrictions, Belgium also turns to hydrogen-fueled fuel cells in the form of combined heat-and-power plants with a higher power-to-heat ratio than the gas-fired CHP plants they replace.

Only in the USA is there no increase in the share of electricity as CO₂ emissions are curtailed; with high growth electricity is even reduced a few percent. Nuclear power expands to its limit with CO₂ reductions, but no new nuclear capacity is expected to start operation before 2010, and nuclear electricity cannot exceed its present level until 2020. By 2020, the input fuel mix changes drastically even without CO₂ restrictions. Renewables increase their share fivefold, accounting for 40 to 50 percent of electric generation. With CO₂ emissions reduced, coal which would otherwise supply 90 percent of fossil-based electricity is severely reduced with natural gas becoming the dominant fossil fuel.

**Accounting of Energy Consumption**

Following conventions for OECD statistics, all nuclear, hydro and other nonfossil energy consumption is accounted as so-called Fossil Fuel Equivalents (FEQs) at the primary level. This implies that energy produced from such technologies is multiplied by a fixed conversion factor and the resulting equivalent inputs are included in total primary energy requirements (TPER).

The fixed factor for all electricity generating non-fossil technologies is the equivalent of an efficiency of 38.5%. Since this is relatively low, especially for future years, nonfossil energy resources --and thus primary energy intensities-- tend to be overestimated. In particular if nonfossil electricity production expands strongly in reduced CO₂ emission cases, the TPER may increase, see e.g. Quebec in figure 2. All TPER --and TPER related-- figures reported should thus be treated with some care in order avoid misunderstandings. In fact significant energy savings may occur at the end-use level, and losses in fossil energy conversion may be cut down without being clearly reflected in the overall TPER figures due to the accounting mechanism.

At the level of final energy delivered to end consumers, accounting problems are far less significant. Here, however, the share of electricity plays a role that should be kept in mind. Typically, electricity substituting for fuels at the end-use level can be applied at higher efficiencies. So, if one compares the final energy consumed in a CO₂ reduction case against the base case, an increased share of electricity (triggered by the availability of nonfossil electricity supply options), tends to exaggerate the role of savings. As with TPER, final energy use and related figures reported should be treated with care.
1. BACKGROUND

This report aims to provide information on and give some insight in strategies to reduce emissions of so-called Greenhouse Gases (GHG's) from energy systems. Analyses performed at the national and sub-national\(^5\) level are aggregated to obtain an overall result. Cross-country analyses are made to illustrate the similarities and differences found within in the group of OECD member states represented.

1.1 History of IEA/ETSAP

The Energy Technology Systems Analysis Programme (ETSAP) was initiated in 1976 for the purpose of providing the International Energy Agency (IEA) with systems analysis capability to assist in establishing its priorities for research, development, and demonstration projects. The project was initially staffed by systems analysts from 16 countries working in two project teams, one located at Brookhaven National Laboratory (BNL), USA, and the other at the Research Center Jülich (then Kernforschungsanlage Jülich, or KFA), Germany. The BNL group consisted of representatives from Canada, Ireland, Japan, New Zealand, Norway, Spain, Sweden, and the United States. The KFA group consisted of Austria, Belgium, Denmark, Germany, Italy, the Netherlands, Spain, Switzerland, and the United Kingdom. The Commission of the European Communities was represented at both laboratories.

In close collaboration, the two groups developed the analytical tools for evaluating energy technologies within the context of national energy systems. These consisted of compilations of data characterizing the candidate technologies, development of the MARKAL software to represent national energy systems, and formulation of the national energy system models using MARKAL. Initially, the project intended to address three objectives: energy security (represented in the models by the amount of imported energy), cost (represented by the total discounted cost of the energy systems over the period modeled), and environmental benefits. Because of wide scope of the latter, it was dropped as a major objective in the modeling work. The result of this initial work was an input to the 1980 IEA report, A Group Strategy for Energy Research, Development and Demonstration.

1.1.1 Annex I

ETSAP was formalized with the signing of an IEA implementing agreement in 1980, with KFA as operating agent. Annex I of this agreement (1980-1983) had the following main objectives:

\(^{5}\) For Canada separate analyses are made for two provinces, Quebec and Ontario. For reasons of simplicity, each of these is referred to as a "country study" like the others.
1. Increase the analytical capabilities of participating countries in the field of energy technology assessment; and

2. Maintain a multilateral capability within the IEA for energy technology systems analysis by making use of and improving the database and modeling techniques developed previously.

Subtasks defined within Annex I included:

- Analyze potential impact of energy technologies; review and expand technology characterizations; review key assumptions about world-traded fuels; review the demand projections, the underlying assumptions for economic growth and other important items

- Study the sensitivity of results to variations of these assumptions; the competitiveness of selected technologies, and analyze the robustness of different scenarios

- Investigate certain environmental questions including the requirements for labour, land, water and structural materials, and specify the inventories of selected pollutants.


### 1.1.2 Annex II

By 1983, the project consisted of a cadre of experienced energy systems analysts that bridged national boundaries. With the MARKAL model, they had a common framework for understanding and evaluating each other’s energy systems. With up to seven years of shared experience, they indeed spoke the same language.

To preserve this international resource, Annex II, an information exchange program for energy modeling, energy systems analysis, and energy technology assessment, was established. With no common project goals, the participants pursued their national interests, keeping in touch through semiannual seminars and a newsletter. The results of the national efforts during this three-year period were compiled in *International Energy Agency Energy Technology Systems Analysis Project Final Report on Annex II*, Jul-Spez-421 (Kernforschungsanlage Jülich, November 1987).

During Annex II, several of the countries began using the MARKAL model to evaluate the effect on energy choices of limiting environmental emissions. This coincided with the encouragement of the Governing Board of the IEA at the Ministerial level to promote the objectives of both energy and environmental policy. Annex II thus culminated in the formulation of Annex III, conceived as an international forum for energy and environment studies.
1.1.3 Annex III

Canada, Germany, Italy, Japan, the Netherlands, Sweden, Switzerland, the United Kingdom, the United States, and the Commission of the European Communities participated in Annex III, with BNL as operating agent, from 1986 to 1989.

The project plan for Annex III differed from earlier phases of ETSAP in concept. Unlike the initial phases of the project, the participating countries were not bound to a single work plan with identical scenarios, identical price forecasts, and identical technology descriptions. The participants' analyses were defined to serve the particular needs in the particular circumstances of each country. Unlike Annex II, however, these were framed within a common project plan with specific project objectives. The aim was to provide useful, relevant national analyses that could be integrated as aspects of a common study plan.

To promote the effective communication of its work in Annex III, ETSAP held an annual International Forum for Energy-Environment Studies in which it met jointly with another international group engaged in complementary work. In June 1987, the first such meeting was held at Brookhaven National Laboratory with the Joint IAEA/UNEP/WHO Project on Assessing and Managing Health and Environmental Risks from Energy and Other Complex Industrial Systems.

In May 1988, the second international joint meeting was held with the Acid Rain Project of the International Institute for Applied Systems Analysis. The proceedings of the meeting were published at Brookhaven National Laboratory in two volumes as *Toward Estimating National Energy Emission Control Costs*, Proceedings of a Joint Workshop held by the Energy Technology System Analysis Project and the Acid Rain Project, International Institute for Applied Systems Analysis, 23-26 May 1988, Laxenburg, Austria.


A primary purpose of Annex III was to include environmental considerations in the evaluation of energy technologies. Initially, the emphasis was on acid rain precursors, but during the three-year duration of the annex there was growing awareness of the greenhouse gas issue. By the end of the annex, several countries were closely examining the effect on their energy systems of limiting carbon dioxide emissions.

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1.2 ETSAP Annex IV

Annex IV of ETSAP was aimed at extending the application of national MARKAL models to emission control of greenhouse gases. It includes steps to widen the circle of MARKAL users to non-IEA countries making use of the new generation of personal computers.

The specific objectives of Annex IV were:

- **Analysis of national energy systems.** To identify the most cost-effective blends of technological options to reduce national or regional emissions of greenhouse gases and secure other energy and environmental objectives, including energy security.

- **Examination of global consequences.** To understand and explain any differences among national results, and to integrate - or collaborate in the integration of - the results of national energy models in the context of global climatic change in order to better inform national and inter-governmental analysis of policies to reduce the emission of greenhouse gases.

- **Outreach.** To design and effect processes to reach out beyond the current ETSAP membership to relevant energy-environment actors in other countries, and to share MARKAL as an analytical tool that will allow a broad range of countries to bring consistent and compatible analyses of national energy systems to various international fora.

With Annex IV ETSAP continues to provide a valuable - possibly unique - international forum for cooperative and collaborative modeling efforts to promote energy security objectives and a healthy environment. The ETSAP participants comprise a cadre of experienced energy systems analysts that is capable of being expanded into a wider international collaborative program.

1.2.1 National Studies

Analyses are conducted to address the particular energy systems and circumstances in each country, mostly using the MARKAL model. These analyses are coordinated, interpreted, and compared at semiannual workshops. This international collaboration achieves not merely peer review but a constructive sharing of methodology and data that builds on the group’s common background.

The results of the common set of standardized national studies are summarized in Appendix B, Summary Country Reports. The concerns of the individual countries, the diversity in their energy systems, their abilities to respond to a need to reduce greenhouse gas emissions, and related work is suggested here by a brief comparison.

**Belgium**

After an absence of some years from ETSAP, Belgium rejoined the project for Annex IV. The Belgian team elected to develop an all-new MARKAL model to address the issue of carbon dioxide emission reduction, also taking into account emissions of sulphur dioxide and nitrogen oxides. CO₂ emission
reduction by 2030 of as much as 60 percent from the 1990 level is found feasible by the model.

Although Belgium has an unusually high percentage of its electricity generated with nuclear power—over 60 percent—it ranks high in the amount of CO₂ produced per unit of primary energy. The value of MARKAL is seen in Belgium to be its consistency in treating technology-related problems in the energy-environment domain. The initial insights into energy policy formulation provided by MARKAL and the guidelines it provides for technology policy will be used with complementary studies in both fields.

Canada
The two Canadian provinces of Ontario and Quebec, with quite different energy and industrial systems, are modeled separately. By exploiting its vast hydroelectric potential, Quebec could reduce its CO₂ emissions by the year 2020 by half. Ontario, with a larger economy and a higher expected growth rate, could achieve about a one-third reduction in part by expanding its CANDU nuclear capacity. Both provinces would gain by the export of Quebec electricity to Ontario. The Canadian studies also examined the implications of limiting the growth of hydroelectric and nuclear power in the two provinces.

Germany
During Annex IV, Germany furthered its outreach program with Indonesia, as reported in Section 1.2.3.

Italy
In an initial evaluation of CO₂ emissions from the Italian energy system, MARKAL was extended to incorporate an input-output model of the national economy, as described in Section 1.4.3. In addition, a database is being developed for CO₂ emissions from the Italian transportation sector that recognizes the effect of traffic congestion as well as vehicle technology. A preliminary analysis of technological options has been made for mitigating greenhouse gas emissions from Italian industry, including iron and steel, cement and bricks, glass and tiles, paper, oil refineries, chemicals, and textiles.

Japan
The official Japanese action program on CO₂ emission reduction aims at stabilizing emissions per capita at the 1990 level by 2000 with subsequent reductions anticipated from further technology improvements. Results of MARKAL runs support the feasibility of the program and estimate the potential improvements due to energy conservation, technology substitution, fuel switching, and substitution of fossil fuels with nuclear and renewable energy. CO₂ emission reduction as much as 35 percent from the 1990 level is feasible in 2030 in the model.

Japan projects the highest economic growth rate of the countries in the study, and the only levelling (about 2010) and subsequent decline in population. Japan would substantially reduce its CO₂ emissions per unit of total primary energy by 2030 even without further emission restrictions, largely because nuclear energy would increase from 10 to 24 percent of primary energy.

Two shock scenarios were examined for Japan: a nuclear moratorium and a sharp increase in the price of LNG. With a nuclear moratorium, nuclear
power would be replaced by more natural gas and oil, increasing its CO₂ emissions in 2030 by 85 percent with the same carbon taxes imposed. With a doubling of the LNG price in 2030, the levelized cost of CO₂ reduction would increase by one-third.

Japan also examined a number of sensitivity cases, among them a modal shift toward more rail and bus transportation. This would result in a decline in the need for transportation fuel, especially for gasoline and diesel oil which would be replaced primarily by compressed natural gas (CNG) and electricity. CO₂ emissions would be reduced by about one-third with the same carbon taxes.

The future radiative forcing by greenhouse gase was estimated, based on the scenarios of CO₂ emission reduction and assumptions on future emissions of other greenhouse gases. The results indicated increasing contribution of CO₂ in the long run, suggesting the importance of CO₂ emission reduction in order to reduce total radiative forcing.

In addition, Japan developed the macro economy model MACROEM to be coupled with MARKAL; see also section 1.4.3. The preliminary studies evaluated the effects of a carbon tax separated into those through macroeconomic cycles and technology changes. According to the results, the former effect increases through 2005, but is stable after 2010. The latter effect is comparable until 2010, but further increases thereafter.

**The Netherlands**

In addition to serving as project manager, the Netherlands has supplemented its MARKAL analysis for the Annex IV scenarios with numerous related studies. A few examples are cited here.

The Netherlands has developed its indigenous natural gas resources including large deposits in the North Sea. In the absence of nuclear power, natural gas will be the major element in the Netherlands response to more stringent greenhouse gas restrictions. These fields may foster the use of natural gas in the Netherlands even after they are depleted. The Netherlands will then have the option of removing carbon dioxide from waste streams and disposing of it in nearby depleted gas fields as well as in aquifers. Accordingly, technologies for capturing CO₂ emissions and disposing of them have been characterized. In several scenarios with stringent CO₂ emission reductions, CO₂ removal and disposal is among the needed measures.

With a major petrochemical industry, the Netherlands developed a method for more precise national accounting of CO₂ emissions taking into consideration non-energy use of fossil fuels. The procedure separates from actual emissions the flows of potential emissions and the recycling and sequestering of manufactured products containing carbon.

The Netherlands also has an intensively farmed agricultural sector. MARKAL has been used to find a role for energy crops in the Dutch energy system with more stringent CO₂ emission constraints. Poplar and then miscanthus burned for heat and electricity production become competitive with other fuels. With even greater CO₂ restrictions, biodiesel fuel from rapeseed and ethanol from sugar beets become competitive.
The global warming potentials of greenhouse gases were calculated and compared taking into account their radiative properties, residence times in the atmosphere, atmospheric concentration, interactions with each other, their progeny resulting from chemical reactions, and ambient atmospheric conditions. Uncertainties in these factors compound the difficulties of comparing greenhouse gases. For analysis of emission controls that affect more than one greenhouse gas, however, estimates must be made of the comparative warming potential of each gas. Figure 1.1 shows the relative importance of several greenhouse gases according to the time horizon considered.

![Graph showing relative importance of greenhouse gases](image)

**Figure 1.1** The relative importance of gases in global warming depends upon the time horizon considered.

**Norway**

Norway was among the group of countries that originally developed MARKAL in the late 1970s and early 1980s. When Norway rejoined ETSAP for Annex IV in 1990, it was decided to develop a new MARKAL model using the personal computer system to evaluate greenhouse gas emissions.

Norway is blessed with energy resources that would be much needed in restricting CO₂ emissions: major offshore natural gas reserves, hydroelectric power, and even a windy coastline. Its offshore oil production in 1990 was twelve times its domestic consumption. A methanol production plant using natural gas as a feedstock and process fuel will start up in 1996. Norway now emits less CO₂ per unit of primary energy than any of the other seven countries reported here. However, with no reduction options in the electricity sector (100% hydropower), electricity already serving large share of heating markets, and with a high expected growth in transportation, further reductions in CO₂ emissions will be more expensive for Norway than for any other country.
Sweden
In Sweden, carbon dioxide emissions declined by more than one-third in the 1980s. This was due to the introduction of nuclear power, which now provides half of Sweden's electricity, the use of biomass in the forestry and pulp and paper industries, and energy planning even on the community level that has encouraged aggressive energy conservation. As a result, Sweden has the lowest level of CO₂ emissions per capita of the eight countries reported here.

As a result of a 1980 referendum, it is current Swedish policy to phase out nuclear power by 2010 beginning in 1995. The Swedish Parliament in 1988 adopted the additional policy of stabilizing national emissions of CO₂ at 1988 levels. Under the circumstances, the issue of phasing out nuclear power is being reexamined.

Swedish national studies using MARKAL indicate that the expected level of economic growth is an important factor in its energy planning. With relatively modest growth, phasing out nuclear power would be more expensive than introducing further restrictions on CO₂ emissions. With higher economic growth and the planning period extended to the point where existing nuclear power plants are replaced, however, the comparison is less clear. Higher economic growth is in any event incompatible with both CO₂ emission reductions and a nuclear phase-out.

Switzerland
Like Norway and Sweden, the example of Switzerland raises the question of how closely each individual country can be expected to comply with international targets for global reductions in greenhouse gases. Using very little coal, with virtually all of its electricity generated by hydroelectric and nuclear plants, Switzerland is now second lowest of the eight countries reported in CO₂ emissions per capita. Switzerland will therefore find further reductions in carbon dioxide emissions very expensive.

Switzerland can best contribute to the goal of reducing global warming if it is also credited with reductions in CFCs and other greenhouse gases, according to its national studies. At a marginal cost of 150 SFr per ton of carbon dioxide equivalent, the major greenhouse gases could be reduced by about 30 percent of the 1990 level. As shown in figure 1.2., only 25 percent of this reduction would be due to carbon dioxide at this marginal cost. CFCs contribute 56 percent of the total, nitrogen oxides and non-methane hydrocarbons (NMHCs) 13 percent, and the remaining 6 percent is due to methane and nitrous oxide.
Switzerland has also supported research into appropriate algorithmic tools to couple MARKAL models to coordinate energy planning policies of several neighbouring countries under a joint constraint on total emissions of pollutants over a period of time. The work furthers the approach of decomposing the problem using the multiregional block structure. The result would be a global optimal allocation of resources which also provides insight into transfer costs between countries to achieve greater equity.

**United Kingdom**
During Annex IV, the United Kingdom undertook a reappraisal of all prospective energy technologies to be used in its evaluations. A system of quality control was set up for the MARKAL input. The result will be a larger, more detailed, and more thoroughly validated MARKAL model of the UK energy system. The work was not completed in time to contribute to the common set of standard country analyses.

The UK also participated in the Crash Programme of the Commission of the European Community described below.

**United States**
Annex IV saw the reincarnation of the MARKAL model of the USA in the form of PC-MARKAL/MUSS, the personal computer version with a highly automated user support system described in Appendix A.3. One of its first applications was a least-cost energy analysis of U.S. CO₂ reduction options prepared for the U.S. Environmental Protection Agency. The analysis concluded that major changes in the energy system would be required to achieve significant CO₂ reductions. Change of this magnitude would stretch the limits of existing energy and economic analysis tools. Recognizing this, the U.S. Department of Energy sponsored the development of MARKAL-MACRO, a "hard-linked" coupling of MARKAL with MACRO, a long-term neoclassical macroeconomic growth model, described in Section 1.4.3.
The new MARKAL was also used to model the energy system of New York State which was found to be less flexible than the rest of the U.S. in its ability to reduce emissions of carbon dioxide. New York has fewer options, and it is now less dependent upon coal the replacement of which produces the largest CO₂ reductions. To reduce its CO₂ emissions by 20 percent by the year 2005, New York would require extraordinary measures: further, very expensive energy conservation, a return to nuclear power, or substantial imports of hydropower from neighbouring Quebec.

The U.S. MARKAL model was also used to evaluate a variety of technologies for removing and disposing of CO₂.

**Commission of the European Community**

During Annex IV, the Commission of the European Community (CEC) conducted its Crush Programme to identify cost-efficient options for CO₂ emission control using a suite of mathematical models centred on EFOM-ENV, a bottom-up model similar to MARKAL. This was complemented with evaluation of the macroeconomic effects of energy taxes using the HERMES and MIDAS models which take a top-down approach. The modeling studies were carried out by a network of economists and engineers from all European Community (EC) countries in a framework established by Directorate-General XII of the CEC.

From its technological and economic research, the CEC concluded that CO₂ emissions from the EC countries can be stabilized by the year 2000. A strategy of fiscal, regulatory, and voluntary steps to accomplish this was subsequently presented by the CEC to the European Council of Ministers.

Two main patterns emerged from the calculation of the costs of reducing CO₂ emissions in ten EC countries. For Denmark, France, Germany, and the United Kingdom, additional CO₂ reductions of 5 percent can be achieved at almost no additional cost. Cost then increases gradually with additional CO₂ reductions. For Greece, Italy, the Netherlands, and Spain, the cost increase is quite sharp beginning with the least reductions in CO₂ emissions. Belgium lies between the two groups. The results diverge considerably from findings for some European countries also participating in ETSAP/Annex IV (e.g. low reduction costs for the Netherlands). Main causes are the time frame, ETSAP looking ahead to 2020 instead of 2005, and the extent to which structural changes and prospective technical options are assumed to contribute.

The tax model studies concluded that a carbon tax is more efficient than an energy tax in reducing carbon dioxide emissions, but that there would not be a substantial difference in their effects before 2000. Also, that a tax to reduce CO₂ emissions would not have macroeconomic impacts if it is revenue-neutral.

### 1.2.2 Common Program of Work

To understand and explain differences among national results and to integrate the results of national energy models, the results of common scenarios were prepared by eight of the participating countries: Belgium, Canada, Japan, the Netherlands, Norway, Sweden, Switzerland, and the United States. The results of the common country reports are summarized in Appendix B.
To assure comparability in the results, the Operating Agent provided guidelines related to:

- General scenario assumptions (GDP, energy intensity, energy prices, discount rate)
- Selection of scenarios and cases, including naming conventions
- Technologies and options to be considered, including "backstopping" and CO₂ removal

**General Scenario Assumptions**

_Economic Growth._ Two ranges of annual increases in Gross Domestic Product (GDP) were specified both for high and low economic growth, the precise ranges varying somewhat according to geographic area:

<table>
<thead>
<tr>
<th>GDP Growth [%/year]</th>
<th>HIGH</th>
<th>LOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>OECD-Europe / EC-12</td>
<td>2.2-2.8</td>
<td>1.4-1.8</td>
</tr>
<tr>
<td>OECD-North America</td>
<td>2.0-2.7</td>
<td>1.2-1.7</td>
</tr>
<tr>
<td>OECD-Pacific</td>
<td>2.5-3.5</td>
<td>1.6-2.2</td>
</tr>
</tbody>
</table>

If only one projection is analyzed, participants were to indicate if this coincides with the High or Low ranges, or somewhere in between: a medium or central growth case.

_Energy Intensity._ The decline in energy intensity, defined as primary energy per unit GDP, in the baseline case without greenhouse gas reductions was to be within the following guidelines:

<table>
<thead>
<tr>
<th>Energy Intensity [%/year]</th>
<th>HIGH</th>
<th>LOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>OECD-Europe / EC-12</td>
<td>-1.8</td>
<td>-1.0</td>
</tr>
<tr>
<td>OECD-North America</td>
<td>-1.5</td>
<td>-0.8</td>
</tr>
<tr>
<td>OECD-Pacific</td>
<td>-2.0</td>
<td>-1.0</td>
</tr>
</tbody>
</table>

Total primary energy figures depend upon conventions used to calculate the contribution of nuclear and renewable energy sources. The use of fossil-fuel equivalents was recommended to indicate the amount of fossil energy saved by the introduction of nonfossil options. For electricity production, the International Energy Agency statistics use 2.5974 (average efficiency 38.5 percent) for all countries except Norway which is 1.7452 (57.3 percent efficiency).
Energy Prices. In order to maintain consistency among the national analyses, energy price projections were to fall within the following ranges:

<table>
<thead>
<tr>
<th>Energy Prices</th>
<th>2000</th>
<th>2010</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil [US$/bbl]</td>
<td>22-28</td>
<td>25-35</td>
<td>30-45</td>
</tr>
<tr>
<td>Coal [US$/t]</td>
<td>43-50</td>
<td>50-60</td>
<td>55-70</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>Oil Product Parity Price (HFO/LDO)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. Low-High Price Range; c.i.f. Europe
2. Metric tonne; as received
3. HFO = Heavy Fuel Oil (for heavy industry, power plants, etc.)
   LDO = Light Distillate Oil (for residential, commercial, etc.)

Discount Rate. The discount rate is to be in the medium range of about 5 percent (not exceeding 7 percent) to reflect real interest rates.

Scenarios and Cases
Participants were requested to calculate the following cases to the extent that they proved feasible:

1. Baseline, or reference case, with no CO₂ restrictions
2. Stabilization case (holding total national CO₂ emissions constant
3. 20% CO₂ reduction by 2005, followed by stable emissions at that level
4. 20% CO₂ reduction by 2005, 40% by 2030 (linear decrease)
5. 20% CO₂ reductions by 2005, 60% by 2030 (linear decrease)
6-10. Taxes on CO₂ emissions as appropriate for the individual country; e.g. 10, 50, 150, 500 and 1000 US$/tonne of CO₂.

It was suggested that 1990 be the starting year for the calculations, 1988 or 1990 the common reference year for measuring CO₂ emissions, and 1995 the year in which emission constraints or emission taxes could start to be implemented.

Technologies and Options
A "shopping list" of options to reduce CO₂ emissions was provided as itemized in Appendix C.

Energy-saving demand technologies could be explicitly modeled, such as those in Section C.1, or could be assumed as autonomous and/or cost-effective energy conservation options. The latter could be either included in the useful demand projections, or represented by increasing efficiencies over time.
1.2.3 Outreach Program

Annex IV made a beginning toward a program to reach out beyond the current ETSAP membership to other countries and to share MARKAL as an analytical tool that will allow a broad range of countries to bring consistent and compatible analyses of national energy systems to various international fora.

India, Poland, and South Africa were represented at various ETSAP workshops. ETSAP provided a training course in China. Several bilateral contacts were made, including those between Canada and Tunisia and Colombia, the Netherlands and India, the U.S. and South Korea, and several countries and China. Germany completed the second phase of a joint Indonesian-German research program.

ETSAP Training Course in China

A training course on the MARKAL and MUSS software was conducted in Beijing, China, in December 1991. The response was enthusiastic, and steps are being taken to assist the host organization, the China Institute of Nuclear Industry Economics (CINIE), to develop a MARKAL model of the Chinese energy system. The training course was ETSAP's first cooperative outreach program.

Following earlier contacts between the Japan Atomic Energy Research Institute and CINIE, ETSAP was invited to China to lecture on MARKAL. PC-MARKAL and the MARKAL User's Support System (MUSS) were used to explain and demonstrate the basics of the model, software and database.

Fourteen people participated in the three-day course. These included high-ranking officials as well as professional staff members of CINIE and a representative of the China Energy Research Institute.

To provide hands-on training, MUSS was installed on three CINIE computers, together with a local network and a laser printer, and the two portable personal computers brought along.

The course started with a half-day lecture, introducing ETSAP and MARKAL, the scope, basic principles and features of the model, and some examples of recent energy-environmental analyses. Emphasis then shifted to the basic concepts of MARKAL and the OMNI language, introducing the CLASS and TABLE structure of OMNI and the primary classes and tables of MARKAL.

At the concluding session, a number of possible follow-up activities to ensure the establishment of a fully equipped MARKAL team at CINIE were identified:

- Efforts to retrieve the data dictionary for Guangdong province generated several years ago in a cooperative project with Research Center Jülich, Germany.
- Six-month visits by CINIE staff at Brookhaven National Laboratory, USA, and ESC/ECN, the Netherlands, arranged through fellowships granted by the International Atomic Energy Agency.
The need for an expert group, similar to the National Reference Groups in ETSAP countries, was recognized. Initially, the group would concentrate on establishing input data, possibly to be reviewed by ETSAP participants.

ETSAP participants will also be asked to help review and comment on results from preliminary MARKAL runs.

Differences between western OECD economies and new MARKAL applications to LDCs and a centrally planned economy in a more or less advanced stage of transition deserve more attention, particularly with regard to the role of subsidies, and pricing principles such as efficiency prices vs. market prices.

**Joint Indonesia-Germany Research Project**

During Annex IV, the Research Center Jülich, Germany, resumed its outreach program with Indonesia. A second phase of a joint Indonesian-German research project evaluated the effects of reducing environmental emissions from the Indonesian energy system. The Indonesian MARKAL model developed in the first phase was used with a set of other models supported by field measurements to project pollutant depositions on the island of Java and its surroundings.

The work involved a group of sixteen Indonesian ministries, departments, and agencies, whose participation generated data and led to broad acceptance of its results.

The burgeoning population and economy of Indonesia will have severe environmental consequences, according to the study. Emissions of particulate matter and nitrogen oxides pose a growing threat to the environment and human health. With its oil reserves running out, Indonesia is likely to turn to its low-sulphur coal to generate most electricity. Liquefied natural gas (LNG) exports are expected to continue despite increased domestic use of natural gas.

The existing geographical patterns of deposition of nitrogen dioxide and particulate matter and those projected for 2021 were shown on computer-generated maps. A frightening finding was that emission reduction measures will be largely undermined by economic and population growth. Pollution levels on Java will increase even with strict German emission regulations on industry and U.S. regulations for automobiles. Primarily due to the increase in coal use, carbon dioxide emissions will increase by seven times from today’s levels by 2021.

**Canadian Outreach Program to Tunisia**

A MARKAL model of Tunisia was developed during 1991-1992 in a collaborative project between the Tunisia Energy Agency (AME) and the Groupe d’études et de recherche en analyse des décisions (GERAD) of Quebec, Canada. Tunisia is the first of the French-speaking developing countries to use MARKAL in its energy planning.

The project extended over a period of 16 months. Initially, four members of AME spend three weeks at GERAD to receive basic training in linear programming and MARKAL equations, applications, and database construction. Members of GERAD later visited AME to review progress in setting up the...
Tunisian data base. The first runs of MARKAL-Tunisia were made by AME staff members at GERAD using GERAD’s PC-MARKAL. Finally, GERAD staff went to AME to fine-tune the Tunisian model, make final runs, write a report, and make a presentation to Tunisian energy officials.

1.3 Energy and the Greenhouse Issue

The earth’s mean temperature is the result of incoming solar radiation and longer wavelength heat loss to the outer space. Not all radiation in either direction can pass unhindered through the earth’s atmosphere. Part of the solar radiation is reflected or scattered and part of the outgoing heat radiation is reflected and absorbed. In these processes water vapour (H₂O) plays an important role, a phenomena well known through less nighttime cooling under a clouded sky than under a bright sky. Besides water vapour, a range of other atmospheric gases are involved, that let the through the sun light, but absorb the outgoing heat radiation. This phenomenon closely resembles the function of glass sheets covering greenhouses in horticulture, the reason why these substances are called greenhouse gases (GHGs). They include carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), halocarbons (CFCs, HCFCs, etc.) and ozone (O₃). In fact, the presence of H₂O and GHGs in the atmosphere makes the mean surface temperature to be currently at 15°C, rather than at the -19°C level that would result if there were no atmosphere at all. This global warming effect is thus a crucial factor in making the earth fit for habitation by the various life forms known today or in the past.

Considerable variations in the mean temperature and in the concentration of the various greenhouse gases have occurred over the history of the earth, e.g. associated with the periodic ice-ages between 10,000 and 100,000 years ago. Large uncertainties still surround the scientific explanations for this behaviour.

Nonetheless, rapidly expanding human activities boost the emission of various greenhouse gases (e.g. CO₂ from fossil fuels burning and deforestation, or CH₄ from rice paddies and from fossil fuel mining, transport and use). This has raised concern over the possibility of climatic change resulting from human induced rises in atmospheric concentrations of GHGs. The potential enhanced, anthropogenic, warming effect is commonly referred to as the Greenhouse Issue. Assessments of the relationships between human activities and GHG concentrations, the nature and magnitude of climatic changes resulting thereof, and their impact on such crucial issues as sea level rise, precipitation patterns, biodiversity, etc. still leave many questions unanswered. Most authoritative studies are those made by the Intergovernmental Panel on Climate Change (IPCC). Adopting IPCC estimates for the equivalent warming effect of man-made emissions in 1990, CO₂ is the most important contributor to enhanced global warming, see figure 1.3. Other estimates may show different breakdowns, but CO₂ emissions consistently outshine other GHGs as driving force behind enhanced global warming.
Figure 1.3 *Role of CO₂ in Enhanced Global Warming from 1990 Emissions*

Various human activities result in CO₂ emissions, from which burning of fossil fuels for energy purposes takes the lion’s share, see figure 1.4. It must be noted that estimates of deforestation related emissions show a wide range, but always come out far less than the well known energy related release.

Figure 1.4 *Sources of Global CO₂ Emissions*
The western industrialized countries currently are the main consumers of fossil fuels, followed by the former centrally planned economies (CPE's), whereas deforestation is concentrated in developing countries (LDC's). As a result, more than half of all CO₂ emissions take place in OECD countries (see figure 1.5), where fossil fuels account for almost all CO₂ released to the atmosphere.

In summary, CO₂ is considered the main contributor to enhanced global warming and fossil fuels burning the main source of man-made CO₂ emissions. Today, the larger part of energy related CO₂ is emitted by western, industrialized economies. Sources outside the energy system play an important, yet uncertain, role in emissions of other, non-CO₂, GHGs and both effects and abatement options are comparatively unknown. Assessments of options to reduce greenhouse gas emissions from energy systems, in particular in industrialized countries, therefore focus on CO₂.

![Figure 1.5 Role of the OECD in Global CO₂ Emissions](image)

REFERENCES

*Climate Change, The IPCC Scientific Assessment*, Intergovernmental Panel on Climate Change, Cambridge University Press, 1990


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1.4 Methodology and Approach

1.4.1 Bottom-Up vs. Top-Down

Models to evaluate the measures that can be taken to reduce CO₂ emissions from the energy system can take a number of forms, often including the economic system in which energy choices are made. Essentially, these can be classified as either bottom-up engineering models or top-down macroeconomic models.

Bottom-up models take a disaggregate approach to modeling energy supply and demand, considering many individual alternatives and their costs. MARKAL is an example of a bottom-up model. Top-down analysis takes a macroeconomic approach to modeling energy-economy interactions and the costs of changing them. MARKAL has been coupled with macroeconomic models in Italy, Japan, and the USA. MARKAL has been "hard-linked" only to MACRO, a long-term neoclassical macroeconomic growth model.

**Top-down**

Top-down modellers use macroeconomic modeling techniques to predict future market behaviour based on information characterizing historical energy-economy interactions. Their models describe, by design, a behaviorally, institutionally and technologically fixed world.

Typically, nonprice-induced energy intensity reductions (AEEI) and the price elasticity of substitution (ESUB) determine top-down forecasts of future energy demand and the cost of changing it. The AEEI and ESUB parameters are used to describe complex behaviour through which actors in the economy have substituted energy, capital (such as investments in energy efficiency) and labour historically and to project such behaviour on to future economic activity. Top-down modellers assume that the relationships between the phenomena of economic behaviour that these parameters represent are fixed -- even if they are not known precisely -- and can be modeled with constant values. In top-down models, energy consumption responds exclusively to price, following the ratios of historical economic indicators.

Top-down models were designed to describe market responses to changing prices at given levels of growth in Gross Domestic Product (GDP). They ask what the relationship is between prices and demand. Applied to the greenhouse problem, they ask the question: How much would price have to change to achieve the desired market response?

**Bottom-up**

Bottom-up models use quantitative data to describe past and present stocks of technologies used for harnessing energy resources and converting them to desired services, such as comfort and mobility, and alternative technologies that can provide the same services using less energy. They observe that the existing stock of energy technologies must be replaced over time as the useful life of each individual component is reached, and propose that more cost-effective technologies be adopted as these replacement investments become necessary. They describe the impacts of such alternative investments on energy supply and demands by developing scenarios that describe possible or potential futures.
The most important assumptions in bottom-up models are the costs, energy consumption and useful lifetimes of technologies currently in use and their alternatives, fuel costs, and the potential rates and limits of alternative technology penetration. The models are designed to identify the opportunities presented by a changeable world. In addition to identifying potentials, bottom-up analysis describes market limitations and barriers, such as equipment turnover rates and capital requirements which may constrain parameter input values.

Bottom-up models focus on the demand for energy services which can be satisfied through an integrated supply and demand approach to energy planning. Bottom-up models aim at a solution: usually the least-cost strategy for providing specified energy services. Applied to the greenhouse problem, they ask the question: How much will it cost to reduce greenhouse gas emissions?

The results reported in this study depend entirely upon the bottom-up model, MARKAL, which is described in detail in Section 1.4.2 and Appendix A.

REFERENCES


1.4.2 The MARKAL Model

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

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

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

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

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

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

- the necessity to satisfy final demands
- the limited availability of primary resources
- the obligation to balance supply and demand for intermediate resources
- the necessity to install sufficient capacity to be able to operate at a desired level
- the capacity accumulation process, through investment, retention, and then phasing out of residual capacity
- the input-output interaction between a set of activities
- other types of constraints, such as upper bounds on market penetration and allowable emissions.
Formulating a MARKAL Model
MARKAL can thus be considered a "model construction kit" for formulating national (or subnational) models.

To build a model, the following data are required:

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

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

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

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

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

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

The values of these variables are determined by the linear programming solution.
Constraints
A MARKAL model is composed of a set of logical relationships that tie together the variables. These relationships are called the constraints of the model. The principal constraints are:

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

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

MARKAL Outputs
MARKAL produces the following outputs for each time period:

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

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

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

Scenario Analysis
An intelligent use of the model consists in running several scenarios carefully constructed by the user in order to conduct an analysis of the differences as well as the similarities of the corresponding MARKAL results. This can reveal those parts of the energy system that are sensitive to the assumptions made in the various scenarios.
By varying some of these parameters the analyst can evaluate the potential impact of a large variety of possible perturbations of the system (e.g., a change in the price of an imported primary resource like oil, a change in the date of availability of a new technology, or a change in annual allowable emissions).

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

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

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

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

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

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

It is advantageous to study energy systems at the national rather than supranational level. Among nations, there are different and independent decision makers, different demands, different regulations, different technical options.
However, it is also advantageous to use the same model formulation for different countries. The common rationale and methodology facilitate comparisons and understanding. In many cases, common data such as technology characteristics and international market prices can be used. Addressing the global climate issue, comparable national models should become particularly valuable in evaluating the national consequences of possible international agreements.

1.4.3 Linking with Economic Models

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

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

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

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

MARKAL-MACRO

In an experiment, MARKAL-MACRO was developed by the USA in Annex IV to be the prototype of a new tool for energy-economic analysis. A simplified version of the MARKAL model of the United States energy system was "hard-linked" to MACRO, a long-term neoclassical macroeconomic growth model. The combined model estimates the costs and evaluates technologies for reducing environmental risks such as regional air pollution and global climate change.
The linkage between MARKAL and MACRO is based upon one key idea: the concept of an economy-wide production function. Just as with any other attempt at understanding the complexities of an economic system, there are pros and cons in adopting this particular abstraction. The principal advantage is that this enables us to make a direct link between a physical process analysis and a standard long-term macroeconomic growth model. The principal disadvantage is that we cannot make a direct connection with the interindustry composition of demands, described, for example, by two-digit Standard Industrial Classification codes.

Both MARKAL and MACRO are solved under the assumption that there is perfect foresight with respect to changing technologies and economic conditions, and both are based on the concept of a single representative producer-consumer. Certain differences in the model formulations had to be reconciled, however; for example, the manner in which the remaining value of capital in the final time period is computed. MARKAL minimizes total discounted system cost of the energy system alone, whereas MARKAL-MACRO maximizes the present value of the utility of consumption.

To marry MARKAL to MACRO, the Brookhaven model of the USA was simplified, reducing the menu of candidate energy technologies by half and replacing nine 5-year time periods with four 10-year time periods.

**Determining Energy Demands**

Whereas a set of projected energy demands are specified exogenously in the stand-alone MARKAL, energy demands in the integrated MARKAL-MACRO model are generated in response to the evolution of energy prices in the context of the economic system. Energy demands are generated at the interface between the two submodels. The linkage is shown in figure 1.6. There are flows of energy ("useful energy demand") from MARKAL into MACRO, and there are interindustry energy cost payments from MACRO into MARKAL.

The relationship of the ratio of energy demands in successive time periods to that of successive shadow prices can be described by a power function that stems from MACRO. The coefficient of the power function is determined primarily by aggregate economic growth rate. If energy prices remained constant, the coefficient would simply equal the ratio of successive energy demands. However, it is modified by an exponential term, the ratio of successive shadow prices raised to a power. The exponent is determined by the elasticity of substitution between the energy and capital-labour aggregates in MACRO. Thus separated into two terms, the effects of economic growth and energy prices can be distinguished.
Figure 1.6 *Linkage of MARKAL and MACRO.*

The cost coefficients are recalculated and used to link the MARKAL variables to the MACRO energy demands. Similarly, the supply coefficients link the MARKAL variables to the MACRO useful energy demands. Quadratic penalty terms are introduced to smooth the rate of market penetration of new technologies. The remainder of the constraint rows are taken over directly from MARKAL.

**Energy Conservation**

In the combined model, it is necessary to disentangle the treatments of energy conservation, defined in this case as those measures that reduce the total amount of final energy used to satisfy a given type of demand.

MACRO handles conservation from a bird’s eye perspective through the macroeconomic production function. There is no technological detail. Inputs to the MACRO production function consist of capital, labour, and useful energy demands, each of which may be substituted for the others but with diminishing returns in the substitution process. In this way, MACRO incorporates price-induced energy conservation. In addition, there is the possibility for autonomous energy efficiency improvements (AEEI, for short): nonprice factors that reduce energy demands per unit of gross output with the passage of time.

The USA MARKAL database includes both autonomous conservation and specific technical options for price-induced conservation. MARKAL does not treat conservation in a comprehensive way, but the database can be very detailed for specific categories of demand.

The problem is how to salvage the engineering information from MARKAL for the linked model. No option should be overlooked, but double-counting in which the same option is used both in MARKAL and in MACRO must be avoided.
Data Requirements
The MACRO submodel requires only modest amounts of data in addition to those that are normally required for MARKAL. Whereas the MARKAL model of the USA contains about 30,000 pieces of data to describe potential energy systems, MACRO uses only about 30 to describe the economic system. The additional data requirements are as follows: base year GDP, potential GDP growth rates, initial capital-output ratio, aggregate depreciation rate, and the elasticity of substitution between capital-labour and useful energy demands.

The latter may be viewed as the elasticity of price-induced energy conservation. If energy prices rise, there will be more energy conservation to a degree measured by this elasticity. In the Leontief input-output model, elasticity is assumed to be zero, which is too pessimistic. In the Cobb-Douglas production function sometimes used in economic models, it is assumed to be one, which is too optimistic. In MACRO for the USA, it is assumed to 0.5.

A Test Run of MARKAL-MACRO
Using MARKAL-MACRO to test the conventional wisdom that a cost deferred is preferred to a cost incurred, it was found that carbon dioxide emission controls - if they are inevitable - should be imposed gradually rather than abruptly. If superior control technologies can be developed in time, emission controls can be delayed.

The model was used to evaluate a policy in which carbon dioxide emissions from the U.S. energy system are reduced by 20 percent from the 1990 level beginning in 2010. In a second model run, the 20 percent reduction was delayed until 2030, but the total amount of carbon dioxide emissions during the 1990-2030 time period was not allowed to increase from that in the first run. The resulting trajectory of CO₂ emissions is shown in figure 1.7.

It proved to be preferable to begin reducing emissions in 1995. The price of meeting useful energy demands increases over time as energy demands climb. The price rise is accentuated by abrupt constraints on carbon dioxide emissions. MARKAL-MACRO finds that a smoother transition is better.

Restrictions on carbon dioxide emissions gradually reduce Gross Domestic Product up to about two percent in 2030. This in turn reduces the demand for energy. As a result, there is a 20 percent reduction in carbon dioxide emissions with MARKAL-MACRO, whereas even stabilizing these emissions is difficult in MARKAL alone.
Figure 1.7 To achieve the same total reduction in CO₂ emissions in the USA from 1990 to 2030, a test version of MARKAL-MACRO finds it better to make less of a reduction sooner.

With reduced energy demands, energy system cost also drops when the carbon dioxide emission constraints are applied in MARKAL-MACRO, as shown in figure 1.8.

Figure 1.8 With macroeconomic effects considered, the cost of energy supply drops when carbon dioxide emission restrictions are introduced because less energy is used.

This is a different result than would be obtained with MARKAL alone where added constraints necessarily increase cost.
The integrated model shows the economic implications of environmental constraints, and the energy implications of macroeconomic factors. It provides the richness of energy technology detail of MARKAL in the user-friendly framework of the MARKAL User Support System (MUSS).

REFERENCE


Input-Output Model of Italy Integrated with MARKAL

To make a direct connection between MARKAL and the interindustry composition of demands, the energy flows represented in MARKAL have been extended to incorporate an input-output matrix of the Italian economy. In this innovative approach, projections of future economic needs are input to the model, and future energy demands are calculated endogenously using the assumed energy prices.

The standard MARKAL model requires as input projections of both future energy demands and future energy prices. To obtain projections of demands that are compatible with the assumed prices, other models are commonly used in conjunction with MARKAL. Among these are accounting models like MEDEE, econometric models, and input-output models. To link the models, it is necessary to iterate back and forth between the models until the results of each are consistent with the assumptions of the other. In Italy, the integration of an input-output model with MARKAL is being developed so that the demands and prices are modified to assure this consistency as part of the model optimization.

In the input-output approach, the domestic economic system is represented by the set of goods and services consumed in the country which are called economic resources and are represented by a column vector \( R \), measured in monetary units. They are used either by the final users--the families, the investments, the foreign countries, represented by a column vector \( F \)--or by intermediate ones--the economic producers, represented by a column vector \( I \).

Under assumptions of linearity, i.e., constant returns to scale and additivity of the results of separate processes, the amount of goods and services consumed by the production process, \( I = A \times R \). Each column of the matrix of technical coefficients \( R \) represents a producer; each value of the technical coefficients of the column represents the fraction of each good or service required by that production process, i.e., identifies the production factors. Each row represents a good or a service; the value of the technical coefficients of each row gives the fraction of each good or service consumed by each production process.

The basic equations: \( R = I + F = A \times R + F \)

link the unknown resources \( R \) to the given final demand \( F \) through the given matrix of technical coefficients \( A \).
In the Leontief approach, there is one average producer for each good and service, the matrix of technical coefficients is a square, the set of basic equations determines a unique solution. The so-called input-output models assume this point of view. In the dynamic input-output models, the time development of the economic resources of the country is calculated assuming a time development of the final demand \( F \) and a price dependence of each technical coefficient of the matrix \( A \).

In the von Neumann approach, each good or service can be produced by more than one producing process. This is represented formally by including in the matrix \( A \) of technical coefficients more than one column per sector.

With a rectangular matrix \( A \), the basic set of equations has more than one solution; i.e., the problem is not deterministic. If an objective function is added, usually the net production has to be maximized, and the problem has a unique optimal solution calculated with the linear programming technique.

The dynamic von Neumann model assumes that in the future new production processes are made available and are in competition with the present ones. The production schedules in these models depend upon the time development of the final demand and on the set of producing processes which are optimal over time for the assumed objective function.

Embodied into MARKAL, the variables representing the resources do not directly contribute to the objective function, which is the total energy system cost. Their values, among the set permitted by the basic input-output equations, are determined in order to minimize the energy-intensive production processes. Therefore, it becomes possible to include in the analysis the effects of structural changes of the production sectors.

The extended model should make it possible to assess:

- structural changes in the economic system that contribute to energy conservation and carbon dioxide emission reduction
- tradeoffs among different greenhouse gases emitted in different economic sectors
- the effect on energy consumption and emissions of changes in consumer demand.

The existing MARKAL software can be used to incorporate the additional input/output matrix with the minor change of allowing activities modeled as "processes" to accept daily and seasonal electric consumption patterns different from the general ones. Each economic sector is modeled as a process that receives in addition to energy an input of goods and services from the others, expressed in monetary units, and produces output measured by its net production.

In place of projected energy demands, then, input to the model is the demand of families for goods and services estimated from projections of population, average family size, and economic growth. Energy demands result from final consumption by families and by intermediate consumption by the economic producing sectors.
Initial Formulation of the Italian Model
To test the model, a 15-sector input-output matrix to represent the Italian economy was formulated. Domestic economic statistics in Italy are usually reported for 44 or 92 sectors; energy consumption is reported for 17 sectors, not entirely compatible with the others. Final demand by families for each of forty categories of goods and services are reported in a time series from 1970 to 1989. For the model the time series was projected to the year 2030 with a bilogarithmic econometric regression on global expenditures, autoregressive with a one-year time lag for stability in the results. The 40 projections were then split into the 92 branches of the national input-output table and then aggregated to the 15 sectors shown in the table below. Family expenditures for goods and services were assumed to increase at the same rate as the economic growth.

| 15 classes of goods and services in preliminary integrated MARKAL and input–output model of Italy |
| Agriculture and fisheries |
| Energy |
| Metals |
| Mechanical |
| Food and drink |
| Textiles |
| Cement and glass |
| Chemicals |
| Paper and pulp |
| Other industries |
| Buildings |
| Trade |
| Public services |
| Private services |
| Transportation |

Preliminary Results
A test of the extended MARKAL model of Italy seems promising. In a scenario without emission restrictions, the energy system does not bias the economic system; import costs and export prices of goods and services follow their projected patterns. With a stringent constraint on carbon dioxide emissions, however, total exports are reduced to their minimum, and total imports go to their maximum.

With stringent carbon dioxide constraints, the mechanical industries which have comparatively low energy expenditures increase their production for export. On the other hand, the industries with high energy costs -metals, chemicals, cement, paper, and rubber- decrease their production and increase their imports.

For the intermediate expenditures of the producing sectors, the cost of energy rises in the scenarios according to the level of the carbon dioxide constraint. With no restriction on carbon dioxide emissions, for example, the cost of energy increases up to 3 to 6 percent in the mechanical industries and up to 14 to 22 percent in the metal industries in the year 2005 due to the rising
international prices of oil and natural gas. In the scenario with minimum carbon dioxide restrictions, however, the intermediate costs of energy rise to 30 and 45 percent, respectively.

In preliminary runs, the integrated model was used to compare seven scenarios with increasingly stringent carbon dioxide emission restrictions with results as shown in figure 1.9. Without constraints, carbon dioxide emissions would double from 1990 to 2030. The reduction of CO₂ emissions to a profile intermediate between the unconstrained case and the minimal case, the so-called medium constraint case, can be achieved at reasonable extra cost. The further reduction of CO₂ emissions to a profile intermediate between the medium case and minimal case, the so-called strong constraint case, requires considerably higher costs.

Three additional scenarios aimed at the Toronto protocol targets with reductions of 5, 10, and 20 percent by the year 2005. In the model it proved feasible to meet the 20 percent target by 2005, but not the further goal of a 50 percent reduction. In all three cases, carbon dioxide emissions began to rise again after 2010.

Minimizing total carbon dioxide emissions for the entire period made a difference primarily from 1990 to 2005; subsequently the pattern was the same as the 20 percent reduction case.

![Graph showing emission trends](image)

Figure 1.9 Severe CO₂ emission constraints may enable Italy to reach a 20 percent reduction from the 1990 level by 2005, but not a long-term reduction of 50 percent.

The changes in final energy consumption in the residential sector, determined in part by the input-output matrix, are shown in figure 1.10. Most of the reduction would result from the medium carbon dioxide constraint.
\begin{figure}
\centering
\includegraphics[width=\textwidth]{Figure1.10.png}
\caption{	extit{CO$_2$ emission constraints would sharply reduce final energy consumption in the Italian residential sector.}}
\end{figure}

There is little difference between the strong carbon dioxide constraint and the several scenarios aimed at the Toronto target in 2005. The largest source of reductions is energy conservation, but fossil fuel switching and the use of renewables are also used to the maximum.

**Further Model Development**

In further development of the integrated model, alternative consumption patterns represented by different demand devices will be included so that final demand for goods and services is determined endogenously according to energy price variations. The stock of capital will be included in the input-output submodel so that the demand for investments is endogenous. The existing stock of capital and its depletion rate will be taken into account.

Projection of the input-output matrix to the distant future will require the use of multiple "processes" (that is, technical coefficients) for each producing sector. This will lead to different intermediate cost patterns for some projected future production sectors.

**REFERENCES**


**MARKAL-MACROEM of Japan**

Japan has also begun development of a macroeconomic model, MACROEM, to be coupled with MARKAL. Essential considerations required for modelling are as follows.

**Requirements in Modelling**

The framework of the economic model should be based on the concept and the structure of the system of national accounts (new SNA) in order to analyze a national economy quantitatively. In the new SNA, an economic cycle is divided into seven stages, i.e. assets at a BOC, production, consumption, accumulation, external transaction, adjustment, and assets at an EOC. The transactors for goods and services are divided into three divisions, i.e. industry, producers of government services, and producers of private non-profit services to households. The transactors for financial transaction are divided into five divisions, i.e. non-financial corporation, financial institution, government, private non-profit institutions serving households, and households (including private unincorporated enterprises). Accounts for flows of goods and services are made on production, consumption expenditure, and capital formation, and those for financial flows on income and expenditure and on capital finance for financial flows. A balance sheet account is given for stock of goods and funds.

From the viewpoint of linking to MARKAL, macro economy models do not necessarily include all above elements of the SNA. Since the basic objective of linking is to take into account the interactions between energy and economy systems, it would be enough to incorporate only those aspects closely relevant to energy-environment studies. The important aspects to be considered are:

1. Useful energy demand should be based on gross production of goods and services including intermediate demand for them.

2. Competition and substitution among factor inputs such as capital, labour, etc. should be considered for industrial production.

3. Value added should be accounted for through processes of generation, distribution, and appropriation.
4. Investment should be divided into energy related one and the other. The energy related investment should be further divided into that for energy conservation, for environment protection, and for other purposes.

5. Since the role of taxes and subsidies becomes important, effects or impacts should be considered for their uses for different purposes.

It may be needless to say that all quantities should be expressed both in their specific units (or in real terms) and in a monetary unit (or in nominal terms), and that some freedom should be incorporated in equilibrium processes.

The first aspect above stresses the significance of gross production together with a corresponding energy intensity in order to determine requirements for energy inputs in industries. It will be difficult to analyze the effect by structure changes, if an energy intensity measured by value added is used, since relatively large part of products are used as intermediate inputs particularly in energy intensive industries producing raw materials. Accordingly it is desired to cypress industrial outputs in terms of gross production including demand for intermediate inputs, and to define an energy intensity based on this.

The second aspect is important in the sense that socio-economic activity in a society heavily depending on industries cannot be evaluated if lacking a viewpoint of effective utilization of economic resources such as capital, labour, or energy. However in order to deal with this subject fully, a multi-sectoral approach will be required, typically such as using an input-output method, apart from the macro economy framework. It is thought that an inter-industrial econometric approach described below can be to some extent a useful alternative.

The third aspect can be managed, e.g. as follows. The amount of value added is derived by subtracting sum of intermediate inputs from gross production, and distribution and appropriation are determined by calculating compensation of employees, consumption of fixed capital, operating surplus, indirect taxes, etc. One important point from the viewpoint of modelling is to use operating surplus as a key parameter being accompanied with production gap later mentioned to determine the level of real investment by private sector.

The fourth aspect requests separation of investment for energy and that for environment protection from other investment by private sector. In particular, the effect on CO₂ reduction by energy conservation is possibly be divided into the technical part to be handled in the MARKAL framework through modelling of conservation technologies, and the economic part to be accounted for through changes in useful demand as a response to prices. Economic compensation for the former is accounted for in MARKAL, while that for the latter in macro economy models. For this purpose investment on energy conservation is separated from the rest of energy investment.

The fifth aspect is necessary for analyzing macro economic responses to a carbon tax. The model developed in this study incorporates following points:
1. Changes in prices of goods and services through shifting of the tax to pricing by industries.

2. Changes in gross demand via changes of prices.

3. Generation of induced investment through using the tax revenue as subsidies.

4. Reduction of consumption expenditure by households due to the reduction of disposable income after payment of the tax.

**Structure of Macro Economy Model**

The overall structure of the macro economy model MACROEM consists of six blocks: the real expenditure block; the real production block; the nominal expenditure block; the nominal production block; the distribution block; and the price block.

The real expenditure block determines components of the GNE, while the real production block calculates outputs and inputs by industry sectors. In the distribution block disposable income, operating surplus, etc. are determined. The price block determines wage rates, prices of products, prices of intermediate inputs, etc. reflecting changes of an import price index and influences by a carbon tax. The nominal production block, while focusing on factor inputs, determines operating surplus, depreciation, taxes and subsidies from the viewpoint of their distribution. The nominal expenditure block has a function to convert components of the real GNE into nominal terms.

The real production block determines first industrial productions by sectors, which are based on final consumption from the real expenditure block and production inducement coefficients (induced production per unit of final consumption) from the input-output table. Although intermediate inputs can be also determined similarly, they are determined econometrically at this moment. Value added by sectors is then calculated by using the amounts of production and intermediate inputs. While, using wage indices from the price block and number of persons engaged, compensation of employee can be determined for the use in the nominal production block. The industry is divided into seven sectors in this model as shown in the table below.
### Disaggregation of Production Sector in MARKAL-MACROEM

<table>
<thead>
<tr>
<th>Sector</th>
<th>Industries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Industry</td>
<td>Agriculture, Forestry, Fishery</td>
</tr>
<tr>
<td>Secondary Industry (Others)</td>
<td>Mining, Food, Textile, Metal Products, Machinery, Other Manufacturing, Construction</td>
</tr>
<tr>
<td>Services (Excl. Electricity &amp; Gas)</td>
<td>Wholesale, Retail, Finance, Insurance, Real Estate, Transportation, Communication Services</td>
</tr>
<tr>
<td>Energy Industry - 1</td>
<td>Oil and Coal</td>
</tr>
<tr>
<td>Energy Industry - 2</td>
<td>Electricity and Town Gas</td>
</tr>
<tr>
<td>Government Services</td>
<td></td>
</tr>
</tbody>
</table>

The real expenditure block determines components of the GNE such as consumption, investment, export, or import. In particular, the determination of real investment by private sector via the inter-industrial econometric model is made as follows. For non-energy industries, production gap is derived from potential production calculated by using real intermediate inputs $M_i$ from the real production block, the number of persons engaged $L_i$, and productive capital stock $K_i$ from the capital stock sub-model. The production gap in the energy industries is derived similarly. Real investment by the private sector is determined from the gap and operating surplus.

The structure of the nominal production block confirms the equivalence of three aspects of a national economy, i.e. gross national product, national income, and gross national expenditure. After this, it determines the operating surplus, incorporating payment of a carbon tax and receipt of subsidies.

The price block determines domestic prices of energy, prices of intermediate inputs, output prices, wage indices, wholesale price index, and other price deflators by using imported energy prices and prices of non-energy imported goods given externally, payment of a carbon tax corresponding to CO$_2$ emissions as calculated in the MARKAL model.

As for the appropriation of the carbon tax revenue, the model provides three options, i.e. for use as subsidies, for reduction of personal income, as a source of general account revenue, or for any combinations thereof.

### Linkage with MARKAL

The concept of linking MACROEM with MARKAL is illustrated in Fig.1.11. The information that MARKAL transfers to MACROEM includes energy imports, investment by energy industries, investment on energy conservation by industries, production by energy industries, and CO$_2$ emissions by sectors. MARKAL can also provide such information as heating and lighting expenditures by the household sector, or expenditures on fuels by the transportation sector.
MACROEM provides MARKAL with the information to adjust useful demand and to convert all cost data into nominal terms. The former includes gross domestic production and production by sectors. The latter includes output prices, investment deflator, wholesale price index, consumption deflator, and so on. The useful demand is to be adjusted by using real GDP and a relevant price deflator, since changes in the level of useful demand can be caused by changes both in the scale and in the price index of a national economy. In this study it is assumed that the useful demand has a linear logarithmic relationship with both real GDP and a price deflator.

Figure 1.11 Concept of MARKAL-MACROEM Combined Analysis

Example of Application
The possible reduction of CO₂ emissions by using a carbon tax has been analyzed by applying the MARKAL-MACROEM model for the energy and economy system of Japan. The time horizon of the analysis is from 1990 to 2030. The analytical cases consist of the case P without a carbon tax and the case S2 with a carbon tax. The carbon tax rate is assumed to increase from 20$/tonne CO₂ in 1995 to 250$/tonne CO₂ in 2030.

The reference energy system for the analysis has the same energy and technology configuration as that established in the ETSAP/Annex IV study. However cost components of the energy system (fuel cost, investment cost, O&M cost) are converted from real term to nominal term by using price deflators determined by MACROEM, and the energy system is optimized by minimizing the nominal system cost.

One important aspect in linking MARKAL and MACROEM is to determine useful demand required for MARKAL by using outputs of MACROEM. In this analysis a simple function involving GDP and a price deflator is utilized as mentioned above. Here an energy price index, defined as final energy consumption divided by the sum of costs for energy supply, conversion, and
transportation, is utilized for the price deflator. Although there have been many studies on the price elasticity of final energy demand, no such studies are available on useful energy. Therefore three cases, are examined for the value of price elasticity $\beta$, i.e. 0.0, -0.2, and -0.3.

Economic Responses and Technology Changes
The amounts of CO$_2$ emissions are shown in figure 1.12 for the case P/M-M, PD/M-M, S2/M-M, where "M-M" means MARKAL-MACROEM combined calculation, and "PD" the case under the same useful demand as in the case S2/M-M. MARKAL stand-alone analyses are also made for the case P/MARKAL and S2/MARKAL, but analytical results are not shown here (see reference below).

In the case S2/MARKAL, the index of CO$_2$ emissions (1990=100) in the year 2000, 2010, and 2030 are 102, 94, and 62 respectively. While in the case S2/M-M, they are 98, 89, and 55 for $\beta=0.0$; 92, 78, and 43 for $\beta=-0.2$; 89, 73, and 39 for $\beta=-0.3$.

![Figure 1.12 CO$_2$ Reduction through Economic Cycles and Technology Changes](image)

Figure 1.12 CO$_2$ Reduction through Economic Cycles and Technology Changes

The CO$_2$ emission reduction in the MARKAL-MACROEM analysis can be divided into the part achieved through economic cycles and that realized by technology changes as indicated in figure 1.12. Here the reduction through economic cycles refers to the overall effect of the carbon tax resulting in the reduction of useful demand. On the other hand reduction by technology changes refers to the technical responses on the side of MARKAL including introduction of conservation technologies, switching among fossil fuels, application of nuclear and renewable technologies. The effect through economic cycles expands until 2005, but is almost constant after 2010. The contribution by technology changes remains at a comparable scale with the effect through economic cycle until 2010, however it increases strongly with time after that year.
The results of the above application example, analyzing the effect by a carbon tax within the framework of energy-economy interactions, indicate that in the initial stage of using the tax, the effect through the reduction of GDP or useful demand is almost comparable with that by price induced technology changes, however this effect does not continue to expand in the longer term even under the rapid increases of the tax rate, while the effect by price induced technology changes has a potential to contribute to the long term reduction of CO₂ emissions. It is noted, however, that sufficient technology options should be available for the future energy system for this purpose.

REFERENCES


2. BASELINE PROJECTIONS

Before looking at strategies to reduce emissions of CO\textsubscript{2}, it is of vital importance to get a good impression of both the current situation and the development in the absence of specific constraints with regard to emissions of CO\textsubscript{2}, the baseline projection. This constitutes the starting point for further assessments and determines to a great extent such important aspects as the level of reduction attainable, the feasibility of various options and the cost of CO\textsubscript{2} reduction strategies.

The total CO\textsubscript{2} emissions from any energy system is determined by social, economic, technological and energy/environment policy related factors. It can be broken down as follows:

\[
\text{CO}_2 = \text{CAP} \times \left( \frac{\text{GDP}}{\text{CAP}} \right) \times \left( \frac{\text{TPER}}{\text{GDP}} \right) \times \left( \frac{\text{TFOS}}{\text{TPER}} \right) \times \left( \frac{\text{CO}_2}{\text{TFOS}} \right)
\]

with: \(\text{CAP} = \text{Population}\)
\(\text{GDP} = \text{Gross Domestic Product}\)
\(\text{TPER} = \text{Total Primary Energy Requirements}\)
\(\text{TFOS} = \text{Fossil Primary Energy Consumption}\)

The first factor, Population, is derived from demographic projections. Growth of the second factor, GDP per capita, is related to such issues as the sectoral contribution to GDP, development of the active labour force and labour productivity per sector, governed by technological progress, and the capital stock available for production. The third factor, the overall energy intensity of GDP, depends again upon the sectoral breakdown, but also on physical and geographical factors like climatic conditions, population density, etc. Technological change, e.g. new industrial processes, products and materials, but also more efficient energy supply and end-use technologies play a crucial role in this factor. The fourth factor depends heavily upon availability and cost of nonfossil energy resources, (relative) prices of imported energy carriers and technical or policy related constraints, such as infrastructure and security of supply. Finally the relative shares of coal and other solid fuels, oil (products) and natural gas determine the average CO\textsubscript{2} emission per unit of fossil fuel or "carbon intensity". Roughly the ratio of CO\textsubscript{2} emission per unit of energy between the three classes of fossil fuels is \(1.7-2 : 1.3-1.4 : 1\).

It will be clear that starting from a relatively inefficient, solid fossil fuel based energy system more reductions are feasible at lower cost than starting from an already efficient system in which nonfossil energy take a significant share.

The first two factors, Population and GDP per capita, are entirely exogenous to the analyses presented here. The same goes in part for the Energy Intensity (sectoral breakdown and for technological progress), energy prices and technical and policy constraints affecting the energy sector development. Internally consistent sets of assumptions for the exogenous elements form scenarios that serve as the background for baseline energy and emission projections, which
in turn serve as reference for alternative CO₂ reduction strategies. The following paragraphs describe the basis assumptions used in the scenarios and the energy and emission profiles resulting from the baseline.

2.1 SCENARIO ASSUMPTIONS

Five countries, including the two Canadian provinces, submitted separate analyses for a high and a low scenario\(^1\), the four others only assessed one single, central projection. Since most of these single projections are more in line with the five high scenarios, a set of nine country scenarios is selected, consisting of the 5 high and 4 central scenarios. This set is referred to as "All(9)".

Separately the impact of differences in growth projections is addressed by comparing the assumptions and results of the five studies for which both high and low scenarios are considered. These are referred to as "High(5)" and "Low(5)" respectively.

Population
The projected population growth in OECD countries is very moderate. For the group of countries represented in this study the average between 1990 and 2020 is 0.4% per year, declining from around 0.5% in the first decade to 0.25% in the last decade. Some countries deviate significantly from the general trend. In Japan the population would peak around 2010 and decrease afterwards to end below the current figure by 2030. The province of Ontario, Canada shows a markedly higher population growth of almost 1.1% on average, while the Belgian population increases at a steady rate of 0.1% per year. In aggregate the population in the ETSAP countries will increase from 435 to 490 million between 1990 and 2020, an increase of 12.5%; see also figure 2.1.

\(^1\) Japan analyzed two scenarios, but only for the High demand scenario detailed results were submitted. Japan is thus only represented in the All(9) analyses and not in the High(5)/Low(5) aggregates, averages and sensitivity analyses in chapters 2 and 3.
Figure 2.1 *Population Projection*

Only for Quebec and Ontario slightly different population growth assumptions are assumed in the high and low scenarios, together amounting to 0.8 million fewer inhabitants by 2020.

Clearly this modest population growth alone will play no significant role in increasing energy demand and GHG emissions.

**Gross Domestic Product (GDP)**

Table 2.1 shows the relative size of the economies and their projected future growth. Some countries studied various economic scenarios, reflecting uncertainties in major determining factors. Others took single central projections.

The average GDP growth rate of all (high and central) scenario cases is 2.35%; most high and central projections lie around 2-2.5% per year on average over the period 1990-2020. Outside this range are Ontario and Japan on the higher end, around 2.8%, and Norway and Switzerland on the lower end, 1.8% and 1.35% respectively.
Table 2.1 *GDP Growth Projections*

<table>
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<td>2.25</td>
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<td>1.62</td>
<td>1.48</td>
<td>1.24</td>
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</tbody>
</table>

* USA, Quebec, Ontario, Netherlands and Sweden

For the 5 high cases the average GDP growth is slightly lower at 2.2%, because Japan with its above average growth rate is not included. The average of the low scenarios is 1.45%, ranging from 1% to 2.1%. The single projection reported for Switzerland is more in line with most of these low estimates, but since only one projection is made it is still included with the high scenario.
GDP per Capita
Since population growth is a significant factor determining (potential) GDP, it is worthwhile to look at the resulting GDP per capita figures; see table 2.2. The 1990 figures confirm the relatively high income in OECD countries, compared to the world average of around US$ 4000. The absolute figures should be treated with some care: purchasing power can differ significantly between countries and the US$ exchange rate of national currencies is subject to large fluctuations. The future GDP per capita still grows considerably, by 2020 it is assumed to be at least 22% and at most 122% higher than in 1990.

Table 2.2 GDP per capita

<table>
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<td>140</td>
<td>162</td>
<td>189</td>
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<td>-Low 110</td>
<td>120</td>
<td>130</td>
<td>140</td>
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<td></td>
<td>-Low 118</td>
<td>131</td>
<td>150</td>
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<tr>
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<td>-High 24.8</td>
<td>120</td>
<td>141</td>
<td>168</td>
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<td>-Low 113</td>
<td>125</td>
<td>140</td>
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<td>-Low 129</td>
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</tr>
<tr>
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<td>143</td>
<td>161</td>
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<tr>
<td>NORWAY</td>
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<td>156</td>
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<tr>
<td>SWEDEN</td>
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<td>147</td>
<td>179</td>
<td>218</td>
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<tr>
<td></td>
<td>-Low 106</td>
<td>114</td>
<td>122</td>
<td>131</td>
<td></td>
</tr>
<tr>
<td>SWITZERLAND</td>
<td>29.1</td>
<td>113</td>
<td>124</td>
<td>137</td>
<td>n.a.</td>
</tr>
<tr>
<td>AVERAGE</td>
<td>-All(9) 22.3</td>
<td>124</td>
<td>150</td>
<td>179</td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>-High(5)* 21.9</td>
<td>118</td>
<td>140</td>
<td>164</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Low(5)* 21.9</td>
<td>110</td>
<td>121</td>
<td>131</td>
<td></td>
</tr>
</tbody>
</table>

* USA, Quebec, Ontario, Netherlands and Sweden

Energy Prices
Most OECD countries rely to a lesser or greater extent on imported coal and oil (products), in many cases also on internationally traded natural gas. This implies that regional and world market prices play a major role in (a) the competitiveness of nonfossil resources and (b) the mix of fossil fuels.
With respect to internationally traded natural gas it is assumed that in the first instance the price would follow the trend of oil (product) prices. In some cases the possibility of amplified gas price increases, resulting from additional demand in CO₂ reduction cases, was included specifically. In general the guidelines issued by the Operating Agent (see table 2.3) were observed, although significant deviations are also reported. It should be noted that the absolute price level of individual fuels has limited influence. Competitiveness of nonfossil fuel resources, efficiency improvements and energy savings suffer from relatively low prices, leading to higher fossil fuel use and thus higher CO₂ emissions. However, more important are however price differences when it comes to the fossil fuel mix. Typically oil, and thus natural gas, prices are assumed to rise more steeply than coal prices. This favours the use of coal at the expense of oil and gas, raising the "carbon-intensity" and thus CO₂ emissions in the baseline.

Table 2.3 Guidelines for Oil and Coal Prices

<table>
<thead>
<tr>
<th>FUEL PRICE RANGES</th>
<th>UNIT</th>
<th>2000</th>
<th>2010</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>STEAM COAL</td>
<td>[US$/ton$^1$]</td>
<td>43-50</td>
<td>50-60</td>
<td>55-70</td>
</tr>
</tbody>
</table>

$^1$ Metric ton, as received

Other Constraints

Many studies, including earlier MARKAL studies in the framework of IEA-ETSAP, indicate that e.g. severe acid emission reduction policies tend to foster structural changes in energy systems: more savings, more nonfossil fuels, more clean fossil fuels like natural gas. This helps to bring CO₂ emissions down, albeit to a limited extent. In most country studies acid emissions are reduced by in the baseline scenarios reported; see Appendix B and Volume II.

Another important issue is the future role of nuclear power. Specific policies, such as temporary or permanent freezes or moratoria, upper limits on total installed capacities, etc. exist in many countries, inspired by concerns over safety risks and waste disposal.

2.2 Baseline CO₂ Emissions

The sets of assumptions are translated into input data on energy demands, energy supply availability and prices and constraints. Together with technological, cost and environmental data of energy technologies, these data are fed into the MARKAL model and optimized. The resulting baseline CO₂ emissions for all (high and central) scenarios are shown in figure 2.2.

Total CO₂ emissions rise by 40% from 6.6 Gt (Gigaton or $10^9$ ton) per year in 1990 to 9.3 Gt by 2020, an average annual growth rate of around 1.1%. The 1990 level accounts for around one third of total global CO₂ emissions.
The 1990 emission of the subset of five countries is 5.3 Gt, covering 80% of the total for all nine countries. With high growth this increases to 7.65 Gt (+44%); low growth leads to a level of 6.2 Gt (+17%). Figure 2.3 shows the two baseline CO₂ emission profiles.

### 2.3 Scenario Indicators

**Energy Intensity**
The total primary energy requirements (TPER) per unit of GDP, or overall energy intensity, has decreased over time in industrialized countries and con-
times to do so. Structural changes in the economy and technological progress in industrial processes and energy technologies more than offset the increasing demand for energy services. Table 2.4 gives an overview of the current intensities and the development over time.

Table 2.4  *Primary Energy Intensity, Ranked by the 1990 Level*

<table>
<thead>
<tr>
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</thead>
<tbody>
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<td>High</td>
<td>18.0</td>
<td>88</td>
<td>76</td>
<td>69</td>
</tr>
<tr>
<td></td>
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<td>89</td>
<td>81</td>
<td>74</td>
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<tr>
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<td>High</td>
<td>15.0</td>
<td>86</td>
<td>77</td>
<td>74</td>
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<tr>
<td></td>
<td>Low</td>
<td>15.0</td>
<td>88</td>
<td>80</td>
<td>79</td>
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<tr>
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<td>73</td>
<td>63</td>
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<tr>
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<td>91</td>
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<td>88</td>
<td>80</td>
<td>78</td>
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</table>

* USA, Quebec, Ontario, Netherlands and Sweden

These primary energy intensity figures must be treated with some care. Following OECD conventions nonfossil energy sources are accounted as so-called "fossil fuel equivalents" or FEQ's, meaning that the output from nuclear, hydro and other renewable power plants is multiplied by a fixed conversion factor to obtain their contribution to primary energy use. The OECD conversion factor applied is 2.5974, equivalent with an efficiency of 38.5%. In particular for future years this factor is rather high, causing an over-estimation of primary energy consumption and thus energy intensity in cases with a large share of nonfossil energy supply.

The total average energy intensity improvement, comprising both autonomous "technological progress" and energy price effects, is 1.18% per year (range: 0.74%-1.63%) in the high scenarios. In the low scenarios the energy intensity decreases less (0.82% average with a range from 0.66%-1.91%), reflecting the notion that higher economic growth rates yield a faster dissemination of new, more efficient technologies. The exception is the Netherlands where the low
projection is associated with more structural changes in the economy and different modal splits in the transport sector (more trains and buses, fewer cars, trucks and planes) than in the high projection. The other low projections are basically characterized as "doing less of the same" than in the high cases.

**CO₂ per Capita**

When it comes to comparing the contribution of countries to the global emission of CO₂, the amount released per capita is often used as a yardstick. As mentioned earlier this indicator is a compound of various factors, including economic growth, energy intensity and composition of the primary energy mix. As table 2.5 shows, large differences exist between the various cases examined here. In part this variance is explained by scenario specific assumptions, see paragraph 2.1., and the energy intensity given in table 2.4.

Table 2.5 CO₂ per Capita, Ranked by the 1990 Level

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<th>CO₂ per Capita</th>
<th>1990 [Ton/Cap.]</th>
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<th>2020</th>
<th>2030</th>
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<td>92</td>
<td>98</td>
<td>100</td>
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<tr>
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<td>123</td>
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<td>96</td>
<td>93</td>
<td>100</td>
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</tr>
</tbody>
</table>

* USA, Quebec, Ontario, Netherlands and Sweden

**CO₂ per Unit of GDP**

Another widely used indicator is the amount of CO₂ emitted per unit of GDP, which reflects the CO₂ intensity of economic growth. So on top of the factors determining the CO₂ release per capita, the economic development is also taken into account. Since GDP per capita shows a stronger growth than the per capita emission of CO₂, the CO₂ released per unit of GDP will obviously come down.
Table 2.6 CO₂ per Unit of GDP, Ranked by the 1990 Level

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<td>86</td>
<td>76</td>
<td>75</td>
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<td>76</td>
<td>68</td>
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<td>82</td>
<td>71</td>
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<td></td>
<td>0.535</td>
<td>86</td>
<td>68</td>
<td>59</td>
</tr>
<tr>
<td>QUEBEC</td>
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<td>90</td>
<td>87</td>
<td>78</td>
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<tr>
<td></td>
<td>Low</td>
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<td>84</td>
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<tr>
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<td>78</td>
<td>63</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>0.381</td>
<td>80</td>
<td>69</td>
<td>65</td>
</tr>
<tr>
<td>NORWAY</td>
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<td>0.334</td>
<td>93</td>
<td>83</td>
<td>74</td>
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<tr>
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<td>High</td>
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<td>91</td>
<td>79</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>0.237</td>
<td>88</td>
<td>69</td>
<td>84</td>
</tr>
<tr>
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<td>0.220</td>
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<td>81</td>
<td>75</td>
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<td>74</td>
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<tr>
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<td>86</td>
<td>78</td>
<td>75</td>
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<tr>
<td></td>
<td>Low(5)*</td>
<td>0.832</td>
<td>87</td>
<td>77</td>
<td>76</td>
</tr>
</tbody>
</table>

* USA, Quebec, Ontario, Netherlands and Sweden

2.4 CO₂ Intensity of Primary Energy Consumption

The large differences found between the various baseline projections (see chapter 2.3.) clearly indicate that besides the relative efficiency of energy use other factors play a decisive role. First of all, total primary energy use (TPER) can be broken down into fossil fuels, responsible for the CO₂ release, and nonfossil energy carriers with virtually no CO₂ emissions.

2.4.1 Fossil Fuel Share

The current fossil fuel shares vary widely from one third to almost 100%, and quite different trends emerge from table 2.7. Some cases show a stable share of fossil fuels, e.g. in the Netherlands, USA, Belgium and Switzerland. These stable levels are quite different however, ranging from almost 100% to around 50%. Cases starting from a low share in 1990 of around 1/3 (Quebec, Norway and Sweden) show a rising trend, indicating that to maintain a high nonfossil supply level is more difficult than to use more fossil fuels to meet growing demands. This is even more true in the case of Ontario: nonfossil fuel supply decreases while total demands almost double, resulting in a fossil
fuel share of well over 90%. Finally, Japan shows an initially low contribution of nonfossil supply of around 15%, which almost doubles in 30 years time largely due to a continued expansion of nuclear energy.

Table 2.7 Fossil Fuel Share of TPER, Ranked by the 1990 Level

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NETHERLANDS</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>-High</td>
<td>97</td>
<td>97</td>
<td>98</td>
<td>96</td>
<td>95</td>
</tr>
<tr>
<td>-Low</td>
<td>97</td>
<td>97</td>
<td>98</td>
<td>97</td>
<td>95</td>
</tr>
<tr>
<td>USA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-High</td>
<td>85</td>
<td>84</td>
<td>85</td>
<td>84</td>
<td>81</td>
</tr>
<tr>
<td>-Low</td>
<td>85</td>
<td>84</td>
<td>83</td>
<td>82</td>
<td>79</td>
</tr>
<tr>
<td>JAPAN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-High</td>
<td>85</td>
<td>79</td>
<td>75</td>
<td>71</td>
<td>66</td>
</tr>
<tr>
<td>-Low</td>
<td>85</td>
<td>79</td>
<td>75</td>
<td>71</td>
<td>67</td>
</tr>
<tr>
<td>BELGIUM</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>-High</td>
<td>80</td>
<td>80</td>
<td>78</td>
<td>78</td>
<td>76</td>
</tr>
<tr>
<td>-Low</td>
<td>80</td>
<td>80</td>
<td>78</td>
<td>78</td>
<td>76</td>
</tr>
<tr>
<td>ONTARIO</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-High</td>
<td>72</td>
<td>77</td>
<td>89</td>
<td>95</td>
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<tr>
<td>-Low</td>
<td>72</td>
<td>76</td>
<td>86</td>
<td>92</td>
<td></td>
</tr>
<tr>
<td>SWITZERLAND</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-High</td>
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<td>51</td>
<td>51</td>
<td>52</td>
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<tr>
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<td>51</td>
<td>52</td>
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<tr>
<td>QUEBEC</td>
<td></td>
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<td></td>
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<td>37</td>
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<td>40</td>
<td>42</td>
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<td>-High</td>
<td>34</td>
<td>36</td>
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<td>-Low</td>
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<td>33</td>
<td>30</td>
<td>39</td>
<td>40</td>
</tr>
<tr>
<td>NORWAY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-All(9)</td>
<td>32</td>
<td>36</td>
<td>37</td>
<td>38</td>
<td>39</td>
</tr>
<tr>
<td>-High(5)*</td>
<td>82</td>
<td>81</td>
<td>81</td>
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</tr>
<tr>
<td>-Low(5)*</td>
<td>83</td>
<td>82</td>
<td>83</td>
<td>83</td>
<td></td>
</tr>
</tbody>
</table>

* USA, Quebec, Ontario, Netherlands and Sweden

2.4.2 Nuclear and Renewables

As stated before, many factors determine the different role of nonfossil resources in the cases examined. In the case of nuclear power specific policy considerations are a main factor, besides the cost relative to fossil fuel alternatives with in general improving performance/cost ratios. Of course the energy price projections used are decisive when it comes to the mutual competitiveness. For renewables, besides physical conditions, generating cost is often the decisive factor, again relative to that of fossil fuel burning competitors. Table 2.8 summarizes the role of nuclear and renewable energy with the main factors explaining their behaviour in the baseline scenarios.
Table 2.8 *Role of Nuclear (N) and Renewables (R) in the Baseline*

<table>
<thead>
<tr>
<th>Country</th>
<th>Development</th>
<th>Main Driving Force(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>N</td>
<td>Until 2010 no expansion allowed; hardly any new plants built thereafter</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>Steady increase to 4 times the 1990 level</td>
</tr>
<tr>
<td>QUEBEC</td>
<td>N</td>
<td>Negligible; one plant commissioned; no further expansion</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>Slight increase, mainly in hydro power</td>
</tr>
<tr>
<td>ONTARIO</td>
<td>N</td>
<td>Decreasing to zero by 2020</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>Gradual decrease</td>
</tr>
<tr>
<td>JAPAN</td>
<td>N</td>
<td>Steady increase to 3 times the 1990 level</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>Share in TPER only slightly increasing</td>
</tr>
<tr>
<td>BELGIUM</td>
<td>N</td>
<td>Hardly changed from current 6 GW; limit of 8 GW not reached until 2030</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>Increasing after 2000 to 2 times the 1990 level; limited potential</td>
</tr>
<tr>
<td>NETHERLANDS</td>
<td>N</td>
<td>Phased-out completely (sensitivity with nuclear expansion - allowing new reactor designs after 2010- show marginal competitiveness)</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>Steady increase to 2-3 times 1990 level; mainly wind and bio-energy with limited potential</td>
</tr>
<tr>
<td>NORWAY</td>
<td>N</td>
<td>No option (policy constraint; large hydro power potential)</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>Hydro power production only slightly increasing</td>
</tr>
<tr>
<td>SWEDEN</td>
<td>N</td>
<td>Current phase-out policy not implemented; rebuilding up to current capacity allowed. In high scenario always up to the maximum. In low scenario initially less, but increasing again from 2020.</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>Mainly hydro power, no expansion and limited other options</td>
</tr>
<tr>
<td>SWITZERLAND</td>
<td>N</td>
<td>Moratorium: total number of plants fixed at current level; output increases 18%</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>Mainly hydropower, total hardly increasing</td>
</tr>
</tbody>
</table>
2.4.3 Fossil Fuel Mix

The current shares of oil, coal and gas vary widely; see the left bars in figure 2.4. In countries relying heavily on nuclear and/or hydro power for their electricity production (Quebec, Norway, Sweden, Switzerland and to a lesser extent Belgium) the position of coal is weak, except for specific industries like iron and steel (important e.g. in Belgium). Consequently the share of oil is relatively high. With time considerable shifts take place in the high scenario, but the nature of the changes varies due to different conditions and assumptions; see the right bars in figure 2.4. On aggregate the share of oil decreases from 50% to 40%, coal filling the larger part of the gap.

Despite the observed shifts over time the CO$_2$ intensity of fossil fuel use, that is the CO$_2$ released per unit of fossil energy, does not change drastically. It never falls outside a range of plus or minus 10% from the 1990 level and on aggregate it grows by less than 2%.

![Graph showing Fossil Fuel Mix in 1990 and 2020](image)

**Figure 2.4 Fossil Fuel Mix in 1990 and 2020**

Similar trends are observed in the low scenarios, but are less pronounced due to the lower growth in energy demand. In particular coal is growing far less, just maintaining its market share. The declining oil share (45.5% to 41.5%) is almost entirely compensated for by using more natural gas.

The CO$_2$ intensity of TPER --the CO$_2$ emitted per unit of primary energy used and the aggregate of the fossil fuel share and the fuel mix-- is given in table 2.9. In the high scenario a small decrease in the share of fossil fuels is offset by a shift towards more coal. In the low scenario both the fossil fuel share and the CO$_2$ intensity of the fossil fuel mix decline slightly, the latter due to a shift from oil to natural gas.
Table 2.9  \( \text{CO}_2 \) Intensity of Total Primary Energy, Ranked by the 1990 Level

<table>
<thead>
<tr>
<th></th>
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<td>JAPAN</td>
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</tr>
<tr>
<td>-High</td>
<td>59.8</td>
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<td>59.0</td>
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<td>90</td>
<td>90</td>
<td>89</td>
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<td>59.0</td>
<td>99</td>
<td>99</td>
<td>100</td>
<td>96</td>
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<tr>
<td>-Low</td>
<td>59.0</td>
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<td>95</td>
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<td>91</td>
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<tr>
<td>-High</td>
<td>54.9</td>
<td>102</td>
<td>106</td>
<td>109</td>
<td>108</td>
</tr>
<tr>
<td>-Low</td>
<td>54.9</td>
<td>102</td>
<td>105</td>
<td>110</td>
<td>112</td>
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<tr>
<td></td>
<td>53.2</td>
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<td>96</td>
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<td>95</td>
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<tr>
<td>-High</td>
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</tr>
<tr>
<td></td>
<td>38.3</td>
<td>93</td>
<td>96</td>
<td>98</td>
<td>n.a.</td>
</tr>
<tr>
<td>QUEBEC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-High</td>
<td>26.9</td>
<td>101</td>
<td>114</td>
<td>113</td>
<td>n.a.</td>
</tr>
<tr>
<td>-Low</td>
<td>26.8</td>
<td>96</td>
<td>103</td>
<td>102</td>
<td></td>
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<td>26.2</td>
<td>105</td>
<td>108</td>
<td>134</td>
<td>148</td>
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<tr>
<td>-Low</td>
<td>26.1</td>
<td>95</td>
<td>86</td>
<td>118</td>
<td>126</td>
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</tr>
<tr>
<td></td>
<td>22.9</td>
<td>110</td>
<td>114</td>
<td>117</td>
<td>120</td>
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<td></td>
</tr>
<tr>
<td>-All(9)</td>
<td>56.5</td>
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<td>56.7</td>
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<td>102</td>
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<td>-Low(5)*</td>
<td>56.7</td>
<td>99</td>
<td>96</td>
<td>97</td>
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</tr>
</tbody>
</table>

* USA, Quebec, Ontario, Netherlands and Sweden
3. CO₂ REDUCTION STRATEGIES

3.1 CO₂ Reduction Options

In chapter 2, the baseline projections of CO₂ emissions and the underlying factors are addressed. Looking at the breakdown of CO₂ emissions, a range of options to reduce emissions from the baseline can be considered.

\[
CO₂ = CAP \times \left( \frac{GDP}{CAP} \right) \times \left( \frac{TPER}{GDP} \right) \times \left( \frac{TFOS}{TPER} \right) \times \left( \frac{CO₂}{TFOS} \right)
\]

with:
- \( CAP \) = Population
- \( GDP \) = Gross Domestic Product
- \( TPER \) = Total Primary Energy Requirements
- \( TFOS \) = Fossil Primary Energy Consumption

**Population**

First of all, one might try to control the population growth. Although this is often suggested as a panacea for a wide range of problems in particular for Less Developed Countries, it appears to be of minor interest for the group of countries addressed here.

**Economic Growth**

The next issue of slowing down economic growth per capita may seem a valid one at first glance, especially for the "rich" western industrialized countries. It is however a disputable idea, against which many arguments can be raised. Among these is the notion that the undisputed need for global economic growth to raise the standard of living for the large and growing population in LDC's, would suffer from a stagnating economy in the richer parts of the world. A slowdown of economic growth per se, doing "less of the same" is also believed to hamper technological progress, i.e. required to tackle environmental problems. Although this discussion falls outside the scope of this study, investigating the impact of various levels of economic growth on the issues addressed proves to be extremely rewarding; see chapter 3.6.

**Energy Intensity**

The third constituent to reduce CO₂ emissions is using less energy per unit of GDP. It covers a wide range of measures and options, in part socio-economic or institutional in nature, often closely related to policies. To name a few: waste management policies aiming at a maximum recycling of materials, transport policies discouraging the use of private cars and stimulating public transport, regulated packaging practice, etc. For the time being such issues are largely exogenous to the assessments considered here, but may be included in scenario specific assumptions. Besides such exogenous factors technological measures within the energy system, the main topic of this study, enter into play: energy savings and efficiency improvements.
Still affecting the energy intensity of GDP, enhanced energy savings and application of more efficient energy technologies, including new industrial production processes, can make a sizeable contribution.

**More Nuclear and Renewables**
The fourth factor deals with enhancing the share of non-fossil energy forms to cover (reduced) primary energy requirements. Besides already well-established options like nuclear power, hydro power and fuel wood, new options like large scale growing of plant species to produce bio-fuels, solar, wind, tidal and wave energy are considered.

**Fossil Fuel Switching**
The next constituent is to reduce the CO$_2$ release per unit of fossil fuel used. This covers switching from solid fuels like coal and lignite to oil and/or natural gas, and from oil to natural gas.

**CO$_2$ Removal and Storage**
Another, in principle very efficient, means to reduce this factor is CO$_2$ removal and storage. A number of process routes to remove CO$_2$ are investigated, entirely fossil-fuel based or using a mix of renewables and fossil inputs. Once removed the CO$_2$, or in some cases solid carbon, must be stored. Underground disposal of compressed CO$_2$ in depleted gas and oil fields or in aquifers and disposal in deep ocean water are considered. Finally processes for recycling of CO$_2$ and other carbonaceous substances can help to reduce CO$_2$ emissions. Clearly substantial parts of the inputs into such processes must be of non-fossil origin to yield a positive net effect.

A more comprehensive list of options to be considered can be found in Appendix C.

**Interactions**
It must be noted, that many of the individual technological options are strongly interrelated and mutually influence each other across the borderlines drawn between the various factors above. A couple of examples may illustrate this:

- Switching from coal to gas-based energy conversion technologies (e.g. power plants) or end-use devices (e.g. industrial boilers) not only reduces the carbon intensity of fossil fuel use. It also decreases the energy intensity, while gas burning technologies typically have up to 10% higher conversion efficiencies than comparable coal alternatives.

- Introduction of electricity saving devices (e.g. fluorescent light bulbs) may not reduce CO$_2$ emissions if electricity production relies entirely on non-fossil energy forms. However, if the non-fossil supply has a limited capacity, savings on traditionally electricity dependent energy services like lighting may still be attractive. The electricity thus saved could then replace fossil fuels in other places, e.g. for heating or transportation.
• Nuclear heat may be used to produce synthetic fuels like hydrogen from fossil fuels. If in this process CO$_2$ is either removed or recycled the carbon intensity of fossil fuel use drops, but the share of nuclear in TPER rises simultaneously.

• More generally the cost per ton of CO$_2$ reduced by measures belonging to one group of options depends on factors ranked under another heading. The example given in the box below may serve to illustrate this phenomenon.

**CO$_2$ Reduction Cost of Compact Fluorescent Light Bulbs**

A 75 Watt incandescent light bulb may be replaced by a 15 Watt compact fluorescent bulb, yielding the same amount of light. Assuming an extra cost of 35 US$ -incl. charges for new lighting devices- over a lifetime of 5000 hours, 300 kWh electricity are saved at a net cost of 5 US$: 35 US$ minus the benefit arising from not buying 300 kWh from the grid at a rate of 10 cents/kWh.

If this electricity were generated from coal power plants, the associated reduction of CO$_2$ emissions is around 220 kg. Per tonne of CO$_2$ reduced the cost is thus 23 US$. Alternatively, if the electricity comes from a gas fired power plant, the CO$_2$ reduction is about half and consequently the cost per tonne of CO$_2$ reduced ends up twice as high at 46 US$.

### 3.2 CO$_2$ Reduction Strategies

#### 3.2.1 Maximum Reduction

From each of the country studies maximum reduction cases are selected and aggregated into an overall maximum reduction strategy. The cases included reflect the limit beyond which further reductions by technical measures alone are judged unrealistic within the given scenario framework; see also Appendix B. As an arbitrary cut-off point a marginal cost of US$ 500 per tonne of CO$_2$ reduced is applied. This level is equivalent to a CO$_2$ tax, that would raise the price of crude oil in 2030 by a factor of five.

Figure 3.1 shows the resulting CO$_2$ emission profile, compared against the baseline projection and against the current level. Compared with the 1990 level a maximum reduction of 6% is reached by 2010, rising to 12% by the year 2020.
Figure 3.1 *Baseline and Maximum CO₂ Reduction Profiles; All(9) Cases*

The shaded area in figure 3.1 represents the total amount of CO₂ reduced from the baseline. Due to the increasing trend of this starting point, emissions are reduced by 23% in 2010 and 37% in 2020. The shaded area is broken down into the contributions from each of the (groups of) countries in figure 3.2.

Figure 3.2 *Contribution to the Maximum CO₂ Reduction*

Figure 3.3 illustrates how key scenario indicators evolve from 1990 to 2020 in the baseline and how they change from the baseline to the maximum reduction attainable in the year 2020.
3.2.2 Similarities and Differences

In principle changes in all major factors (energy intensity, fossil fuel share and carbon intensity) are likely to occur if CO₂ emissions are reduced. Similar reactions may be expected in all cases. However, the large differences found between the factors determining the individual baseline CO₂ emission levels will cause the relative contributions of each of the factors to be different. Table 3.1 illustrates these differences by comparing the factors between the baseline and the maximum reduction cases. Besides the primary energy intensity the final energy intensity is displayed. The former may be somewhat misleading in cases where the fossil fuel share changes strongly, due to the accounting convention for non-fossil energy applied. The latter gives an indication of energy savings at the end-use level, but includes the inherent savings effect from increasing the share of electricity.
Table 3.1  *Energy Intensities, Fossil Fuel Share, Carbon Intensity of Fossil Fuel Mix and CO₂ per unit of GDP in 2020 for the Baseline and Maximum Reduction Cases*

<table>
<thead>
<tr>
<th></th>
<th>Baseline/Max. Reduction in 2020 (Index, 1990 =100)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energy Intensity Final</td>
</tr>
<tr>
<td>USA</td>
<td>74/70</td>
</tr>
<tr>
<td>QUEBEC</td>
<td>69/78</td>
</tr>
<tr>
<td>ONTARIO</td>
<td>80/83</td>
</tr>
<tr>
<td>JAPAN</td>
<td>61/55</td>
</tr>
<tr>
<td>BELGIUM</td>
<td>61/53</td>
</tr>
<tr>
<td>NETHERLANDS</td>
<td>63/61</td>
</tr>
<tr>
<td>NORWAY</td>
<td>63/66</td>
</tr>
<tr>
<td>SWEDEN</td>
<td>62/64</td>
</tr>
<tr>
<td>SWITZERLAND</td>
<td>76/73</td>
</tr>
<tr>
<td>AVERAGE</td>
<td>70/66</td>
</tr>
</tbody>
</table>

* With CO₂ Removal and Storage Options

3.2.3 Equal Targets versus Cost Efficiency

Many different schemes and yardsticks are suggested and discussed when it comes to the question of how various countries or regions should contribute to a global emission reduction strategy if the need for such concerted actions were assumed.

A first group can be distinguished, in which *equal targets* are defined. Relatively simple, and at first glance looking fair enough, are schemes whereby every person would be allowed to emit the same amount of CO₂. The per capita emission in a given future year would then be equal to or less than the agreed budget for the world, a world region or a group of countries, divided by the associated number of inhabitants. However, in particular in the shorter run such schemes ignore the differences that currently exist and would lead to very inefficient strategies.

Acknowledging the differences existing today, a second strategy would be to request *the same reduction percentage* from each party. So if an overall reduction in a given year should be set at x% from the year 1990, each participant in this scheme should reduce its emission by that same percentage. For the sake of the argument, calculations were made aiming at an overall 12% reduction by the year 2020 (the overall feasible maximum) using the two yardsticks mentioned above. The resulting emission levels per capita are given in table 3.2, compared with the levels in the year 1990 and the baseline and maximum reduced levels in 2020. Strategy A represents the same emission level per capita, Strategy B the same emission reduction percentage from the 1990 level.
Table 3.2  CO$_2$ per Capita in 1990 and in 2020 under Various Strategies

<table>
<thead>
<tr>
<th>CO$_2$ per Capita [Ton/CAP]</th>
<th>1990</th>
<th>-12% Strat.A</th>
<th>-12% Strat.B</th>
<th>Baseline</th>
<th>Maximum Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>19.5</td>
<td>11.9</td>
<td>14.6</td>
<td>23.4</td>
<td>15.3</td>
</tr>
<tr>
<td>ONTARIO</td>
<td>14.3</td>
<td>11.9</td>
<td>9.1</td>
<td>27.2</td>
<td>8.7</td>
</tr>
<tr>
<td>NETHERLANDS</td>
<td>10.8</td>
<td>11.9</td>
<td>8.4</td>
<td>11.8</td>
<td>5.1</td>
</tr>
<tr>
<td>BELGIUM</td>
<td>10.5</td>
<td>11.9</td>
<td>8.9</td>
<td>11.2</td>
<td>5.8</td>
</tr>
<tr>
<td>QUEBEC</td>
<td>9.7</td>
<td>11.9</td>
<td>7.5</td>
<td>13.3</td>
<td>4.9</td>
</tr>
<tr>
<td>JAPAN</td>
<td>9.1</td>
<td>11.9</td>
<td>7.8</td>
<td>11.2</td>
<td>7.1</td>
</tr>
<tr>
<td>NORWAY</td>
<td>8.3</td>
<td>11.9</td>
<td>6.7</td>
<td>9.6</td>
<td>7.5</td>
</tr>
<tr>
<td>SWITZERLAND</td>
<td>6.4</td>
<td>11.9</td>
<td>5.2</td>
<td>6.5</td>
<td>4.9</td>
</tr>
<tr>
<td>SWEDEN</td>
<td>6.3</td>
<td>11.9</td>
<td>5.0</td>
<td>9.3</td>
<td>4.6</td>
</tr>
<tr>
<td>AVERAGE</td>
<td>15.2</td>
<td>11.9</td>
<td>11.9</td>
<td>18.9</td>
<td>11.9</td>
</tr>
</tbody>
</table>

Table 3.2 shows that Strategy A. would allow inhabitants of a majority of countries to emit even more CO$_2$ than the baseline, a rather unrealistic approach. Strategy B. looks definitely more realistic, although the gap between the associated level on the one hand and the baseline and maximum reduction levels on the other hand still varies considerably.

Another point of view is to look at what might happen if equal efforts are requested, e.g. an equal GDP loss attributable to the emission reduction. This approach cannot be studied unless one and the same integrated energy/economy model were applied. Moreover, it is difficult to imagine how to implement such a yardstick in practice.

The fourth and more promising approach is based on the concept of cost-efficiency, using the marginal cost of CO$_2$ reduction as the yardstick. For the group of countries as a whole it is inefficient to reduce emissions at a higher specific cost in one country, while at the same time lower cost options are not fully deployed in other countries. For the country facing higher reduction costs it is more efficient to spend money in the country having lower cost options available, than to spend more money at home to achieve the same overall result. The same principle forms the basis for two often suggested instruments to implement CO$_2$ reduction in an international context: (a) tradeable emission permits; and (b) CO$_2$ or carbon taxes.

In the following, two strategies will be compared: the same percentage reduction (PR) strategy vs. the same marginal cost of CO$_2$ reduction or cost-efficiency (CE) strategy.

As to the PR (= same reduction percentage) strategy, clearly this ends at the first percentage beyond which further reduction is deemed infeasible in any of the countries considered. From that point onwards, further reductions are possible for a smaller number of countries only, etcetera, until finally one
country case with the highest reported reduction percentage remains and the total reduction amounts to the maximum achievable.

For the CE (= cost-efficiency) strategy, all individual reduction cases are first ranked by order of their ascending marginal cost. Following that order cases are added until the last one with the highest marginal cost reported is reached, yielding again the maximum overall reduction level.

Figure 3.4 illustrates the differences found between the various countries. The marginal cost to reach stabilization ranges from less than 10 to 400 US$. A reduction of 20%, in those countries where it is feasible, yields marginal costs between 50 and 450 US$ per tonne of CO₂. Vice versa, a marginal cost level of US$ 200 would suffice to reduce emissions in 2020 by over 40% in some cases, while the emission level is just about lowered to its 1990 level, or not even that, in others.

![Image of Figure 3.4: Marginal Cost of CO₂ Emission Reduction in 2020 by Country](image)

Figure 3.4 Marginal Cost of CO₂ Emission Reduction in 2020 by Country

Now if all reduction cases of all countries are combined and the two strategies are applied, it will be clear from the above that the order in which cases are selected must differ significantly between the PR and CE strategies. As expected the cost-effective strategy (CE) will yield more emission reduction at a given level of spending than the PR strategy. Or, vice versa, the same reduction can be reached by spending less money; see figure 3.5. The points marked on the PR curve indicate the emission reduction level requested by 2020. Those on the CE curve give the marginal reduction cost in the same year. It is interesting to note that the more significant deviation between the two curves does not start until stabilization is reached.
Figure 3.5 Trade-off between CO₂-reduction and Undiscounted System Cost for the PR (same Percentage Reduction) and CE (Cost-Effective) Strategies in 2020.

For the group of countries the overall effect on CO₂ emissions from moving to more and more expensive measures is shown by the marginal reduction cost curve in figure 3.6.

Figure 3.6 Marginal CO₂ Reduction Cost Curve for the CE Strategy

The primary energy consumption changes with increasing marginal CO₂ reduction costs in the CE strategies and with lower CO₂ emission caps in the PR strategies. It is interesting to note some differences between the two approaches; see figure 3.7. The contribution from renewables e.g. grows only
marginally up to the 100 US$ CE-strategy, whereas in all other strategies selected its contribution is almost as large as in the maximum reduction case.

![Primary Energy Consumption in 2020 - Selected CE and PR Strategies](image)

Figure 3.7 Primary Energy Consumption in 2020 - Selected CE and PR Strategies

A significant share of the nuclear potential unused in the baseline is already taken up in the 100 US$ CE-strategy; the remainder however is not used unless a much higher marginal cost level is reached (US$ 250) or if similar reductions are requested from all countries (PR strategies). For natural gas the same increase is found in all CE-strategies. Only in the more expensive PR-strategies is further expansion of its role observed.

So apparently country-specific conditions and assumptions do not allow for general conclusions regarding the attractiveness of various options for CO₂ emission reduction. Nuclear energy, renewables and natural gas each have their own "market niches", where they contribute at relatively low costs. On the other hand each of these resources have an additional potential at higher reduction cost levels.

It was observed that lowering the share of fossil fuels makes a larger contribution than changing the fossil fuel mix to reach the maximum reduction. Regardless of which strategy is followed, this is generally true for less far reaching reduction levels also. The exception is the CE-strategy, where both measures make an equal contribution initially; see figure 3.8. This suggests that at relatively low reduction cost levels switching from coal to natural gas is equally attractive as introducing more nuclear and/or renewable energy.

### 3.3 Primary Energy Impacts

In the baseline total primary energy consumption grows by 40% from 1990 to 2020. Moving to the maximum reduction cases reduces this growth to 32 %;
see figure 3.9. The total consumption thus does not change much; additional savings account for less than 6% in the year 2020.

![Graph showing CO2 emission reduction and energy strategies](image)

**Figure 3.8** *Scenario Indicators in 2020 - Selected CE and PR Strategies*

The composition of primary energy, however, changes drastically. In the baseline total fossil fuel use grows at the same rate as total primary energy. With the maximum CO₂ reduction strategy, the 2020 level is the same as in 1990.

Even in the baseline the use of oil increases by only 11%. With maximum CO₂ reduction it ends up just below the 1990 level.

![Bar chart showing primary energy consumption](image)

**Figure 3.9** *Primary Energy Consumption in 2020 - Baseline and Maximum Reduction*
The demands for natural gas and coal are most strongly affected by the CO₂ reduction strategies. For natural gas the 45% growth in the baseline increases to a growth of 78%. The demand for coal changes even more drastically: an 80% increase in the baseline is reversed to a 70% decrease.

The total contribution of nuclear energy fails to increase in the baseline as a combined result of expansion in some countries and phase-outs in others, where it cannot compete against cheaper coal. As expected the position of nuclear improves with CO₂ reduction strategies; the total use in 2020 almost doubles. An important reason for its still limited contribution in 2020 is the fact that in many instances investments in new nuclear power plants are not expected until 2005 or 2010.

In 1990 renewable energy sources supply some 10% of all primary energy. Even in the baseline the contribution doubles by 2020, due to further development of technologies and rising energy prices, both helping to make renewables more competitive. Its contribution in 2020 almost doubles again in the maximum CO₂ reduction case, reaching the fourfold from 1990.

3.3.1 Fuel Imports and Security of Supply

Following the changes observed in total primary energy requirements and its composition, the impacts on net import of fossil fuels for the countries considered are estimated. It must be noted that most larger West European OECD economies are not represented in this study. On the other hand the major regional gas and oil exporters (Netherlands and Norway) are included in the analysis. As for North America, the entire USA, Quebec and Ontario are included, but the major fossil energy producing provinces of Canada are not. The figures below can therefore only provide some insights in general trends and do not allow for conclusions regarding the net import from outside the OECD (or regions thereof).

Since oil and coal are traded essentially on world markets, only the aggregate figures for all countries included are addressed here. In 1990 over 60% of the oil and oil products consumed are imported. With time the demand is growing in the baseline, while domestic production is expected to decline. Net imports therefore increase much faster than demand; see figure 3.10.(a). If all OECD members in West Europe were included, the picture would have looked even more dramatic. In the baseline, only in Japan do net oil imports decrease. In aggregate the dependency on imported oil rises, worsening the future security of supply situation.

With maximum CO₂ emission reduction the oil consumption in 2020 is decreased from the baseline and hardly exceeds the 1990 level. Consequently the oil import level is somewhat lower than in the baseline, but due to declining domestic production still far above the current one.

The demand for coal increases sharply in the baseline, driving up the net import requirements more than seven-fold between 1990 and 2020; see figure 3.10.(b). This is generally not considered to pose serious security of supply problems, since (potential) coal suppliers are manifold, including OECD member states like Australia, and the remaining world coal reserves are enormous. Today Germany and the UK, not included in the figure, are producing
large amounts of coal. Both countries are expected to reduce production in future, driving up the potential demand for imported coal even further. The maximum CO$_2$ reduction strategy features a much lower coal use; consequently the projected exports from North America exceed the import requirements of Japan and West Europe.

Figure 3.10 *Net Imports of Oil, Coal and Gas in 2020 - Baseline vs. Maximum Reduction*
Natural gas is traded largely on regional markets, with the exception of LNG. Therefore results are presented by region in figure 3.10.(c). In North America the demand for gas grows faster than the domestic supply, but probably the increasing import volumes can be covered primarily by other Canadian provinces. With maximum CO$_2$ reduction the demand increases, but so does domestic supply due to higher prices, and consequently total imports remain at the same level in 2020. In Japan and West Europe the demand remains at the 1990 level in the baseline. Higher production by Norway offsets decreasing production in the Netherlands. The slight increase in net exports is expected to fall far below the demand in the rest of West Europe. With Maximum CO$_2$ reduction gas demand rises sharply in both regions. Again, other West European countries are expected to show a similar increase in demand, leading to even higher total import volumes than in the rightmost bars in figure 3.10.(c). Potential suppliers for both regions are the former Soviet Union and the Middle East. Despite recent political developments this could be regarded as a serious potential risk for the future security of supply of natural gas.
3.4 Final Energy Impacts

3.4.1 Electricity

In most industrialized countries a general trend towards a larger share for electricity has been observed. The growth in electricity demand has equalled, or even exceeded, economic growth while the final demand for fuels stagnated since the mid-seventies. A range of factors contribute to this phenomenon. First of all, structural changes in the economies, whereby the share of basic materials production (iron and steel, petro-chemicals) in GDP declined and less energy intensive sectors like manufacturing industries (e.g. electronics) and services took a larger share in GDP. Typically, the latter activities require less fuel input but more electricity. Secondly, overall energy savings in industrial processes are often achieved by large savings on heat, accompanied by a larger demand for (electric) drive power. In paper industries, for instance, the steam demand for drying purposes is cut drastically by rolling using electric motors. Similarly, heat recovery systems require electricity for pumps or fans. Moreover switching from heat from burning fuels to electric heating in industry can be induced by other considerations than energy cost savings, such as product quality or ease of process control. Thirdly, the savings potential for heat applications is most often much larger than for electric applications, on the one hand for technological reasons, but also because electricity is generally far more expensive than fuels. Furthermore, electricity is a clean and convenient form of energy from the end-users perspective. Finally, new applications for electricity continue to appear on the market, while new heat-requiring applications are very rare. Industrial process automation, office and home computer systems, consumer electronics, microwave ovens, etc. are typical examples.

As a result, the share of electricity in total final energy use continues to rise in the baseline. With increasing CO$_2$ emission reductions, two opposing tendencies emerge. On the one hand higher electricity prices will lead to enhanced savings and efficiency improvements in markets dominated by electricity (lighting, cooling, mechanical power, communication, etc.). On the other, electricity may substitute for fuels in other markets traditionally depending on fuels (process and space heating, transport). The remaining potential and the cost of low or zero-CO$_2$ emission electricity supply options is a main factor determining which one of the two tendencies will dominate.

An illustrative example is reported for Switzerland; see also Vol.II. In the Swiss baseline, electricity consumption rises from 168 PJ in 1990 to 227.5 in the year 2025. However, specific technical electricity conservation measures already save 21.7 PJ in the last year. If CO$_2$ emissions are reduced by 30%, the specific conservation increases to 53.1 PJ, but at the same time total use increases to 241 PJ. The balance of (241-227.5)+(53.1-21.7) = 44.9 PJ is taken up by new applications, such as electric vehicles, electric (assisted) space and water heating, etc. In aggregate the share of electricity in final energy demand increases from 21.5 to 27.5% in the baseline, and grows further to 31% in the most severe CO$_2$ reduction case.
3.4.2 District Heating and Cogeneration

One way to reduce overall energy consumption is to introduce or expand combined generation of heat and electric power. This comes in many different shapes, temperature levels and unit sizes. Net savings of 20 to 30% can be achieved by combined generation compared with separate production of the same amounts of heat and electricity. In practice many obstacles are encountered, keeping the potential for combined generation well below 100% of the total electricity and/or heat demand. To name a few:

- the temperature level required by some industrial processes is higher than cogeneration units can provide;
- the high cost of heat transport and distribution systems, in particular for residential space heating in areas with a low demand density per square kilometer;
- a poor match between electricity and heat load patterns;
- institutional and organizational barriers, tariff structures.

Nevertheless it remains attractive to strive for utilization of at least part of the heat wasted in electric power generation, in particular if CO$_2$ emissions are to be reduced and nuclear or renewable electricity supply is limited or expensive.

Heat can also be supplied from large-scale renewable sources, such as geothermal energy or centralized thermal solar collectors. By installing heat pumps, low-temperature waste heat, e.g. in sewage water or cooling water of large industries, can be raised to temperatures sufficient to heat houses and buildings.

A common characteristic of all options mentioned above is the delivery of heat (steam or hot water) to consumers, instead of electricity or fuels.

3.4.3 Fuels

**Fossil Fuels**

While the shares of electricity and heat tend to rise with stricter emission limits, direct use of fuels by end-users has to come down. Where available, biomass (direct burning and/or synthetic biofuels) and hydrogen contribute to further reduce final consumption of fossil fuels; see below. If natural gas is available, it will expand its share among the remaining fossil fuels at the expense of coal and oil products. Relative prices and special applications requiring specific fuels (not or not easily substituted, e.g. petrochemical feedstocks, or coal and coke for iron and steel making) further determine how soon the maximum penetration of natural gas is reached.

**Biomass**

A range of sources of organic matter can be put to use for energy purposes in various forms. Waste products include the organic fraction of municipal waste, wastes from agriculture and food industry, wastes from paper and wood industries, etc. Alternatively, wood or crops may be grown specifically for energy purposes. Such energy plantations or crops require vast land areas to make significant contributions to meet energy demands.
Solid biomass like wood, straw or miscanthus, etc. can be burned directly to generate industrial process steam, to heat houses and buildings, or to generate electricity. In some countries, e.g. Sweden with its vast wood and paper industrial sector, burning of wood wastes already constitutes a sizeable energy resource.

Like solid fossil fuels, solid biomass can also be gasified, either integrated with electricity production or stand-alone.

Organic wastes can yield gaseous fuels through anaerobic digestion (e.g. manure, organic municipal waste, sewage and other waste water). This process also takes place spontaneously in landfills; under controlled conditions the methane-rich gas may be collected, cleaned and fed into gas grids.

Liquid biofuels can be produced from a score of materials through different process routes. These include ethanol from fermentation of sugar-rich crops (corn, wheat, sugarcane, sugarbeet, etc.); methanol synthesis from solid biomass (wood, straw, miscanthus, etc.); diesel-type fuel from upgraded vegetable oil, extracted from oil-rich crops (e.g. rapeseed) or from pyrolysis of solid biomass (e.g. wood).

Since organic wastes have no, or even negative costs, fuels produced from them are cheaper than from energy farming. In general the cost of biofuels goes up with the quality desired. In particular liquid fuels for transportation are relatively expensive to produce. While energy from organic wastes is in many instances competitive with fossil fuels, energy farming is only attractive at more stringent CO₂ reduction levels.

Since waste volumes are limited in size (related with economic activities) their potential is soon exhausted with reduced CO₂ emissions. The potential for energy farming, incl. wood plantations, varies widely between the countries. Even under very favourable conditions, biomass energy cannot fully replace fossil fuels; see also table 3.3.

<table>
<thead>
<tr>
<th></th>
<th>1990</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base case</td>
<td>Max.Reduction</td>
</tr>
<tr>
<td>USA</td>
<td>3.3%</td>
<td>2.7%</td>
</tr>
<tr>
<td>Netherlands*</td>
<td>-</td>
<td>1.9%</td>
</tr>
<tr>
<td>Norway</td>
<td>2.5%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Sweden</td>
<td>11.9%</td>
<td>9.6%</td>
</tr>
</tbody>
</table>

* Excl. Biogas from Manure and other Organic Wastes (1990: 0.2%; 2030: 1.0 and 2.5% for Base case and Max.Reduction)

**Hydrogen**

Only if options are considered to produce hydrogen from fossil fuels with CO₂ removal (Netherlands, Belgium), from nuclear reactors (Japan) or from renewables (from PV in the Sahara and by pipeline to the Netherlands, Belgium), does it enter the energy system. Hydrogen can be used for many pur-
poses. It may replace natural gas in grids at similar pressures, either fully or as a mixture. Compressed to higher pressures, it can serve as a fuel for road vehicles, either in internal combustion engines or in fuel cells. Liquid hydrogen is considered for use in airplanes.

In the Netherlands, the large potential assumed for CO$_2$ storage allows for vast quantities of hydrogen to be produced from coal and natural gas at low emission levels. Although utilization in fuel cells for combined electricity and heat generation is preferred, hydrogen also meets an increasingly important share of final energy demand; see table 3.4.

<table>
<thead>
<tr>
<th></th>
<th>CO$_2$ Emission Reduction in 2030</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40%</td>
</tr>
<tr>
<td>All Fuels</td>
<td>74.0%</td>
</tr>
<tr>
<td>Hydrogen (%)</td>
<td>4.6%</td>
</tr>
<tr>
<td>(% of Fuels)</td>
<td>(6.3%)</td>
</tr>
</tbody>
</table>

In Belgium the CO$_2$ storage capacity assumed is much smaller, and due to the preference for using hydrogen in fuel cells, hardly any is consumed as final energy. In the 60% reduction case in 2030, hydrogen reaches its maximum share of 1.7% (or 2.8% of all fuels).

In Japan hydrogen production from nuclear energy, using Very High Temperature Reactors, is included within the so-called Integrated Energy System (IES). In the most severe emission reduction case (a carbon tax increasing to $250 by 2030), the direct use of hydrogen is again very limited: around 1.2% of total final energy (or 2% of all fuels). Much larger volumes are used in the energy sector, in particular in a sensitivity case with earlier introduction and a bigger potential for the IES. Besides oil refining and fuel cell electricity production, hydrogen is used within the IES for methanol production; see also Vol.II.

3.5 Role of Technologies

Vast arrays of technological options are included in various parts of the rational models; see also appendix C. In this chapter the role selected technologies play in CO$_2$ reduction cases is summarized.

3.5.1 Power and Heat Production

**Nuclear Power Reactors**

If nuclear power is considered and if it is not already utilized to the assumed maximum in the base case (as is the case in Belgium, Sweden and Switzerland), the capacity is always expanded in CO$_2$ reduction cases. The only exception is Quebec, where the one nuclear power plant already commissioned is never followed by further units because of the availability of large quantities of cheap hydro. Except in Canada (only CANDU reactors) and
Japan (also advanced concepts including fast breeder reactors), only light water reactors (LWR) are considered.

**Hydro Power**
In Norway and Quebec, already relying (almost entirely on hydro), its production is further increased to meet the demand for electricity that grows with more severe CO₂ reduction. In Sweden, Switzerland and Ontario, where hydro is a major resource, the larger part of the potential is already utilized in the base case. The remaining potential is called upon under CO₂ constraints.

**Solar Power**
Only in the USA does solar power (central PV and thermal) become competitive in the base case, due to the assumed low future cost and favourable conditions. In all other cases solar power only makes a contribution at relatively high CO₂ reduction cost levels, when most other "CO₂-free" supply options are exhausted.

**Other Renewables**
Where available, other renewables like wind, geothermal, wave, etc., are expanded. Wind power relies heavily on local conditions. Whereas limited potentials are identified at relatively low cost, in part already competitive in the base case, more expensive applications (e.g. in Switzerland, or offshore in Sweden and the Netherlands) are only chosen at more stringent CO₂ constraints.

**Fossil Power with CO₂ Removal**
In the Netherlands and Belgium, centralized power generation from coal and gas with CO₂ removal are a very important option, using combined cycles (IGCC, IGMCFC and GCC). If CO₂ storage capacity becomes tight, decentralized, combined heat and power generation is preferred. Hydrogen from natural gas with CO₂ removal is then used in molten carbonate fuel cells (MCFC) for cogeneration in industrial, residential and commercial sectors.

**Combined Heat and Power Generation**
In general, the application of cogeneration is enhanced if CO₂ emissions are reduced, unless sufficient nuclear and/or renewable resources can be introduced to meet the entire electricity demand. The tendency is towards technologies with higher power-to-heat ratios, since these allow for more electricity produced with low losses, given that heat markets are limited. Hence back-pressure turbines are replaced by gas turbines and combined cycles and in some cases even by fuel cells. If low- or zero-CO₂ hydrogen is available (Japan, Netherlands and Belgium), fuel cells become even more attractive, since these have a higher efficiency running on hydrogen than on gas.

### 3.5.2 Other Supply Options

**Biofuels**
With the exception of gaseous fuels generated from organic wastes (biogas from manure or sewage water treatment, gas recovered from landfills, etc.), producing synthetic fuels from biomass is hardly ever competitive, even under severe CO₂ limits; see also chapter 3.4.3. The cost of growing, or collecting, and transporting the organic matter is already considerable. In addition the fuel properties are relatively poor (low energy content by weight and
volume, high water content), giving rise to high capital costs and low net efficiencies for processing plants. Only in the USA do synthetic gaseous and liquid fuels from wood, herbaceous crops and other resources make a significant contribution in CO₂ reduction cases. In fact these options account for almost the entire increase in energy from biomass reported in table 3.3. Relatively low cost estimates for both resources and processing technologies, and comparatively high efficiencies contribute to these dissimilarities. In Norway and the Netherlands, relatively small volumes of straw and miscanthus are used to synthesize methanol for transport, but only at relatively high CO₂ reduction cost levels of over US$ 200 per tonne. In Belgium it is assumed that ethanol, produced from wheat in southern European countries, could be imported. This is actually introduced in the 40 and 60% reduction cases, at a lower marginal cost level of around US$ 125 per tonne of CO₂ reduced.

**Synfuels from Renewables**

Belgium and the Netherlands have included hydrogen produced from solar energy, as a backstop option in their analyses. The technical concept is to build large solar PV arrays in the Sahara desert, with electrolysis equipment and storage facilities. The hydrogen produced is to be transported to Northwestern Europe by long distance pipelines, crossing the Mediterranean Sea. Despite large declines assumed for the future cost of PV cells, the estimated cost of the hydrogen as delivered at the border ends up high at around US$ 30 per GJ in the year 2030 (equivalent with an oil price of US$ 170 per barrel). Only under extreme conditions, when almost all other options are exhausted and specific CO₂ reduction costs are thus very high, does this option become viable.

**Fossil Synfuels with CO₂ Removal**

Hydrogen (and methanol) can be produced from coal or gas, with removal of (part of) the carbon contained in the feed fuel. These options are included in the Netherlands and Belgium, besides CO₂ removal from fossil power plants and from industrial processes (Netherlands: nitrogen fertilizer from natural gas, hydrogen for internal use from refinery gases). Depending upon the assumed availability and cost of storage reservoirs, such options make significant to decisive contributions to reduce CO₂ emissions, starting from the 20% reduction cases and increasing with more severe reductions. When storage capacity becomes the limiting factor, gas-based production of hydrogen is the most favoured route. This is because the amount of CO₂ to be stored, as well as the residual emissions, per unit of fuel are the lowest. But also because fuel cells (for combined heat and power generation and to drive vehicles) are assumed available for high efficiency utilization of the hydrogen.

**Nuclear Fuel Upgrading**

Only in Japan are combined processes modelled, utilizing heat from Very High Temperature Reactors (VHTR) to upgrade fossil fuels and biomass, and even synthesize methanol from recovered CO₂. A range of interlinked conversion processes is integrated with VHTRs to yield electricity, heat at various temperature levels, hydrogen and synthetic gases and liquids. The total system is referred to as the Integrated Energy System (IES). In the tax case for CO₂ reduction, corresponding to the most severe CO₂ reductions, the IES is introduced up to the maximum capacity assumed; see also Vol.II.
3.5.3 Energy Saving at the End-Use Level

In each of the assessments a rich menu of energy saving options in the end-use sectors is included. The level of detail, also depending upon the level of sectoral aggregation adopted, differs from country to country.

Industry
In some cases individual industrial sectors are distinguished (e.g. Canada, Japan and Belgium), allowing for sector-specific conservation options and energy saving processes to be included. In other cases (e.g. the Netherlands and Switzerland) industry is highly aggregated, and technological progress, assuming reference energy price projections, is largely exogenous to the assessment. In both approaches alternatives to save energy on industry-wide unit operations are possible (e.g. more efficient steam boilers, furnaces and electric motors, heat pumps, waste heat recovery). Moreover, for some applications electricity and/or heat from cogeneration may substitute for fuels, reducing losses at the end-use level.

Residential and commercial
In the residential and commercial sectors, space heating requires the larger share of total energy demand. In general, existing houses and buildings are treated separately from new construction. The new houses and buildings often require less energy (insulation standards), and additional savings, through improved insulation and/or more efficient devices, are often cheaper or exclusive for new construction. Single family dwellings are distinguished from apartments and other buildings of different size. Energy conservation options included in the analyses are: high efficiency boilers, improved insulation (new and retrofitted) and various types of heat pumps. Similarly, savings for space cooling can be attained by better insulation and more efficient coolers. Space cooling is treated in detail in a few studies only; climatic conditions in many countries make space cooling less relevant.

Although water heating demand is also very significant, not many saving options are explicitly assessed. Heat pumps, either combined devices for space and water heat or small stand-alone electric heat pump boilers, are considered in some cases. For example, in the Netherlands the latter are introduced in CO₂ reduction cases. Moving from oil or gas water heaters to electricity can also reduce final demand for water heating.

Electric appliances and lighting account for a sizeable and growing share of total final demand. Options like more efficient light bulbs, improved refrigerators and freezers, hot-fill dishwashers and laundry machines, etc. are either modelled in detail as individual technologies, or as aggregated conservation supply packages yielding savings at extra investments.

Many conservation options identified and included in the residential and commercial sectors already become cost-effective in the base cases, leaving limited potential for further demand reductions if CO₂ constraints are imposed.

Transport
In most analyses, autonomous efficiency improvements are assumed for cars, trucks and other vehicles. In the US no autonomous improvements are assumed, but more efficient private cars running on oil products are included.
These are progressively introduced with more severe CO\textsubscript{2} constraints. In Switzerland and the Netherlands advanced, efficient car types are included, but these are already cost-efficient in the base case, due to rising energy prices and acid emission considerations. Diesel cars are in general more efficient than gasoline cars, but their market share is mostly limited exogenously to reflect market behaviour, which is often distorted by tax regimes. In principle, significant energy savings are possible by changes in the modal split, e.g. a shift from road to rail transport. Although MARKAL allows for such shifts to be modelled, this option is nowhere addressed.

**Savings on End-Use**

In aggregate, less final energy is used in the CO\textsubscript{2} reduction cases by implementing conservation options, introducing more efficient technologies and switching from fuels to electricity and heat. As shown in figure 3.11, the overall savings in 2020 range from 3.5% to close to 20%. It also illustrates the effect of switching to electricity: higher savings coincide with larger shifts to electricity. Only in the USA is less electricity used, because of the limited potential for additional nuclear and renewable capacity; see also Appendix B.

![Figure 3.11 Savings on Final Energy Use in the Maximum Reduction Cases](image)

**3.5.4 Alternative Transport Technologies**

**Alternative fuels**

Alternative fuels often have a lower CO\textsubscript{2} emission than oil products. For alcohols and hydrogen this depends on the energy carrier from which they are produced, but compressed natural gas (CNG) cars emit around 22% less. Using gaseous fuels in internal combustion cars requires extra costs for fuel injection and storage tanks, that are only made up for by reduced emissions at very high marginal costs (e.g. in Norway starting from the 400\$ CO\textsubscript{2} tax case).
If alcohol fuels from biomass (USA, Norway) and/or methanol from coal with CO₂ removal (Netherlands) become available, these fuels are used as car fuels; see also chapter 3.5.2.

**Electric Cars**
Provided that improved batteries become available, and that sufficient low-CO₂ electricity is available, electric cars can contribute to reduce emissions from the transport sector. In all studies one or more electric cars are assessed, but the estimated costs and efficiencies, relative to conventional cars, differ considerably. Leaving aside results from strongly deviating assumptions, electric cars appear attractive only to meet stringent CO₂ reduction targets at very high reduction costs. Electric city cars, assuming limited mileage and overnight recharging, come out as more promising than electric cars allowing for similar use patterns as conventional cars by exchanging empty battery packs for recharged ones at "refill" stations.

### 3.6 Cost of CO₂ Emission Reduction

The cost of CO₂ reduction strategies is of course of paramount importance. Ideally one would like to compare reduction costs with benefits from emitting less CO₂ to the atmosphere. The benefits represent either the reduction of environmental damages, or the cost of taking effective adaptive measures to deal with the consequences of substantially higher CO₂ concentrations in the atmosphere. The emission level where costs and benefits are equal then represents the optimal emission reduction level: reducing either more or less would yield less net benefit. However, both the damage function and the costs of adaptive strategies are extremely difficult to estimate in the light of the uncertainties associated with all factors linking CO₂ emissions to long-term effects.

Despite these uncertainties it is widely acknowledged that reducing CO₂ emissions will reduce risks of potentially serious consequences from climate change. The costs can thus be looked upon as paying for an insurance policy, aiming to reduce the risks. "Willingness-to-pay" for such an insurance policy then determines which actions to take, implicitly weighing short and medium term expenditures against potential long-term societal costs.

A frequently referenced problem when comparing costs across different assessments is the definition of what these costs actually stand for. Direct costs of optimized energy systems, as found e.g. by exercising models like MARKAL, may be confused with GDP losses indicated by macro-economic models. Average costs may be confused with marginal costs, direct costs with total costs including implementation costs to overcome market barriers, etc.

Cost indications derived from assessments with the MARKAL model clearly do not provide the full picture, since direct links with other sectors of the economy are not included. Nevertheless some useful insights can be gained from cost indicators derived from the analyses.

#### 3.6.1 Total Reduction Cost

The total amount of money incurred to reach a certain reduction of CO₂ emissions is found by comparing the energy system cost of the case
considered with e.g. the baseline. Some care must be taken if the reduction is
brought about by imposing a CO$_2$ tax, rather than a cap on emissions. The
CO$_2$ tax revenues are included in the energy system cost figure and, assuming
they are compensated for by lowering other tax rates, do not constitute a real
additional cost for the economy. Tax revenues should thus be removed from
the energy system cost of the reduction case considered.

In order to put the emission reduction cost in perspective, they are often
expressed as a percentage of the total GDP. It must be stressed that this per-
centage does not reflect the GDP loss associated with the reduction case.
Total reduction costs, average for the group of countries and the range for
individual countries, are presented in table 3.5 for selected CE and PR stra-
tegies and for the maximum reduction case.

Table 3.5 Total Reduction Cost in 2020 as Percentage of GDP$^*$

<table>
<thead>
<tr>
<th>% of GDP in 2020</th>
<th>Average</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE Strategies</td>
<td>Up to $100/tCO$_2$</td>
<td>0.14%</td>
</tr>
<tr>
<td></td>
<td>Up to $150/tCO$_2$</td>
<td>1.10%</td>
</tr>
<tr>
<td></td>
<td>Up to $250/tCO$_2$</td>
<td>1.16%</td>
</tr>
<tr>
<td>PR Strategies</td>
<td>Up to stabilization</td>
<td>1.07%</td>
</tr>
<tr>
<td></td>
<td>Up to 10% reduction</td>
<td>1.63%</td>
</tr>
<tr>
<td></td>
<td>Up to 20% reduction</td>
<td>1.67%</td>
</tr>
<tr>
<td>Maximum Reduction</td>
<td></td>
<td>1.75%</td>
</tr>
</tbody>
</table>

* Excl. Japan, for which costs for the energy sector only are given

3.6.2 Specific Reduction Cost

Besides the total cost it is interesting to investigate how much money is spent
per tonne of CO$_2$ reduced, the specific reduction cost. Clear distinctions must
be made between average, incremental and marginal cost of CO$_2$ reduction.

When comparing a certain case, say 30% reduction by 2020, with the base-
line, the average cost per tonne of CO$_2$ reflects the overall costs per tonne of
CO$_2$ reduced incurred with reaching this set target. A clear drawback of presen-
ting just average costs is that increasing costs associated with increasing
emission reduction targets are levelled out; see figure 3.12.

By comparing a certain case with the previous case, e.g. 30% with 20% re-
duction by 2020, rather than with the baseline, more insight is gained into the
cost consequences of each additional set of measures. These incremental costs
show how expensive each additional step becomes per tonne of extra CO$_2$
reduced from the previous case.
Figure 3.12  *Average Reduction Cost - All(9) Cases*

The last unit of CO$_2$ reduced will by definition be the most expensive one in optimization models, referred to as the *marginal cost*. Using MARKAL, the marginal costs equal the so-called shadow price of the CO$_2$ constraint imposed, or alternatively the CO$_2$ tax level introduced.

It will be obvious that incremental costs are always equal to or higher than average costs, and that marginal costs are in turn equal to or higher than incremental costs; see the example in figure 3.13.

Figure 3.13  *Average, Incremental and Marginal Reduction Cost in Belgium*
3.6.3 Cost Structure

The total system cost of any energy system consists of three basic elements:

- investment costs to replace and expand the capital stock in energy supply, conversion and end-use sectors
- fuel supply costs, broken down into expenditures for domestic fuels and/or for (net) imported fuels
- other costs like operating and maintenance costs, fuel delivery costs, et cetera.

Besides looking at how total additional costs develop when moving to lower CO$_2$ emission levels, it is also interesting to monitor how the different cost components change.

Typically, capital costs show the largest increase. More energy savings and higher efficiency equipment enter the system, substituting capital outlays for fossil fuel costs. Nuclear and renewable energy also require higher first cost than fossil fuel options. On the other hand, switching from coal to gas or to CO$_2$-free hydrogen may increase the average price of fuels. Depending upon domestic resource bases, a larger or smaller share of TPER may be served by domestic resources. When it comes to estimating macro-economic impacts, these individual effects are of at least equal weight as the overall cost increase. For instance, if the total extra cost amounts to 0.5% of GDP, but is the balance of 1% higher capital cost and 0.5% lower fuel cost, those extra capital costs may raise the total capital expenditures in the economy, typically around 20% of GDP in industrialized economies, by as much as 5%.

3.7 Impact of Growth Projections

For five countries (and provinces) two economic growth projections are used; see also chapter 2 for the baseline assumptions and results. In all cases the model structure and the technological and resource assumptions are equal in the High and Low projections, except for international energy price assumptions. Comparison of the results obtained for the High and Low projections can thus be made on a consistent basis.

CO$_2$ Emission Profiles and Maximum Reduction Attainable

Naturally less economic growth leads to a lower energy consumption and less CO$_2$ emissions. Figure 3.14 illustrates that not only the baseline emissions are much lower, but also that much more reductions from the 1990 level can be attained in the Low cases. Comparing with the respective baselines, similar reduction percentages of around 35% are observed in the year 2020.
Figure 3.14 Baseline and Maximum CO₂ Emission Profiles - High(5) vs. Low(5) Cases

The development of key scenario indicators does not differ much between the High and Low cases (see table 3.6) although the latter generally shows less extremes.

Table 3.6 Energy Intensity, Fossil Fuel Share, CO₂ Intensity of Fossil Fuel Mix and CO₂ per unit of GDP in 2020 for the Baseline and Maximum Reduction - High vs. Low Cases

<table>
<thead>
<tr>
<th></th>
<th>Baseline/Max. Reduction in 2020 (Index, 1990 =100)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energy Intensity</td>
</tr>
<tr>
<td></td>
<td>Primary Final</td>
</tr>
<tr>
<td>USA</td>
<td>-High 74/70 78/75</td>
</tr>
<tr>
<td></td>
<td>-Low 79/76 84/80</td>
</tr>
<tr>
<td>QUEBEC</td>
<td>-High 69/78 76/72</td>
</tr>
<tr>
<td></td>
<td>-Low 74/77 81/75</td>
</tr>
<tr>
<td>ONTARIO</td>
<td>-High 80/83 80/69</td>
</tr>
<tr>
<td></td>
<td>-Low 82/82 84/71</td>
</tr>
<tr>
<td>NETHERLANDS</td>
<td>-High 63/61 71/67</td>
</tr>
<tr>
<td></td>
<td>-Low 56/55 66/63</td>
</tr>
<tr>
<td>SWEDEN</td>
<td>-High 62/64 67/65</td>
</tr>
<tr>
<td></td>
<td>-Low 71/73 77/76</td>
</tr>
<tr>
<td>AVERAGE</td>
<td>-High 74/70 78/74</td>
</tr>
<tr>
<td></td>
<td>-Low 78/76 83/79</td>
</tr>
</tbody>
</table>

Cost Effective Reduction Strategies (CE)
Following the same approach as before (see chapter 3.2.), the compound cost-effective (CE) trade-off curves were established for the High and Low cases.
It is interesting to note that the two curves are not very different; see figure 3.15. The big difference however is the effort required to keep CO₂ emissions at the 1990 level, indicated in figure 3.15 by the difference in cost to reach stabilization.

![Graph showing cost-effective reduction strategies between High(5) and Low(5) cases.]

**Figure 3.15 Cost-Effective Reduction Strategies - High(5) vs. Low(5) Cases**

The associated marginal reduction cost curves in figure 3.16 confirm these findings. Stabilization of emissions for the High cases is reached at a marginal cost level that exceeds the Low case figure by a factor of two.

![Graph showing marginal cost curves between High(5) and Low(5) cases.]

**Figure 3.16 Marginal Cost Curves - High(5) vs. Low(5) Cases**
Primary Energy Consumption

The pattern is again very similar for the two growth projections; see figure 3.17. The baseline demand for coal is affected most by the lower consumption level. The increase of 20% versus 71% underlines the role of coal as the most important supplier of growing future demand if no CO₂ restricting policies are assumed.

In both projections renewables and natural gas are the key supply options if CO₂ emissions are to be reduced, whereas nuclear just about recaptures its 1990 market share.

Figure 3.17  Primary Energy Consumption in 2020 - High(5) vs. Low(5) Cases
APPENDIX A. THE MARKAL MODEL

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

A.1 Basic Principles

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

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

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

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

The solution to the linear program describes a set of energy technologies and energy flows that constitute an energy system that is feasible and optimal. Feasibility means that all the numbers add up correctly and that all the constraints are satisfied. Optimality means that of the hundreds or thousands of feasible solutions, this is the one that has the least cost (if cost is the objective function). To see how the MARKAL linear program finds an optimal energy system, consider the following simple example.
A.1.1 MARKAL Demystified

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

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

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

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

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

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

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

These results are shown in the primal solution of the linear program. Additional information on the value of the technologies is given in the dual solution which is obtained at the same time.
Figure A.1.1  Example Problem: Data
Figure A.1.2 Example Problem: 1st Period Solution
Figure A.1.3  Example Problem: 2nd Period Solution
A.1.2 Shadow Prices

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

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

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

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

A.1.3 Reduced Cost

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

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

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

1988

Market Penetration

Maximum
Actual

Technology Z
Pulverized Coal
$C/kWh

Technology Y
$B/kWh

Technology X
$A/kWh

Actual

Figure A.1.4 Example Problem: Shadow Price and Reduced Cost
A.2 Modelling Emission Reduction

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

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

A.2.1 Modelling Environmental Constraints

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

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

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

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

A.2.2 Modelling Emission Reductions with the Objective Function

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

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

A.2.3 Summary of the Example

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

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

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

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

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

A.3 PC-MARKAL and MUSS Development

The MARKAL model now operates in a "user-friendly" PC-based processing environment centered around an integrated analysis support tool, the MARKAL Users Support System (MUSS). The system features the conveni-
ent management of the MARKAL data dictionary which can be used to represent related aspects of the energy system as flow charts. Model execution turnaround time is typically less than one hour for matrix generation, optimization and report writing of several scenarios. Side-by-side comparison of results across scenarios are seen and printed with "touch-of-a-button" graphics.

A.3.1 PC-MARKAL

Originally, the MARKAL model was run on large mainframe computers. Results were in the form of lengthy paper-copy printouts, one for each scenario. To show comparisons of different scenarios on graphs, data would have to be extracted from different printouts, compiled, and plotted.

In the present personal computer form, corresponding results from different scenarios are shown side-by-side and can be printed as graphs by pressing one key. Computer costs are far less, and the modeller does not depend upon a staff of computer operators. There is no compromise in the size of the models; linear programming matrices of more than 5 thousand rows and columns are common.

The development of personal computers with the 30386 microprocessor running at 25 to 33 megahertz or more, a personal computer version of OMNI software for matrix generation and report writing, 386HSLP and XPRESS LP optimization software, and colour graphics have ushered in a new era.

OMNI-based MARKAL was first run on a personal computer at Chalmers University of Technology, Sweden, in 1988-89 when standard MARKAL Version 2.01 was successfully transferred. To develop the potential of this new modelling platform, Brookhaven National Laboratory undertook an effort to provide a "user-friendly" computer format for applying MARKAL Version 2.11. With the cooperation of Haverly Systems, Inc., necessary syntactical changes were made, and the basic processing environment was established. There was also some minor reprogramming of the interpolation, discounting, and salvage value algorithms. Using the 1985 USA MARKAL database, the Research Center Jülich, Germany, assisted by verifying the model results within 0.01 percent.

A.3.2 MARKAL User’s Support System (MUSS)

Further work at Brookhaven developed an integrated processing environment, MUSS, and speeded up overall performance through programming modifications. A set of five runs testing the effect of different input assumptions typically can be solved in less than one hour.

MUSS was developed to handle the three main aspects of working with MARKAL:

- Management of the computer environment
- Data development and maintenance
- Comparison and interpretation of results
MUSS is written in the Clipper/C programming language. MUSS ensures proper use of computer resources by controlling the execution environment and enforcing file naming conversions. The MARKAL data dictionary of classes and tables together with MUSS support files (e.g., analysis tables, help files, OMNI command files) are managed in a relational database. To assist with the interpretation of the optimization results, many of the MARKAL reports are brought on line as part of the relational database where they can be examined by means of numerous graphical displays.

MUSS capabilities can be grouped into five main areas as shown in figure A.3.1: data dictionary processing, MARKAL input and command file generation, optimization results analysis, scenario management, and system utilities.

Figure A.3.1 MUSS Menu Hierarchy
The MUSS user interface has the following features:

- A standard screen layout with consistent presentation of processing options and error conditions
- "Pop-up" menus to control processing
- "Help" information which provides detailed instructions in context at all points in the system at the touch of a key
- Database cross-referencing that provides the user with a high degree of feedback (e.g., technology acronym descriptions, windows to show reduced costs of technology when viewing results)
- "Finger-tip" colour graphics to examine results and compare scenarios and cases
- Point-of-entry quality control that reduces data input errors by warning the user of mistakes
- Function key support to promote ease of use of the system.

Thus, the integrated PC-MARKAL/MUSS system provides a convenient, productive environment in which to carry out energy systems analysis.

REFERENCES


APPENDIX B. SUMMARY COUNTRY REPORTS

B.1 BELGIUM

The country study for Belgium is performed in close cooperation between the Centre for Economic Studies (CES) of the Catholic University, Leuven and the Flemish Institute for Technological Development (VITO) in Mol. The research is financed by the Belgian Science Policy Office in the framework of the impulse programme "Global Change". After having played an active role in earlier phases of IEA-ETSAP, during which the MARKAL model was developed, Belgium did not participate during the larger part of the eighties. At the beginning of Annex IV the decision was made to rejoin and teams at CES and VITO were formed to build national scenarios and model databases, focusing on the impacts of greenhouse gas reduction schemes. Within the joint project CES, having a well established position in the field, takes responsibility for the socio-economic scenario and the associated energy demand projections. VITO compiles information on technological and environmental data and defines suitable structures for the MARKAL model.

B.1.1 Scenario and Cases

The scenario for Belgium is based on an assumed economic growth of 1.8% per year for the OECD and rising energy prices, the price of oil e.g. doubling between 1990 and 2030. In this "business as usual" scenario, no drastic changes in the economic and energy policy are assumed, resulting in a GDP growth just over the OECD average, see table B.1.1.

Table B.1.1 Scenario Assumptions for Belgium

<table>
<thead>
<tr>
<th>Scenario Assumptions</th>
<th>BELGIUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDP (AAGR* 1990-2030)</td>
<td>2.00%</td>
</tr>
<tr>
<td>Population in 2030 (Mln; 1990=10.0)</td>
<td>10.4</td>
</tr>
<tr>
<td>Energy Prices (AAGR* 1990-2030)</td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>0.92%</td>
</tr>
<tr>
<td>Oil</td>
<td>1.84%</td>
</tr>
<tr>
<td>Natural Gas**</td>
<td>1.43-2.11%</td>
</tr>
</tbody>
</table>

* AAGR: Average Annual Growth Rate  
** The lower rate is valid for the baseline demand, higher rates up to the maximum for additional gas demands in CO₂ reduction cases

The growth of the industrial and service sectors falls just above the GDP growth, reaching 2.3%. The useful energy demands show a lower growth (see table B.1.2), due to consumer reactions on energy price increases and structural shifts in the Belgian economy towards less energy intensive sectors. This structural shift continues current trends.
Table B.1.2 *Growth of Sectoral Useful Demand in Belgium (AAGR)*

<table>
<thead>
<tr>
<th>Growth Rate [%/y]</th>
<th>1990/2010</th>
<th>2010/2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial Sector</td>
<td>1.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Residential Sector</td>
<td>-Heating</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>-Other Use</td>
<td>2.0</td>
</tr>
<tr>
<td>Other Sectors</td>
<td>1.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Transport Sector</td>
<td>-Passengers</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>-Goods</td>
<td>1.4</td>
</tr>
</tbody>
</table>

No environmental constraints, other than CO₂, are imposed besides the planned technological prerequisites imposed by the European Community and the agreement between the electric utilities and the Belgian authorities on acid emissions. Sulphur dioxide from electricity production must decrease to reach 50% of the current release by 2010 and subsequently stay on that level, while NOₓ emissions are constrained to 80% of the current release from 2010 onwards. The limits set are binding only in the baseline, with NOₓ appearing to be the more difficult emission to control. In all other cases the caps imposed are not reached, indicating that the CO₂ reduction strategies have a positive side effect on acid emissions from the electricity supply sector.

An ambitious nuclear power programme has resulted in a dominating position in the power sector. The 5485 MW capacity on line today supplies over 60% of all electricity in Belgium. The government has decided to freeze current capacity until 2005, with the exception of one unit of 548 MW starting production in 1997. After 2005 a maximum capacity of 8 GW is allowed, including replacement of expired existing capacity.

### B.1.2 Baseline Scenario and CO₂ Constraints

**CO₂ Emissions**

The baseline CO₂ emissions show a modest increase of 10% until 2005/2010 to stabilize thereafter, see figure B.1.1. In total four different CO₂ constraints are imposed, each starting from 1995 at the current level. One case keeps emission at that same level, while in the other three the annual cap is lowered linearly to reach 20%, 40% and 60% reduction by the year 2030.
Figure B.1.1 CO₂ Emission Profiles for Belgium: Baseline Projection and Constraints.

Final Energy Use
Due to both autonomous efficiency improvements and price-induced savings, final energy demand grows approximately 0.4% less than the demand for energy services in the baseline. The share of electricity and heat is increasing, the latter produced in combined heat and power plants. With moderate CO₂ emission targets, additional savings on fuel use emerge and heat from cogeneration expands. In the more stringent reduction cases, electrical end-use devices are replacing fuel based technologies. Overall final energy use is reduced by up to 22% in 2030, while the share of fuels decreases; see figure B.1.2. The only renewable fuels penetrating are imported bio-ethanol and to a lesser extent solar based hydrogen in the transport sector, and only if 40% or more emission reduction is requested.
Figure B.1.2 *Final Energy Use in Belgium in 2030*

Electricity Production
The larger part of the baseline growth of 1.1% per year in electricity demand is met by production in combined heat and power (CHP) plants up to 2015 and thereafter by expansion of nuclear power. Coal is phased out almost entirely by 2010, but towards the end of the time horizon a revival starts to emerge. High-efficiency, clean integrated coal gasification combined cycle power plants (IGCC) are called upon when further growth of nuclear power and CHP is not economically viable. Following these developments natural gas and oil, used in CHP plants, take a much larger share in the electricity production fuel mix, largely at the expense of coal. With CO₂ progressively constrained the demand for electricity increases, see figure B.1.2. Nuclear power is expanded more rapidly, but is not allowed to exceed the upper capacity limit of 8 GW and coal disappears entirely as a power station fuel. More and more electricity comes from CHP plants, fuelled with gaseous energy carriers, even though the heat production is only marginally increasing, see figure B.1.3. This is explained by a shift from gas turbine and engine powered CHP units to fuel cells with a higher power-to-heat ratio. In conjunction with this shift towards fuel cells, natural gas and oil products are gradually replaced by hydrogen.
Figure B.1.3  *Electricity Generation by Input in Belgium in 2030*

**Primary Energy Consumption**

The prescribed reduction of CO₂ emissions is brought about by an accelerated build-up of nuclear capacity, reaching its maximum already in the stabilization case, by changes in the fossil fuel mix (more gas, less coal and oil), by more efficient energy use and by additional energy conservation. Renewables penetrate only on a significant scale with high CO₂ emission reduction targets.

Hydrogen is in the first instance produced from natural gas with the CO₂ recovered from the process and stored in aquifers. Afterwards, imported renewable hydrogen is gradually replacing hydrogen from natural gas, as the cost to produce it from solar energy in desert areas or from hydropower decreases with the expected technological evolution and as the underground CO₂ storage capacity is limited. Together with much smaller amounts of imported bio-ethanol this renewable hydrogen increases the share of renewables in primary energy supply, see figure B.1.4. With hydrogen and bio-ethanol entering the transport fuel market, the use of oil goes down. Gas takes a larger share and part of the gas is converted into hydrogen with CO₂ removal.
Figure B.1.4 *Primary Energy Consumption in Belgium in 2030*

**CO₂ Reduction Cost**
Up to the 40% reduction case the total cost of capping CO₂ emissions is relatively modest. If 60% reduction is prescribed, total extra cost reaches up to 3% of annual GDP, see table B.1.3. Structural changes in energy supply concentrate on switching fuels for other fossil (gas) or synthetic, renewable (hydrogen, bio-ethanol) energy carriers. Therefore the additional capital outlay required falls below the total extra cost.

<table>
<thead>
<tr>
<th>CO₂ Reduction</th>
<th>Case:</th>
<th>CONSTANT</th>
<th>-20%</th>
<th>-40%</th>
<th>-60%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Cost</td>
<td>Avg.</td>
<td>.04%</td>
<td>.18%</td>
<td>.48%</td>
<td>1.06%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.07%)</td>
<td>(.45%)</td>
<td>(1.28%)</td>
<td>(3.08%)</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>Avg.</td>
<td>.09%</td>
<td>.22%</td>
<td>.42%</td>
<td>.66%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.19%)</td>
<td>(.39%)</td>
<td>(.85%)</td>
<td>(1.34%)</td>
</tr>
</tbody>
</table>

*Average = Unweighted average over all periods in which constraints are imposed
Maximum = Maximum found in any period in which a constraint is imposed

In particular the costs of importing hydrogen from the Sahara are high, driving up the marginal cost of CO₂ reduction in the more severe CO₂ reduction cases, see figure B.1.5.
Figure B.1.5 *Marginal Cost of CO₂ Reduction in Belgium*
B.2 CANADA: QUEBEC AND ONTARIO

The study reported on builds on earlier work done at GERAD, addressing in some detail the impacts of restricting emission of sulphur and nitrogen oxides in the two largest provinces of Canada: Quebec and Ontario. Similar results are obtained for CO₂ emissions, assuming that SO₂ and NOₓ levels emissions are also constrained at pre-specified levels. Both separate models for the two provinces were significantly modified and augmented over the last two years. Besides the cases reported here, a number of sensitivity analyses are carried out, e.g. relating to restricted build-up of nuclear and hydro power. The benefits from interprovincial cooperation is also subject of study.

B.2.1 Scenarios and Cases

For both provinces two economic scenarios were constructed, leading to associated high and low energy demand projections. Underlying assumptions on average GDP growth differ markedly between the two provinces, with Ontario showing higher rates, see table B.2.1. This is in fact well established in the economic history. Starting from slightly different levels in 1990, due to differences in delivery cost and product nature, moderate price escalation rates were assumed for imported energy carriers. In part these moderate prices explain the relatively high GDP growth rates. Another factor, in particular for Ontario, is the population growth.

<table>
<thead>
<tr>
<th>Scenario Assumptions</th>
<th>QUEBEC</th>
<th></th>
<th>ONTARIO</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>GDP (AAGR* 1990-2020)</td>
<td>2.1%</td>
<td>1.35%</td>
<td>2.5%</td>
<td>1.8%</td>
</tr>
<tr>
<td>Population in 2020 (Mln; 1990=6.7 and 9.7)</td>
<td>7.7</td>
<td>7.3</td>
<td>13.7</td>
<td>13.2</td>
</tr>
<tr>
<td>Energy Prices (AAGR* 1990-2020)</td>
<td>Coal</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>Oil</td>
<td>0.92%</td>
<td>0%</td>
<td>0.80%</td>
</tr>
<tr>
<td></td>
<td>Natural Gas</td>
<td>1.97%</td>
<td>0%</td>
<td>1.43%</td>
</tr>
</tbody>
</table>

* AAGR: Average Annual Growth Rate

As to acid gas emissions: NOₓ is limited to its observed 1985 level, while SO₂ is not to exceed 50% of the 1980 level, both from 1995 onwards.

B.2.2 Baseline Scenarios and CO₂ Constraints

CO₂ Emissions
CO₂ constrained cases assume that the 2000 level equals that of 1990, while starting from 2000 emissions are to decline linearly to various percentages by the year 2030. For Quebec the 2030 reduction percentages used are 0, 10, 20, 35 and 50%. For Ontario the highest percentage could not be satisfied at
reasonable costs, therefore only the percentages 0, 10, 20 and 35% were imposed. The resulting emission profiles are given in figure B.2.1.

Figure B.2.1 CO₂ Emission Profiles for Quebec and Ontario: Baseline Projections and Constraints.

Figure B.2.1 indicates that to limit CO₂ emissions to their current level already constitutes a major effort in the Quebec/High scenario and in both the Ontario scenarios. Factors contributing to the strong increase in these baseline profiles are: relatively high per capita economic growth, relatively modest improvement of the energy intensity (in Ontario) and an increasing share of fossil fuels with coal showing the stronger growth (in Ontario). At the same time these baseline trends suggest ample room for improvements.

Final Energy Use
Additional savings at the end-use level of 18% (Quebec) to 23% (Ontario) make a significant contribution, accompanied by a larger share of electricity, see figure B.2.2, and introduction of hydrogen.

Figure B.2.2  Final Energy Use in Quebec and Ontario in 2020

Electricity Production
The resulting additional demand for electricity is met by bringing more hydropower capacity on line in Quebec and by building increasing numbers of new CANDU nuclear reactors in Ontario, replacing new coal fired power plants, see Figure B.2.3.
Figure B.2.3  Electricity Generation by Input in Quebec and Ontario in 2020

Primary Energy Consumption
Overall primary energy consumption, measured as fossil fuel equivalents, increases. In part this is attributable to additional losses in e.g. hydrogen production, but also to the conversion factors used for non-fossil fuels. In fact the demand for fossil fuels drops steeply, see figure B.2.4., yielding the CO₂ emission reduction levels specified earlier. In Ontario the role for coal, expanding in the baseline to up to 1/3 of TPER, becomes negligible starting from the stabilization case.
Figure B.2.4 *Primary Energy Consumption in Quebec and Ontario in 2020*

In summary the CO₂ reductions are brought about primarily by large shifts to non-fossil fuels, in Ontario accompanied by a complete phase-out of coal. Secondly savings at the end-use level make their contribution, helped by a shift to more electricity use.
CO₂ Reduction Cost
The costs of the CO₂ reduction cases are significant, notably the capital requirements associated with energy saving and non-fossil supply options. In both provinces additional investments exceed the total extra costs by a factor of roughly 2, the balance coming from reduced fuel costs.

Table B.2.2 Additional Costs in Quebec and Ontario, Average and Maximum Percentage of GDP*

<table>
<thead>
<tr>
<th>CO₂ Reduction Case:</th>
<th>CONSTANT</th>
<th>-10%</th>
<th>-20%</th>
<th>-35%</th>
<th>-50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUEBEC/High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cost</td>
<td>Avg.</td>
<td>.16%</td>
<td>.20%</td>
<td>.24%</td>
<td>.31%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.45%)</td>
<td>(.58%)</td>
<td>(.70%)</td>
<td>(.87%)</td>
</tr>
<tr>
<td>Investments</td>
<td>Avg.</td>
<td>.26%</td>
<td>.34%</td>
<td>.45%</td>
<td>.59%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.64%)</td>
<td>(.92%)</td>
<td>(1.12%)</td>
<td>(1.33%)</td>
</tr>
<tr>
<td>QUEBEC/Low</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cost</td>
<td>Avg.</td>
<td>.04%</td>
<td>.06%</td>
<td>.11%</td>
<td>.19%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.10%)</td>
<td>(.14%)</td>
<td>(.26%)</td>
<td>(.56%)</td>
</tr>
<tr>
<td>Investments</td>
<td>Avg.</td>
<td>.05%</td>
<td>.08%</td>
<td>.13%</td>
<td>.30%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.17%)</td>
<td>(.21%)</td>
<td>(.31%)</td>
<td>(.99%)</td>
</tr>
<tr>
<td>ONTARIO/High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cost</td>
<td>Avg.</td>
<td>.47%</td>
<td>.58%</td>
<td>.69%</td>
<td>.99%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(1.16%)</td>
<td>(1.29%)</td>
<td>(1.37%)</td>
<td>(1.79%)</td>
</tr>
<tr>
<td>Investments</td>
<td>Avg.</td>
<td>.97%</td>
<td>1.11%</td>
<td>1.26%</td>
<td>1.66%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(1.94%)</td>
<td>(2.07%)</td>
<td>(2.47%)</td>
<td>(3.45%)</td>
</tr>
<tr>
<td>ONTARIO/Low</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cost</td>
<td>Avg.</td>
<td>.26%</td>
<td>.35%</td>
<td>.47%</td>
<td>.67%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.67%)</td>
<td>(.81%)</td>
<td>(.98%)</td>
<td>(1.48%)</td>
</tr>
<tr>
<td>Investments</td>
<td>Avg.</td>
<td>.41%</td>
<td>.61%</td>
<td>.81%</td>
<td>1.08%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.92%)</td>
<td>(1.26%)</td>
<td>(2.05%)</td>
<td>(2.54%)</td>
</tr>
</tbody>
</table>

*Average = Unweighted average over all periods in which constraints are imposed
Maximum = Maximum found in any period in which a constraint is imposed

The high costs are also reflected by the marginal costs per tonne of CO₂ reduced, see figure B.2.5. It is interesting to note the different shapes of the curves. The low demand scenarios tend to level off, whereas the high demand scenarios show a steep increase. This suggests, that in high demand cases call upon more extreme, high cost options to reach the most ambitious targets than are required in the low demand cases to reach the same targets.
Figure B.2.5  Marginal Costs of CO$_2$ Reduction vs. CO$_2$ Reduced in Quebec and Ontario in 2020
B.3 JAPAN

The work reported on is carried out at the Energy Systems Assessment Laboratory at the Tokai Research Establishment of the Japan Atomic Energy Research Institute (JAERI), where MARKAL is in use for many years. Over that period a wide variety of studies was performed, including assessments of new technological options, impacts of acid emission constraints and integrated energy/environment/economy studies. Further work is done, addressing i.a. sensitivity analyses, technology evaluation and energy-economy interactions by using the MARKAL-MACROEM model; see also chapter 1.4.3.

B.3.1 Scenario and Cases

The scenario submitted assumes high and low economic growth and associated energy demands. The population is expected to peak around 2010 and starts to decline afterwards. The prices of imported oil and natural gas (LNG) increase more than the import price of coal, see table B.3.1.

Oil and gas prices roughly double between 1990 and 2030, while the price of coal increases by a factor of around 1.5.

Table B.3.1 Scenario Assumptions for Japan

<table>
<thead>
<tr>
<th>Scenario Assumptions</th>
<th>JAPAN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
</tr>
<tr>
<td>GDP (AAGR* 1990-2030)</td>
<td>2.51%</td>
</tr>
<tr>
<td>Population in 2030 (Mln; 1990=123.6)</td>
<td>121.2</td>
</tr>
<tr>
<td>Energy Prices (AAGR* 1990-2030)</td>
<td>Coal 1.08%</td>
</tr>
</tbody>
</table>

* AAGR: Average Annual Growth Rate

No external constraints on acid emissions are imposed. However, emissions are accounted for in two cases: constant emission coefficients over the entire time horizon and decreasing coefficients associated with additional abatement measures.

The CO₂ reduction measures are divided into energy conservation, further divided into rational utilization of of heat and power, efficiency improvements, recycle of heat and materials, fuel switching, and technology substitution.

Nuclear energy utilization is expected to expand in the future. As for power generation, in addition to the conventional LWR with enriched uranium fuel, plutonium is recycled for use in both thermal and fast reactors. In the field of nuclear heat applications, high temperature heat is applied for producing hydrogen in the Integrated Energy System (IES), featuring the symbiotic use of fossil fuels, biomass and nuclear energy.
B.3.2 Baseline Scenario and CO\textsubscript{2} Constraints

**CO\textsubscript{2} Emissions**
In line with current policy goals, CO\textsubscript{2} emissions on a per capita basis are stabilized until 2005. Starting from that year three alternative constraints are imposed: constant at the 2005 emission level and linear reduction to 20% and 35% reduction from the 1990 level by the year 2030, see figure B.3.1.

Furthermore progressive carbon tax cases for the high and low scenario, starting in 1995, are studied as follows:

<table>
<thead>
<tr>
<th>Carbon Tax Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
</tr>
<tr>
<td>CO\textsubscript{2}-Tax [US$/tonne]</td>
</tr>
</tbody>
</table>

The emission profiles resulting from this carbon tax scheme are also included in figure B.3.1.

![Graph](image)

**Figure B.3.1 CO\textsubscript{2} Emission Profiles for Japan: Baseline Projections, Constraints and Tax Cases**

In the high demand scenario the baseline emissions show a relatively modest increase of about one third, despite the GDP growth by a factor of over 2.5. Under the low demand scenario the increase in the baseline emissions remains at less than 20% of the 1990 level. In the carbon tax case the absolute amount of the emissions is almost constant until 2000, decreasing thereafter with 42% in 2030. The decline of final energy used per unit of GDP in the baseline to 50% of the, already relatively low, 1990 level is the primary explaining factor. Savings and efficiency improvements, fostered by rising energy prices, contribute to this improvement of energy intensity together with structural changes in the economy.
On the supply side nuclear energy production triples and renewable energy supply doubles, reducing the share of fossil fuels from 85% to 69%. Among the fossil fuels coal is growing, while the use of oil declines and natural gas supply remains at the same level. As a result the carbon intensity of fossil fuel use rises.

The carbon tax case yields the lowest CO₂ emissions, indicating that the tax level in each year exceeds the marginal CO₂ reduction cost associated with the most severe CO₂ constraint imposed (35% reduction by 2030).

Final Energy Use
Starting from the baseline, additional savings within the end-use sectors are still available, but only to a limited extent. The final energy intensity in 2030 is reduced by at most 10%. The role of electricity is governed by two opposing forces. On the one hand more efficient electric appliances reduce the electricity demand, on the other hand a switch to electric alternatives replacing fuel use. On aggregate the total electricity demand increases slightly compared to the baseline, see figure B.3.2.

![Final Energy Use in Japan in 2030](image)

**Figure B.3.2** Final Energy Use in Japan in 2030

Electricity Generation
By far the larger part of the growth in electricity demand in the baseline is met by nuclear power. Hydropower and other renewables can just about maintain their market share, while coal increases at the expense of oil products. With increasing CO₂ reductions the share of fossil fuel based electricity declines, see figure B.3.3.

Coal based power generation is affected the most, initially replaced by oil products and LNG and later by LNG alone. In the high demand scenario primarily nuclear power generation increases up to the 20% reduction case. Beyond that point nuclear cannot increase further because of an externally given upper bound. So hydro power and other renewables fill the increasing gap between total demand and fossil supply. The baseline and tax cases in the
low demand scenario show similar results, except for a lesser contribution by nuclear power and renewables because of lower constraints given to them.

Figure B.3.3 *Electricity Generation by Input in Japan in 2030*

**Primary Energy Consumption**
The overall primary energy intensity decreases in the baseline, but less so than final energy intensity. This is caused by the expanded use of coal and also by the larger share for electricity generated with significant heat losses, that could be reduced e.g. by cogeneration. Primary energy consumption in 2030 decreases with higher CO₂ reductions, due to the savings in the end-use sector as well as deployment of more efficient energy conversion technology like combined cycle LNG power plants and fuel cells. Changes in the electricity sector, in terms of both its relative importance and its input fuel mix as mentioned above, are largely responsible for the changed primary energy use patterns, see figure B.3.4.

CO₂ reductions are thus primarily brought about by a shift to non-fossil fuels, in particular for electricity generation. To a lesser extent shifts towards less CO₂ emitting fossil fuels and energy savings at the end-use level help to limit CO₂ emissions. Various technologies contribute to CO₂ reduction through the shift towards non-fossil fuels. In the maximum reduction case even expensive renewable technologies, like solar photovoltaic electricity generation, perform better than fossil technologies. Hydrogen produced by the IES is utilized in various application areas, including recycling CO₂ for methanol production besides use in oil refineries (hydro-cracking and desulphurization of heavy fuel oil), fuel cells and direct consumption.
Figure B.3.4 Primary Energy Consumption in Japan in 2030

CO₂ Reduction Cost
The total costs of CO₂ reduction measures within the energy sector, so excluding most end-use devices, do not exceed 0.2% of GDP, see table B.3.2. The extra expenditures almost entirely consist of additional investments, amounting to less than one percent of total investments in the national economy.

Table B.3.2 Additional Costs and CO₂ Tax Revenues in Japan, Average and Maximum Percentage of GDP*

<table>
<thead>
<tr>
<th>Scenario:</th>
<th>High</th>
<th>High</th>
<th>High</th>
<th>High</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ Reduction Case:</td>
<td>CONSTANT</td>
<td>-20%</td>
<td>-35%</td>
<td>TAX</td>
<td>TAX</td>
</tr>
<tr>
<td>Total Cost</td>
<td>Avg. (Max.)</td>
<td>.02% (.06%)</td>
<td>.07% (.15%)</td>
<td>.08% (.21%)</td>
<td>.11% (.18%)</td>
</tr>
<tr>
<td>Investments</td>
<td>Avg. (Max.)</td>
<td>- .06% (.01%)</td>
<td>.09% (.12%)</td>
<td>.13% (.19%)</td>
<td>.13% (.22%)</td>
</tr>
<tr>
<td>CO₂-Tax Revenues</td>
<td>Avg. (Max.)</td>
<td>- - -</td>
<td>- - -</td>
<td>1.55% (2.25%)</td>
<td>1.81% (3.25%)</td>
</tr>
</tbody>
</table>

*Average = Unweighted average over all periods in which constraints or taxes are imposed
Maximum = Maximum found in any period in which a constraint or tax is imposed

Although less fossil fuel is used, total fuel import costs do not change much because the LNG replacing steam coal has a much higher price.
The marginal costs of CO$_2$ reduction in the high demand scenario are given in figure B.3.5., together with the tax level in the carbon tax case. The cost curves show that with time more CO$_2$ reductions from the baseline are feasible at a given marginal cost reduction level. It is also shown that the carbon tax level, the dotted top end of the curves, exceeds the marginal cost of the 35% reduction case significantly, but does not yield much more emission reductions.

Figure B.3.5  Marginal Costs of CO$_2$ Reduction in Japan
B.4 THE NETHERLANDS

ECN-Policy Studies has been using MARKAL for more than 10 years as a tool in various studies ranging from comparative evaluations of new technologies to assessments of impacts of acid emission constraints and to exploring technological strategies to reduce emission of CO₂. Over the last two years the model has been extended with detailed energy conservation options, technologies for CO₂ removal and hydrogen technologies. This research is co-financed by the National Research Programme on Global Air Pollution and Climate Change and the Ministry of Economic Affairs. Currently the model is being expanded to represent material and product flows in conjunction with energy flows and environmental emissions.

B.4.1 Scenarios and Cases

The two scenarios consider the period between 2000 and 2040. The year 2000 is used as a starting point; energy demand in 2000 is based on a continuing economic growth and current government policy. Starting from 2000 one of the scenarios can be characterized as a high-growth and the other scenario is like a low-growth economic scenario, see table B.4.1. However differences in energy demand are also due to e.g. differing shifts of the industrial structure and different transportation modal splits. The high-growth scenario represents a kind of "business-as-usual" scenario with a continuing large role for the energy-intensive industries, a continuation of the growth in the energy-intensive agriculture and a rapidly growing transportation sector. In the low-growth scenario the service sector becomes relatively more important. Due to a changing public attitude and policy measures, transportation increases less rapid in this scenario. The increase of energy prices is moderate in both scenarios.

Table B.4.1 Scenario Assumptions for the Netherlands

<table>
<thead>
<tr>
<th>Scenario Assumptions</th>
<th>NETHERLANDS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
</tr>
<tr>
<td>GDP (AAGR° 2000-2030)</td>
<td>2.0%</td>
</tr>
<tr>
<td>Population in 2030 (Mln; 1990=15.0)</td>
<td>17.0</td>
</tr>
<tr>
<td>Energy Prices (AAGR° 1990-2030)</td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>1.39%</td>
</tr>
<tr>
<td>Oil</td>
<td>1.96%</td>
</tr>
<tr>
<td>Natural Gas**</td>
<td>1.91-2.67%</td>
</tr>
</tbody>
</table>

* AAGR: Average Annual Growth Rate
** The lower rates are valid for the baseline demand, higher rates up to the maximum for additional gas demands in CO₂ reduction cases

Useful energy demand, excluding international marine bunkers, grows on average by 1.1% in the high-growth scenario and 0.1% in the low-growth scenario, so well below the GDP growth. This decrease in energy intensity is due to autonomous efficiency improvements and structural changes in the economy.
Currently the Netherlands energy system relies heavily on natural gas: 98% of all houses are connected to the natural gas grid and approximately 50% of electricity production is based on natural gas. This is due to existence of considerable domestic gas reserves. The potential for renewable energy within the Netherlands is limited due to climatic and geographical restrictions; only for wind energy do favourable conditions exist. Within 15 years it is expected that the Netherlands will have capacity for storage of CO₂ in depleted natural gas fields or aquifers allowing for CO₂ removal options. Such options have been considered either for electricity generation or for synfuel production (e.g. hydrogen). Nuclear energy was treated as an option in variant scenarios only, not reported here.

Acid emissions (SO₂ and NOₓ) are severely constrained in all scenarios and cases. In 2030 they may not exceed 15% of the 1990 emission level.

B.4.2 Baseline Scenarios and CO₂ Constraints

CO₂ Emissions
Despite continuing economic growth, CO₂ emissions in 2000 are at the same level as 1990 emissions as a result of current energy conservation policy and a constant fuel mix. Thereafter emissions in the high-growth and low-growth scenario show an increase of 32% and 5% until 2030 respectively. The increase of baseline emissions of CO₂ is a result of various mechanisms. Energy demand increases and the share of coal in the primary energy mix grows, especially for electricity generation and methanol production. On the other hand the baseline includes significant efficiency improvements and end-use savings.

![CO₂ Emission Profiles for the Netherlands: Baseline Projections and Constraints](image)

Figure B.4.1 CO₂ Emission Profiles for the Netherlands: Baseline Projections and Constraints

The CO₂ constraints for the reduction cases follow linear paths from 2000 to 2030 and then stabilize. Reduction percentages imposed for the year 2030
include 0%, 20%, 40%, 50%, 60%, 70% and 80%. The latter case resulted in extremely high marginal reduction costs in the High scenario and is therefore omitted from the further analysis.

Final Energy Use
Due to autonomous efficiency improvements and price-induced savings, final energy use in the base case grows approximately 0.4% less per year than the demand for energy services. Under CO₂ constraints final energy requirements decrease further as a result of additional savings and a switch from fuels to electricity, see figure B.4.2. Total use decreases by up to 9% by 2030, while the share of fuels drops from 77% to around 70% in the same year. Starting from the 40% reduction case in the high scenario (and from 60% in the low scenario), hydrogen serves an increasing share of the remaining demand for fuels.

![Figure B.4.2 Final Energy Use in the Netherlands in 2030](image)

Electricity production
Without a constraint on the emissions of CO₂, electricity production evolves gradually. Conventional gas and coal-fueled power plants are replaced by Integrated Coal Gasification Combined Cycle power plants (IGCC) for central electricity production. Additional electricity comes from industrial cogeneration, wind turbines and wood-fired power plants.

The preferred electricity generation mix varies strongly with the CO₂ reduction targets, see figure B.4.3. Under modest CO₂ constraints (up to 20% reduction), total electricity production is stable as a result of a balance between additional use for CO₂ removal and savings on end-use. Industrial cogeneration and renewables (onshore wind turbines) replace coal-fired plants. At medium CO₂ constraints (around 40% reduction), advanced coal power plants (IGCC, IGMCFC) with CO₂ removal are introduced, resulting in less gas-based cogeneration. At severe CO₂ constraints (50% and more reduction), the coal-fired power plants are in turn replaced by hydrogen-fueled cogeneration.
and by solar photovoltaic (PV) cells. The hydrogen is mainly produced from natural gas with CO₂ removal.

![Graph showing electricity generation by input in the Netherlands in 2030](image)

**Figure B.4.3** *Electricity Generation by Input in the Netherlands in 2030*

**Primary Energy Consumption**

At modest emission reduction targets, the shares of the different primary fuels in the primary energy mix is relatively stable. The small potential for renewables in the Netherlands does not allow for a more prominent position. With a ban on new nuclear power plants assumed in this scenario, the energy system continues to rely on fossil fuels. Depending on the fuel prices, specific emissions factors of coal and gas, CO₂ recovery rates of CO₂ removal processes and limitations for the CO₂ storage capacity, the energy system shifts from gas to coal (in combination with CO₂ removal) at medium emission reductions and back from coal to gas (again in combination with CO₂ removal) at more drastic emission reductions (figure B.4.4). Above 50% emission reduction hydrogen becomes a prominent energy carrier. Production of hydrogen from natural gas by steam reforming in combination with storage of CO₂ in gas fields and aquifers is then the dominant option for CO₂ limitation.
Figure B.4.4  Primary Energy Consumption in the Netherlands in 2030

**CO₂ reduction cost**

On the longer run, very substantial emission reductions can be achieved at marginal reduction costs below 200 US$/tCO₂ (see figure B.4.5). However, as CO₂ removal technologies will hardly be available in 2010, the attainable emission reduction is much smaller and marginal costs increase rapidly in that year, in particular in the high scenario.

Figure B.4.5  Marginal Costs of CO₂ Reduction in the Netherlands
Appendix B: Country Summaries

Total costs to reach even the most ambitious CO₂ reduction targets considered do not exceed 2% of the GDP in any year; see table B.4.2. The reduction strategies are capital intensive: up to the 50% reduction cases capital costs rise more than the total costs. Beyond that, they still account for the major part of the additional cost.

Table B.4.2  Additional Costs in the Netherlands, Average and Maximum Percentage of GDP*

<table>
<thead>
<tr>
<th>CO₂ Reduction Case</th>
<th>CONSTANT</th>
<th>-20%</th>
<th>-40%</th>
<th>-50%</th>
<th>-60%</th>
<th>-70%</th>
<th>-80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Netherlands/High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cost</td>
<td>Avg.</td>
<td>.08%</td>
<td>.17%</td>
<td>.41%</td>
<td>.60%</td>
<td>.86%</td>
<td>1.26%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.14%)</td>
<td>(.30%)</td>
<td>(.72%)</td>
<td>(1.03%)</td>
<td>(1.43%)</td>
<td>(2.01%)</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>Avg.</td>
<td>.11%</td>
<td>.20%</td>
<td>.50%</td>
<td>.62%</td>
<td>.75%</td>
<td>.97%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.23%)</td>
<td>(.37%)</td>
<td>(.87%)</td>
<td>(1.03%)</td>
<td>(1.26%)</td>
<td>(1.39%)</td>
</tr>
<tr>
<td>Netherlands/Low</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cost</td>
<td>Avg.</td>
<td>0%</td>
<td>.05%</td>
<td>.15%</td>
<td>.27%</td>
<td>.44%</td>
<td>.65%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.01%)</td>
<td>(.09%)</td>
<td>(.31%)</td>
<td>(.56%)</td>
<td>(.88%)</td>
<td>(1.24%)</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>Avg.</td>
<td>.01%</td>
<td>.07%</td>
<td>.14%</td>
<td>.30%</td>
<td>.40%</td>
<td>.41%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.03%)</td>
<td>(.15%)</td>
<td>(.32%)</td>
<td>(.57%)</td>
<td>(.74%)</td>
<td>(.89%)</td>
</tr>
</tbody>
</table>

*Average = Unweighted average over all periods in which constraints are imposed
Maximum = Maximum found in any period in which a constraint is imposed
B.5 NORWAY

After absence from the ETSAP programme since Annex II, Norway rejoined at the start of Annex IV in 1990. The participation in ETSAP and the studies are performed by the Institutt for Energiteknikk (IFE) at Kjeller and is funded by the Royal Ministry of Industry and Energy and the Research Council of Norway, Department of Scientific and Industrial Research. The results reported here are based upon the first analyses with a newly developed representation of the Norwegian energy system in MARKAL.

B.5.1 Scenario and Cases

One scenario for relevant socio-economic developments is used as starting point for the analyses. It is based on assumptions and outcomes from a macro-economic study made for the Interdepartmental Climate Group in Norway. The scenario was developed in cooperation between the Central Bureau of Statistics and IFE.

The offshore petroleum sector is very important for the Norwegian economy and is treated in this study separately from the mainland economy. Fixed production rates and prices for oil and gas are assumed. The oil production is expected to peak around 1997, while the gas production doubles from today’s level by 2005 and stabilizes thereafter. On aggregate a moderate economic growth is represented in the scenario: 2.0% per year up to the year 2000 and 1.7% in later years, see table B.5.1.

Table B.5.1 *Scenario Assumptions for Norway*

<table>
<thead>
<tr>
<th>Scenario Assumptions</th>
<th>NORWAY</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDP (AAGR* 1990-2030)</td>
<td>1.77%</td>
</tr>
<tr>
<td>Population in 2030 (Mln; 1990=4.25)</td>
<td>4.73</td>
</tr>
<tr>
<td>Energy Prices (AAGR* 1990-2030)</td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>.39%</td>
</tr>
<tr>
<td>Oil</td>
<td>.91%</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>1.25%</td>
</tr>
</tbody>
</table>

* AAGR: Average Annual Growth Rate

In addition to the shift from offshore to mainland industrial activities, a gradual structural change from energy intensive industries (chemicals, base metals) to other manufacturing sectors is assumed in the scenario. For each (sub-)sector and application relevant indicators for the useful energy demand development are identified. Together with autonomous, exogenous assumptions for energy demand coefficients and efficiency improvements these lead to a modest annual growth in useful energy demand of 0.6% overall, ranging from 0.2% for the residential and service sectors to 1.5% for transportation. In addition technological energy saving options in the industry, residential and service sectors are represented in detail in the MARKAL model.
The current Norwegian energy system relies heavily on relatively cheap electricity from hydropower (110 TWh). Due to local environmental impacts, less than half of the remaining potential of 70 TWh is available for building. Furthermore the long and windy coastline offers good perspectives for wind power generation, in this study a potential of 10 TWh is assumed. Nuclear energy is not considered in this study.

Restrictions on emissions other than CO₂ are not included in the analyses reported.

### B.5.2 Baseline Scenario and CO₂ Constraints

**CO₂ Emissions**

Several assumptions and restrictions play an important role in the projected baseline CO₂ emissions and the viability of reduction strategies. First, the exogenously prescribed offshore oil and gas production profiles take into account technical energy efficiency improvements in oil and gas production units, but do not include additional measures like CO₂ removal and storage or electricity supply from mainland hydropower through cables. In the absence of data available for such options, the significant CO₂ release from offshore operations is tied to the production levels, see figure B.5.1. Secondly, no alternatives are considered for the use of coal and coke as reduction agent in metals production, accounting for around 10% of current CO₂ emissions in Norway. Moreover it is decided to build a methanol production plant using natural gas as feedstock and process fuel, starting operation in 1996 for a period of 20 years. The CO₂ emissions associated with this plant will account for around 2% of today’s total emission level.

A wide range of CO₂ reduction strategies is investigated. Besides annual constraints prescribing stabilization and reductions up to 20% by 2030, CO₂ taxes are imposed at various levels: 25, 50, 133, 250, 400, 500 and 1000 US$/per tonne CO₂. Figure B.5.1 shows the baseline emission profile, together with the constraints and emission profiles resulting from various CO₂ tax levels.

Figure B.5.1 clearly shows that, with the assumptions and restrictions in place, significant emission reductions are not easily achieved. Looking at the outcome of the 400 US$/ tax case, stabilizing at the current level is already associated with high marginal costs. Even at very high costs, see e.g. the 1000 US$/ tax case, not much more than 20% reduction from the current level is achieved. This is not surprising, since there is no room for measures in the electricity sector (100% hydropower) and large shares of heat demands are already served with electricity.
Figure B.5.1 $CO_2$ Emission Profiles for Norway: Baseline Projection, Constraints, Impact of $CO_2$-Tax and the Offshore Emission Level

Final Energy Use
In the baseline the share of electricity is decreasing with time, because the transport demand for fuels is growing faster than the largely electricity based industrial, service and residential demands. Due to the introduction of heat pumps and more energy conservation, total final energy demand is growing at 0.44% per year only. This is less than the useful demand growth despite the shift from highly efficient electricity use to less efficient use of fuels. With more severe $CO_2$ emission reduction more expensive energy saving options are introduced, leading to a cut of 10% in final energy demand in 2030, see figure B.5.2. At the same time the trend to use more fuels and less electricity is reversed by bringing more expensive hydropower and other renewable electricity on line. Electricity is also used in the transport sector to replace oil products, either directly in electric vehicles or indirectly for production of hydrogen for vehicles through electrolysis.
Figure B.5.2 Final Energy Use in Norway in 2030

Electricity Generation
Electricity supply in Norway is and remains entirely based on renewable resources. The increasing demand resulting from CO$_2$ reduction schemes is met by building more expensive hydropower capacity and eventually by introduction of wind power, see figure B.5.3. Total supply grows less than inland demands, because exports, up to 10 TWh in the base-case, are reduced. The revenues of exports at the set tariff fall below the value of electricity used domestically to reduce CO$_2$ emissions.

Primary Energy Consumption
In the baseline the growing primary energy consumption is to a large degree met by an increase in the use of fossil fuels, in particular oil products for the transport sector. Imposition of CO$_2$ constraints results in savings on fuel use and a shift to electricity, whereby the share of renewables in total primary energy consumption increases. Oil use is decreased the most as methanol, electricity and hydrogen enter the transport market, see figure B.5.4. Since hydro power production is reported here in fossil equivalents, the switch from fossil fuel to electricity for heat production occurring under CO$_2$ constraints causes primary energy consumption to rise in the figure.
Figure B.5.3  *Electricity Generation in Norway in 2030*

Figure B.5.4  *Primary Energy Consumption in Norway in 2030*
CO₂ Reduction Cost
As figure B.5.5 indicates, reduction of CO₂ emissions from the Norwegian energy system is relatively expensive in terms of the cost per tonne of CO₂.

![Graph showing CO₂ Emission Reduction](image)

Figure B.5.5 *Marginal Cost of CO₂ Emission Reduction in Norway*

The total additional costs are considerable, even though only limited cuts are technically feasible. The increased capital cost requirements are almost as high as the total extra costs. Since even high CO₂ tax levels do not lead to large emission reductions, the tax revenues equal a large share of GDP.

Table B.5.2 *Additional Costs and CO₂ Tax Revenues in Norway, Average and Maximum Percentage of GDP*

<table>
<thead>
<tr>
<th>CO₂ Reduction Case:</th>
<th>CONSTANT</th>
<th>-10%</th>
<th>$133-TAX</th>
<th>$250-TAX</th>
<th>$400-TAX</th>
<th>$500-TAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Cost</td>
<td>Avg.</td>
<td>.44%</td>
<td>.65%</td>
<td>.13%</td>
<td>.16%</td>
<td>.53%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.81%)</td>
<td>(1.65%)</td>
<td>(.19%)</td>
<td>(.27%)</td>
<td>(.90%)</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>Avg.</td>
<td>.38%</td>
<td>.57%</td>
<td>.12%</td>
<td>.14%</td>
<td>.49%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.74%)</td>
<td>(1.49%)</td>
<td>(.17%)</td>
<td>(.25%)</td>
<td>(.81%)</td>
</tr>
<tr>
<td>CO₂-Tax Revenues</td>
<td>Avg.</td>
<td></td>
<td></td>
<td>2.7%</td>
<td>5.0%</td>
<td>7.6%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td></td>
<td></td>
<td>(3.8%)</td>
<td>(7.2%)</td>
<td>(11.4%)</td>
</tr>
</tbody>
</table>

*Average = Unweighted average over all periods in which constraints or taxes are imposed
Maximum = Maximum found in any period in which a constraint or tax is imposed
B.6 SWEDEN

In former years the Energy Conversion Department of Chalmers University of Technology in Gothenburg concentrated on MARKAL applications on the local (communities) and regional (e.g. areas served by electric utilities) level. These assessments, always done in close cooperation with all relevant stakeholders, have often resulted in a successful transfer of the MARKAL model to an institution responsible for energy planning in the community or region. The question of environmental constraints such as acid emission and CO₂ reduction policies has been the focal point for these studies, together with establishment of robust strategies to hedge against uncertain future stresses on the energy systems. Building upon the knowledge gained in the sub-national studies, Chalmers University recently executed the national assessment for Sweden reported here.

B.6.1 Scenarios and Cases

Contrasting high and low economic growth scenarios were estimated to serve as background for the assessment of CO₂ reduction strategies. Population growth is estimated at 0.3% per year in both cases, with the GDP growing at 2.3% and 1% respectively.

In contrast to most other assessments, energy taxes are included in the Swedish model to capture their influence on the actual decision making process. Taxes imposed are excise fuel taxes by fuel type, electricity consumption taxes for small consumers, a special fee on nuclear generated electricity to cover waste disposal costs. In addition emission fees for SO₂ and CO₂ are included, the latter equivalent to 42 US$ per ton CO₂. A value added tax of 25% is levied on the prices including all other taxes and the emission fees. Provisions are made to avoid double taxes in the case of electricity generation.

Table B.6.1 Scenario Assumptions for Sweden

<table>
<thead>
<tr>
<th>Scenario Assumptions</th>
<th>SWEDEN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
</tr>
<tr>
<td>GDP (AAGR* 1990-2030)</td>
<td>2.30%</td>
</tr>
<tr>
<td>Population in 2030 (Mln; 1990=8.59)</td>
<td>9.78</td>
</tr>
<tr>
<td>Energy Prices (AAGR* 1990-2030Coal Before Taxes)</td>
<td>1.11%</td>
</tr>
<tr>
<td>Oil Prod.</td>
<td>1.51-1.56%</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>1.78%</td>
</tr>
</tbody>
</table>

* AAGR: Average Annual Growth Rate

The currently prevailing policy with regard to nuclear power is a phase-out of reactor capacity in place today at the end of their lifetime. However, with the baseline technology characterisation, no reductions in CO₂ emissions from today’s level could be achieved in the High scenario in that case. Therefore two alternative assumptions were adopted: (a) to allow rebuilding nuclear
power plants replacing those discarded, thus maintaining up to the current 10 GWe capacity; or (b) unbounded future capacity. The cases considered here start from the first alternative, so capping nuclear capacity at 10 GWe.

B.6.2 Baseline Scenario and CO₂Constraints

CO₂ Emissions
In Sweden CO₂ emissions were already reduced by 30% during the eighties, largely due to a large-scale nuclear programme, making electricity the most cost-effective option for e.g. heating of single family houses and replacing individual oil heating. Furthermore biomass burning for oil in primarily the pulp and paper industry due to rising oil prices and energy conservation in the residential sector. As a consequence the electricity sectors CO₂ emissions are negligible today and emissions from the industrial and the residential sectors are far less than a decade ago. After the completion of this massive transfer of the energy sector Sweden’s CO₂ emissions levelled over the last few years, with only the transport sector showing a growing trend. Following the above evolution, Sweden now falls below most other industrialized countries when it comes to the CO₂ released per unit of GDP, despite the large share of energy intensive industries in the economy.

Starting from this position, CO₂ emissions will start to rise again in the baseline high demand scenario, despite an improvement in energy intensity, resulting in a 43% increase in final energy demand at the same time where GDP increases by almost 150%. In the low scenario CO₂ emissions drop further from the current level until 2010, before starting to rise again. The energy intensity improvement is less than in the high scenario, reflected in the final demand ending up 14% higher than today.

Two reduction cases are identified: keeping CO₂ emissions constant at the 1990 level from the year 2000 onwards and a reduction of 10% in 2005 and of 20% from 2010 onwards, see figure B.6.1.

Emissions increase in the baseline, while fossil fuels and coal in particular supply the larger part of the growing energy demand. The share of fossil fuels thus increases and so does their carbon intensity. On the final energy level heat and electricity are growing faster than the use of fuels. This indicates that changes in the energy conversion sector and the fuel mix play a dominant role. In fact imported steam coal alone account for an increase of CO₂ emissions of 43 million tonnes in the high scenario, slightly less than 90% of the total increase between 1990 and 2030.
Figure B.6.1 CO₂ Emission Profiles for Sweden: High and Low Baseline Projections and Constraints

Final Energy Use
Since nuclear expansion is limited and additional renewable electricity capacity is increasingly expensive, no major contribution to CO₂ reduction can be expected from a larger share for electricity in final energy use. The major change observed is to move from (fossil) fuels to renewables, mainly biomass for industrial process heat, see figure B.6.2.

Figure B.6.2 Final Energy Use in Sweden in 2030
Electricity Generation
Electricity supply is currently dominated by nuclear, hydropower and other renewables, together serving 94% of the total demand. In the baseline scenarios renewables only grow modestly, while nuclear does not even reach its upper bound in the low scenario, see figure B.6.3. The growth in electricity demand is covered primarily by fossil fuelled power plants. With CO₂ constraints imposed, changes in the energy supply mix are quite different in the two scenarios. If demand is low, fossil fuels are replaced by nuclear power up to its maximum capacity. In the high demand scenario this option is no longer available and more expensive wind and wave power is introduced on a large scale to make up for the fossil based electricity.

Primary Energy Consumption
The overall primary energy intensity deteriorates, but this is due to the increased electricity production from non-fossil fuels and the accounting factor used. In fact final energy use declines slightly, helped by the switch from fuels to electricity. The use of fossil fuels drops, coal is squeezed out and natural gas replaces oil for heating purposes. Small amounts of natural gas are also used in CHP plants. As figure B.6.4 illustrates, the share of fossil fuels in 2030 is decreased by one-third to half and this shift to non-fossil fuels thus provides the largest contribution to reduce CO₂ emissions. Next comes a 10% to 17% lowering of the carbon intensity of fossil fuel use. Additional savings in the end-use sectors make only a modest contribution.
Figure B.6.3  Electricity Generation by Input in Sweden in 2030

Figure B.6.4  Primary Energy Consumption in Sweden in 2030
CO₂ Reduction Cost
The total costs of CO₂ reductions are not easily determined, since all energy and emission tax revenues are included. These tax revenues decrease with cuts in CO₂ emissions, leaving the question open of alternative taxation policies to off-set this loss in government income. Clearly such questions cannot be answered without turning to sufficiently detailed economic impact assessments. As a first approximation the loss in tax revenues could be added again to obtain a result comparable to results of other analyses not including taxes. Additional investment expenditures are considerable in the high scenario. Table B.6.2 illustrates the extra investments, together with the total extra cost, underestimated due to the tax effect.

Table B.6.2 Additional Cost in Sweden, Average and Maximum Percentage of GDP*

<table>
<thead>
<tr>
<th>CO₂ Reduction Case:</th>
<th>CONSTANT</th>
<th>-20%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SWEDEN/High</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cost</td>
<td>Avg.</td>
<td>.16%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.37%)</td>
</tr>
<tr>
<td>Investments</td>
<td>Avg.</td>
<td>.38%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.91%)</td>
</tr>
<tr>
<td><strong>SWEDEN/Low</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cost</td>
<td>Avg.</td>
<td>.01%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.13%)</td>
</tr>
<tr>
<td>Investments</td>
<td>Avg.</td>
<td>.05%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.22%)</td>
</tr>
</tbody>
</table>

*Average = Unweighted average over all periods in which constraints are imposed
Maximum = Maximum found in any period in which a constraint is imposed

The marginal costs of CO₂ emission reduction, including the tax effect, are presented in figure B.6.5. As might be expected the CO₂ reduction costs are much higher in the high scenario. The baseline emissions end up at a far higher level in 2030 and with nuclear restricted more expensive renewable options are called upon to meet the prescribed emission constraints.
Figure B.6.5  *Marginal Costs of CO₂ Reduction in Sweden*
B.7 SWITZERLAND

The study on the Swiss energy system and greenhouse gas scenarios is performed by the Section of Environmental Economics of the Paul Scherrer Institute, Villigen. It is the most recent one in a sequence of MARKAL applications for Switzerland addressing varying topics related to energy supply and demand, which started in the early eighties. This study evaluates scenarios on the medium term development (up to 2025) of the Swiss energy system, taking into consideration recommendations of the IPCC and the Toronto Conference on world climatic sustainability. In addition to the impact assessment of CO$_2$ control only work is done on various ways to include other greenhouse gases, released from the energy system as well as other economic sectors.

B.7.1 Scenario and Cases

Socioeconomic assumptions, i.e. population, GDP growth, industrial production, building stock and car ownership, underlying the scenario for Switzerland are taken from a study by the St-Gallen Centre for Future Research. The annual population growth of 0.3% combined with a moderate productivity growth, allows a relatively low economic growth of 1.55% up to 2000, which is then reduced to 1.25%. In total the GDP increases by 60% over the time period considered, see table B.7.1. The shares of industrial and service sectors in GDP increase marginally.

The prices of oil and gas are assumed to double in the next 15 years and remain constant afterwards. The price of coal does not change from the current level.

Table B.7.1 Scenario Assumptions for Switzerland

<table>
<thead>
<tr>
<th>Scenario Assumptions</th>
<th>SWITZERLAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDP (AAGR* 1990-2025)</td>
<td>1.33%</td>
</tr>
<tr>
<td>Population in 2025 (Mln; 1990=6.72)</td>
<td>7.46</td>
</tr>
<tr>
<td>Energy Prices (AAGR* 1990-2025)</td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>0%</td>
</tr>
<tr>
<td>Oil</td>
<td>2.0%</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>2.0%</td>
</tr>
</tbody>
</table>

*AAGR: Average Annual Growth Rate

Together with estimates of the specific energy consumption coefficients, the socioeconomic parameters are fed into a sectoral energy demand simulation model (SMEDE). The resulting energy demand projection includes technical improvements of energy consuming devices, but excludes additional strong conservation measures that would only be implemented by policy measures like legislation. It must be noted that the scenario assumptions and energy projection are associated with the so-called "Nuclear Moratorium" imposed by public vote in 1990. The Moratorium restricts nuclear power capacity to the
current level. Due to technical improvements and an enhanced utilization of the capacity, the production can still increase 25%.

Acid emissions are constrained in all cases to comply with a proposed "clean air concept" of the Swiss Government. This concept implies that by the year 2000 NO\textsubscript{x} emissions may not exceed 54 kilotons, or a reduction to 1/3 of the 1990 level. After 2000 a linear further reduction to 45 kilotons by 2025 is imposed. The annual SO\textsubscript{2} emission cap proposed appears to be underscored in all cases.

B.7.2 Baseline Scenario and CO\textsubscript{2} Constraints

CO\textsubscript{2} Emissions
Three CO\textsubscript{2} reduction cases are studied, in all three emissions up to 2000 are the same as in 1990. From 2000 onwards emissions are stabilized at the same level and reduced linearly by 20% and 30% in the year 2025 respectively, see figure B.7.1.

![Figure B.7.1 CO\textsubscript{2} Emission Profiles for Switzerland, Baseline Projection and Constraints](image)

In the baseline CO\textsubscript{2} emissions increase by around 12%, at the same time where final energy consumption grows by 22.5%. Therefore structural changes contribute to restrict the growth of CO\textsubscript{2} emissions, like a larger share of electricity, see figure B.7.2, and natural gas gaining at the expense of oil products.

Conservation options are introduced in different subsectors, mainly for electricity and heat demands, by means of step-functions defining conservation potential against its cost. Energy demand could be further reduced due to e.g. emission constraints depending upon the competitiveness of energy conservation relative to supply options.
Final Energy Use
Moving to lower CO$_2$ constraints energy savings and a shift to electricity replacing fuels for e.g. residential heating using electric heatpumps and electric city cars. In the 20% and 30% reduction cases the final energy use in 2015 ends up at the 1990 level again, see figure B.7.2.

![Final Energy Use in Switzerland in 2025](image)

**Figure B.7.2 Final Energy Use in Switzerland in 2025**

Electricity Generation
On aggregate electricity production grows faster than final or primary energy use in the baseline. Up to the year 2000 nuclear power plants supply the major part of increasing electricity demand. Electricity production from renewables, mainly hydropower, grows slightly and after 2000 fossil fuel, mainly coal for industrial cogeneration power plants, play the leading role to meet growing demands.

The total electricity demand in 2025 is subject to two opposing trends. On the one hand savings in electric appliances in the residential and commercial sectors, on the other hand introduction of electric cars, electric heat pumps, electric back-up for solar water heaters, etc. On aggregate the total production increases, despite additional conservation equivalent with up to 14% of the baseline demand. Further growth of nuclear electricity is not possible under the Moratorium and fossil fuelled electricity generation is squeezed out. Due to the higher demand and the reduction of fossil power plants, renewable electricity production increases its share, mainly by calling upon wind and solar power, see figure B.7.3.
Figure B.7.3  
Electricity Generation by Fuel in Switzerland

**Primary Energy Consumption**

Primary energy consumption grows in the baseline by almost 1% per year on average. The share of fossil fuels decreases only slightly from 54% to 52% and because both coal and gas increase at the expense of oil the carbon intensity of the fossil fuel mix remains at the same level. In the CO₂ constraint cases the total primary energy consumption ends up around the same level in 2025, in part the fossil fuel equivalent accounting of non-fossil fuels being responsible for off-setting the savings accomplished at the end-use level. The share of fossil fuel declines further from 52% to 35%. First coal is affected and then also oil, see figure B.7.4, leading to a lower carbon intensity of fossil fuel use.

The reduction of CO₂ in the constraint cases is brought about primarily by a shift to non-fossil fuels. With the electricity production becoming almost "CO₂-free", energy conservation and a shift to electric devices at the end-use level, both leading to savings on fuels, are also major contributors. The less carbon intensive fossil fuel mix also helps to cut back emissions.
Figure B.7.4  Primary Energy Consumption in Switzerland in 2025

**CO₂ Reduction Cost**
The total costs of reducing CO₂ emissions in Switzerland to the prespecified levels do not exceed 0.9% of the GDP. Due to the conservation measures and capital intensive renewable options that are introduced, additional investments are higher than extra total cost, see table B.7.2.

Table B.7.2  Additional Costs in Switzerland, Average and Maximum Percentage of GDP*

<table>
<thead>
<tr>
<th>CO₂ Reduction Case:</th>
<th>CONSTANT</th>
<th>-20%</th>
<th>-30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Cost</td>
<td>Avg.</td>
<td>.03%</td>
<td>.22%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.07%)</td>
<td>(.45%)</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>Avg.</td>
<td>.10%</td>
<td>.46%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.15%)</td>
<td>(.81%)</td>
</tr>
</tbody>
</table>

*Average = Unweighted average over all periods in which constraints are imposed
Maximum = Maximum found in any period in which a constraint is imposed

It must be noted that the total CO₂ emission level per unit of GDP is already low in the baseline and so the reductions achieved cumulatively do not amount to large absolute quantities. The specific costs of CO₂ reduction in Switzerland are high, as is illustrated by the marginal reduction costs in figure B.7.5.
Figure B.7.5 *Marginal Costs of CO₂ Reduction in Switzerland*
B.8 UNITED STATES

From the very beginning of the development of energy systems analysis in the framework of cooperative IEA activities Brookhaven National Laboratory (BNL) in Upton, Long Island was involved as a crucial contributor. In fact the MARKAL model was developed drawing i.a. upon earlier similar models developed and used at BNL. After a period of less active modelling work in the mid-eighties, more recently new MARKAL applications are developed to analyze the New York State energy system and the nationwide USA system, both primarily concentrating on greenhouse gas abatement strategies. Besides PC versions of MARKAL and the MARKAL User's Support System (MUSS) were developed, together constituting the commonly used set of tools within ETSAP. Very interesting pioneering work is done in the field of linking MARKAL with macro-economic approaches, which has lead to the new, fully integrated energy/economy/environment model MARKAL-MACRO (see also chapter ...). The study reported on is carried out with financial support from the Department of Energy.

B.8.1 Scenarios and Cases

Two socio-economic scenarios are developed, a high-growth (2.1% GDP) and a low-growth (1.3%) scenario. The population is expected to grow at the same rate in both scenarios, resulting in a 20% larger population in 2030. The price of internationally traded fossil energy carriers increases, the price of imported crude oil doubling between 1990 and 2030. The price of imported gas, both by pipeline and as LNG shipped in tankers, grows faster than that the oil price. The same is true for export of hard coal, see table B.8.1. It should be noted that the import and export volumes of gas and coal respectively are restricted. The price on the domestic market of these fuels is therefore governed by the inland resource base and extraction costs, rather than by the international market prices given here.

Table B.8.1 Scenario Assumptions for the USA

<table>
<thead>
<tr>
<th>Scenario Assumptions</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
</tr>
<tr>
<td>GDP (AAGR* 1990-2030)</td>
<td>2.07%</td>
</tr>
<tr>
<td>Population in 2030 (Mln; 1990=250.6)</td>
<td>302.2</td>
</tr>
<tr>
<td>Energy Prices (AAGR* 1990-2030)</td>
<td>Coal 2.15%</td>
</tr>
<tr>
<td></td>
<td>Oil</td>
</tr>
<tr>
<td></td>
<td>Natural Gas</td>
</tr>
</tbody>
</table>

* AAGR: Average Annual Growth Rate

Assuming sectoral changes and exogenous efficiency improvements, energy demand projections were derived from the two macro-economic scenarios. The resulting demand for energy services grows by around 1.5% per year in the high scenario and 1% in the low scenario.
Acid emission policies are not specifically addressed in this study.

For nuclear power only conventional LWR reactors are considered. The currently operating capacity of 99.6 GWe is gradually withdrawn, while new capacity is not assumed to start operation before 2010. Consequently the maximum nuclear capacity cannot exceed the current level until after the year 2020. By 2030 at most twice the current LWR capacity could be installed: 210 GWe.

Separate analyses are performed, assuming various technologies for CO$_2$ removal and storage to become available. The options include CO$_2$ scrubbers for power plants and hydrogen production from coal, the CO$_2$ to be stored in depleted gas wells or in the deep ocean. Other routes consider integrated processes, the so-called Hydrocarb technologies, producing methanol from coal or gas and biomass. The solid byproduct carbon from the Hydrocarb plants must either be used in coal power plants or stored, see also Appendix D.

B.8.2 Baseline Scenarios and CO$_2$ Constraints

CO$_2$ Emissions
In the high scenario the baseline CO$_2$ emissions increase continuously to reach a 57% higher level than today by 2030. Due to the lower growth the baseline emissions in the low scenario remain more or less stable until 2005 and start to increase afterwards. The 2030 level is some 20% above the current release, see figure B.8.1. Starting from 1995 CO$_2$ constraints are imposed, either keeping emissions at the current level or decreasing linearly to reach -10%, -20% and -30% in the year 2030. The two most severe constraints appeared to be feasible in the low scenario only. In addition a carbon tax case was analyzed for the high scenario. The tax is imposed from 1995 onwards, starting at 15$ per tonne C and increasing at 10% per year. As figure B.8.1 shows this increasing tax scheme is insufficient to reach stabilization within the timeframe considered.
Figure B.8.1 CO$_2$ Emission Profiles for the USA: Baseline Projections, Constraints and Impact of an Increasing Carbon Tax on the High Scenario

Final Energy Use
Final energy demand grows slightly less than the demand for energy services in the baseline, due to cost-efficient savings at the end-use level. Nevertheless, final energy use in 2030 is 40% and 70% higher than today in the low and high scenario. The breakdown of final energy use is hardly changed over time, with fuels supplying around 80% of the total. Heat from cogeneration or coupled production plays no significant role and renewables serve no more than 3%.

With increasingly severe CO$_2$ constraints additional savings up to 3.5% are realised, while the direct use of renewables at the end-use level increases, reaching a share of up to 10%. In contrast to many other analyses no growing share for electricity is observed, in the high scenario it even loses a few percent, see figure B.8.2. The share of fuels drops to around 75%, with coal being replaced progressively by gas in the industrial, residential and commercial sectors.
Figure B.8.2  *Final Energy Use in the USA in 2030*

**Electricity Generation**

Since the share of electricity is not changed over time much in the baseline, total electricity produced grows at about the same rate as final energy use. However, the fuel input mix for power plants changes drastically. In 1990 two thirds of all electricity comes from fossil fuels, with coal alone supplying over 50%. Nuclear power plants take a share of almost 20% and renewables, almost entirely hydropower, supply the balance of almost 15%.

Building new nuclear power plants appears hardly or not competitive against cheap coal power and new renewable electricity options. A large fraction of the renewable electricity potential included in the analyses, consisting of various geothermal, wind, wave, OTEC and solar technologies, becomes attractive. In total the electricity production from renewable resources increases by a factor of 5 and consequently it’s share in total electricity production by 2030 rises to 40% to 50%, see figure B.8.3. Coal remains the dominant fossil fuel, supplying some 90% of all fossil fuel based electricity.

Under CO₂ constraints nuclear power is expanded up to the maximum allowed in both scenarios. More renewables are introduced, primarily biomass and solar, but only to a limited extent since most other, cheaper options are already fully exploited. Among the, strongly reduced, fossil power generation coal is affected the most and gas becomes the dominant fossil fuel.
Figure B.8.3  *Electricity Generation by Input in the USA in 2030*

**Primary Energy Consumption**

Largely due to changes in the electricity generation input, the primary energy mix in 2030 differs markedly from the current one. The role for nuclear energy becomes negligible, while renewables expand their share so strongly that they more than compensate the lacking nuclear contribution.

In the CO₂ reduction cases nuclear energy is re-introduced and renewables grow further, eventually supplying one third or more of all primary energy, see figure B.8.4. Consequently the share of fossil fuels drop further to around 50%. Within the fossil fuels coal is losing ground to natural gas, making the average fossil fuel CO₂ emission coefficient 11% to 13% lower than in the baseline. The total amount of primary energy consumed remains roughly the same, illustrating the relatively small contribution of energy savings in the reduction strategies.

In summary reductions of CO₂ emissions are brought about primarily by a larger share for non-fossil energy carriers, the largest changes occurring in the electricity generation sector. Secondly a shift from coal to gas results in a lower carbon intensity of the remaining fossil fuel use.
Appendix B: Country Summaries

![Energy Consumption Chart](image)

**Figure B.8.4 Primary Energy Consumption in the USA in 2030**

**CO₂ Reduction Cost**

Additional costs associated with CO₂ reduction are considerable, especially in the high scenario. Since capital intensive options like renewables and nuclear play a dominant role, additional capital cost expenditures equal the total extra costs incurred. On an annual basis extra investments of up to 2% are required (see table B.8.2), amounting to 10% of all investments in the economy.

The increasing tax scheme ($15 in 1995 increasing at 10% per year) is not sufficient to stabilize CO₂ emissions, see figure B.8.1. The revenues are thus also increasing with time, ending at 4.8% of GDP in 2030.

As table B.8.2. shows, the cost of CO₂ reduction is higher in the high scenario (a larger percentage of a larger GDP). This is also reflected in the marginal reduction costs, see figure B.8.5. Interestingly the tax level in 2030, equivalent with $115 per tonne CO₂, is practically the same as the marginal cost to stabilize emissions. This indicates that if the tax scheme was just marginally higher and/or reach the higher level earlier in time might have been sufficient to achieve stabilization well before the year 2030.
Table B.8.2 Additional Costs and CO₂-Tax Revenues in the USA, Average and Maximum Percentage of GDP*

<table>
<thead>
<tr>
<th>CO₂ Reduction Case:</th>
<th>CONSTANT</th>
<th>-10%</th>
<th>-20%</th>
<th>-30%</th>
<th>CO₂-TAX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>USA/High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cost</td>
<td>Avg.</td>
<td>.68%</td>
<td>1.09%</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(1.33%)</td>
<td>(2.22%)</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>Avg.</td>
<td>.74%</td>
<td>1.11%</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
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<td>(Max.)</td>
<td>(1.49%)</td>
<td>(2.17%)</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>C-Tax Revenues</td>
<td>Avg.</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>USA/Low</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cost</td>
<td>Avg.</td>
<td>.08%</td>
<td>.24%</td>
<td>.50%</td>
<td>.86%</td>
</tr>
<tr>
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<td>(Max.)</td>
<td>(.23%)</td>
<td>(.58%)</td>
<td>(1.06%)</td>
<td>(1.74%)</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>Avg.</td>
<td>.12%</td>
<td>.21%</td>
<td>.47%</td>
<td>.83%</td>
</tr>
<tr>
<td></td>
<td>(Max.)</td>
<td>(.27%)</td>
<td>(.48%)</td>
<td>(1.08%)</td>
<td>(1.86%)</td>
</tr>
</tbody>
</table>

*Average = Unweighted average over all periods in which constraints are imposed
Maximum = Maximum found in any period in which a constraint is imposed

---

Figure B.8.5 Marginal Cost of CO₂ Reduction in the USA
APPENDIX C. OPTIONS TO REDUCE CO₂-EMISSIONS

The annual CO₂ emissions from any national energy system can be calculated from the following formula:

\[
    \text{CO}_2 = \text{CAP} \times \left( \frac{\text{GDP}}{\text{CAP}} \right) \times \left( \frac{\text{TPER}}{\text{GDP}} \right) \times \left( \frac{\text{TFOS}}{\text{TPER}} \right) \times \left( \frac{\text{CO}_2}{\text{TFOS}} \right)
\]

with:
- CAP = Population
- GDP = Gross Domestic Product
- TPER = Total Primary Energy Requirements
- TFOS = Fossil Primary Energy Consumption

In most cases where MARKAL-type models are applied, the scenario-specific socio-economic development projection (population, per capita GDP) is entirely exogenous. In order to reduce CO₂-emissions at the given GDP level three rather obvious groups of measures can be derived from the formula above:

1. Reduce the amount of primary energy consumption per unit of GDP (= reduce the energy intensity of GDP). This includes structural changes in the economy, recycling of materials to reduce primary production of materials, more efficient energy technologies (e.g. heat pumps to replace boilers) and energy conservation (e.g. improved building insulation);

2. Reduce the share of fossil energy carriers in the total primary energy consumption by introducing more nuclear and renewable energy;

3. Reduce the average CO₂-emission per unit of fossil energy by switching to fuels with a lower carbon content per unit of heat value, e.g. natural gas to replace coal and/or oil products. Other options in this group are removal and storage of CO₂ and upgrading of fossil fuels using non-fossil fuels (e.g. coal gasification using high temperature nuclear reactors, or the HYDROCARB processes with mixed biomass and coal as input).

The system boundaries assumed, the availability of data and the level of detail of the models used, may limit the size of the subset of options to be included in the scenario analyses.

Most often socio-economic developments are entirely exogenous to the analyses and only the resulting energy demand projections are fed into energy models like MARKAL. In this case assessment of the impact of structural changes in the economy is not feasible, unless variant scenarios including such changes are made available by the institutes/organisations responsible for supplying the demand data.
Another item mostly treated exogenously is the modal split in transportation, the breakdown of passenger and goods transport over various modes (bicycle, car, bus, train, plane and truck, train, ship, plane respectively). Furthermore not all options are applicable in all national analyses, due to physical, technical or policy constraints (e.g. no hydro electricity potential, no natural gas grid or a ban on nuclear energy).

The following list of options for consideration is organized to reflect the usual way of operation to analyze national energy systems using models of the MARKAL/EFOM type. The sections C.1, C.2 and C.3 relate to the three groups of options above, broken down further by sector.

Note that various options are strongly interrelated. E.g. if no nonfossil sources of hydrogen (section C.2.3) and/or fossil hydrogen processes with CO₂ removal (section C.3.3) are included in the model, it is hardly worth while to include hydrogen using end-use devices (sections C.2.4-C.2.7).

Carbonaceous materials recycling and waste disposal policies (sections C.1.1 and C.1.5) can only be considered and assessed if actual CO₂ emissions are calculated, see the box at the end of this chapter.

Note also that many measures are not necessarily or exclusively inspired by greenhouse gas concerns. This goes e.g. for policy measures like promoting a shift from private car transport to public transport to reduce congestion and/or local air quality problems.

For each country (or province) study an indication is given to identify the options considered in its analysis, marked as follows:

- X Option is represented as technological process in MARKAL
- S Variant exogenous assumptions adopted in different scenarios
- C Sensitivity analysis performed in variant cases (not reported here)

The country/province code in the header row reads as follows:

US United States
CQ Quebec (Canada)
CO Ontario (Canada)
JA Japan
NL the Netherlands
BE Belgium
NO Norway
SW Sweden
CH Switzerland
IT Italy
## C.1 Improve Energy/GDP Ratio

### C.1.1 Economy/Policy
- Structural changes in the economy
- More recycling (aluminium, paper, glass, etc.)
- Recycling of carbonaceous materials
- Waste disposal policy
- Change modal splits (e.g. more rail, less road/air)
- Conservation by Pricing and Taxation

<table>
<thead>
<tr>
<th>US</th>
<th>CQ</th>
<th>CO</th>
<th>JA</th>
<th>NL</th>
<th>BE</th>
<th>NO</th>
<th>SW</th>
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<td>S</td>
<td>S</td>
<td>X</td>
<td>S</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

### C.1.2 Electricity/Heat Supply
- Coupled production and cogeneration
- Gas combined cycle
- Coal combined cycle
- Other advanced fossil power plants
- Fuel cells

<table>
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<th></th>
<th>X</th>
<th>X</th>
<th>X</th>
<th>X</th>
<th>X</th>
<th>X</th>
<th>X</th>
<th>X</th>
</tr>
</thead>
</table>

### C.1.3 Other Supply
- More efficient fuel conversion processes
  (refineries, synthetic fuel prod., etc.)

<table>
<thead>
<tr>
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<th>X</th>
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</tr>
</thead>
</table>

### C.1.4 Industry
- More efficient industrial processes
- Gas fired heatpump/heat transformer
- Electric heatpump/vapour recompression
- Heat recovery/energy cascading
- More efficient electric drive
- More efficient lighting
- Advanced manufacturing processes
- Recycling use of COG, BFG and LDG
- Recycling of black liquor (pulp)

<table>
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<th>X</th>
<th>X</th>
<th>X</th>
<th>X</th>
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<th>X</th>
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<th>X</th>
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</thead>
</table>

### C.1.5 Non-Energy Use
- Recycling of plastics
- Re-refining of lubricants

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### C.1.6 Residential and Commercial
- Condensing gas boiler
- Gas fired heatpump
- Electric heatpump
- Improved building insulation (new/retrofit)
- Minimum energy houses and buildings
- More efficient electric appliance
- More efficient lighting
- More efficient non-electric appliance

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### C.1.7. Transport
- More efficient engines
- More efficient vehicles
- Brake energy recuperation
- Improved Traffic System

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</table>
### C.2 Reduce Share of Fossil Fuels

#### C.2.1 Economy/Policy
- Relax constraints on nuclear power (e.g. moratorium, ban)
- Foster use of renewables (e.g. physical planning regulations)
- Fuel policy/security

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#### C.2.2 Electricity/Heat Supply
- LWR nuclear power plant
- CANDU nuclear power plant
- BFR nuclear power plant
- VHTR steam electric
- Hydrogen fuel cell
- Wind turbine
- Solar Photovoltaic cell
- Geothermal energy
- Hydro energy
- Wave energy
- Ocean Thermal Energy Conversion (OTEC)
- Biomass Power Plant
- Helium gas turbine
- Thermochemical heat pipe
- Centralized supply of process heat

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#### C.2.3 Other Supply
- Landfill gas utilization
- Biogas (from manure/organic waste)
- Liquid Biofuel (from wastes/from farming)
- Solid Biomass (from wastes/from farming)
- Hydrogen from non-fossil energy
- IES for SNG and liquid fuel
- Reducing gas production

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#### C.2.4 Industry
- Solar heat
- Biomass burning equipment
- Electric heatpumps
- Hydrogen fired equipment
- Nuclear iron & steel making
- Utilization of new fuels (methane, hydrogen)

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#### C.2.5 Non-Energy Use
- Agricultural feedstocks
- Hydrogen feedstocks (e.g. for fertilizers)

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C.2 Reduce Share of Fossil Fuels (cont’d)

C.2.6 Residential and Commercial
- Solar heat
- Biomass burning equipment
- Hydrogen fired equipment
- Electric heatpumps

C.2.7 Transport
- Biofuel engines
- Electric vehicles
- Hydrogen vehicles
- Hydrogen airplanes
- Nuclear ships

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</tbody>
</table>
C.3 Reduce CO₂-Intensity of Fossil Fuels

C.3.1 Economy/Policy
• Relax constraints on natural gas imports
• Stop subsidies on domestic coal
• Carbon Tax

C.3.2 Electricity/Heat Supply
• Gas power plants
• CO₂ removal from fossil fuel power plants

C.3.3 Other Supply
• Nuclear upgrading of fossil fuels
• Hydrogen from fossil fuels with CO₂ removal
• CO₂ removal at oil refineries
• CO₂ methanation
• CO methanol production
• CO₂ methanol production
• Gasoline synthesis (MTG)

C.3.4 Industry
• Gas boilers/burners
• CO₂ removal from fossil fuel use

C.3.5 Non-Energy Use
• CO₂ removal from fertilizer production

C.3.6 Residential and Commercial
• Gas boilers/burners

C.3.7 Transport
• LPG engines
• CNG engines
• Methanol engines

C.3.8 CO₂ Storage
• Depleted gas fields
• Aquifers
• Deep ocean water
• Forestry
ACTUAL AND POTENTIAL CO$_2$ EMISSIONS

For reasons of simplicity CO$_2$ emissions from an energy system are often calculated by multiplying the net amounts of fossil fuels used by their respective emission coefficients.

Indeed, when a fossil fuel is burned to yield energy, close to one hundred percent of all it’s carbon content is transformed directly, or soon thereafter indirectly, to carbon dioxide (CO$_2$).

However, a greater or smaller share of the total net amount of fossil fuels used is not burned, but used as feedstock in chemical industries or for other non-energy purposes. Not all of these non-energy uses of fuels contribute to CO$_2$ emissions from the energy system under consideration.

The level calculated in the simple way is referred to as the potential emission, reflecting the notion that sooner or later all carbon might become CO$_2$.

In order to estimate the actual CO$_2$ release more accurately corrections can be made, taking into account the products manufactured from the feedstocks and the destination of those products. Depending upon a range of conditions the actual emission level can be lower or higher than the potential level. The largest corrections are related to oil products, significant shares of which may be used as feedstocks for monomers and plastics in petrochemical industries. In these processes, but e.g. also in formaldehyde production from methanol or siliconcarbide production from cokes, carbon is embodied in the products. Some of them may have a long life, some of them may be exported to other countries. Eventually carbon containing products are discarded at the end of their lifetime, but CO$_2$ is not released unless the wastes are burned.

Key questions to estimate actual emissions are: (a) are carbonaceous materials produced locally or imported; (b) is the embodied carbon inevitably and soon transformed to CO$_2$ (e.g. solvents and detergents); and (c) are carbonaceous wastes burned, dumped or recycled.

Table C.1 gives an indication for the year 1985 of the differences related to oil products and commodity plastics only [ECN-Rx--90-048]. It illustrates but that quite different results are found for various countries. Since not all products are fully covered, it suggests that potential emissions overestimate emissions by at least a few percent for the total OECD.

Table C.1: Potential and Actual CO$_2$ Emissions, Oil Products and Commodity Plastics

<table>
<thead>
<tr>
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<th>CO$_2$ Emission [Mt]</th>
<th>Difference [%]</th>
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<tbody>
<tr>
<td></td>
<td>Potential</td>
<td>Actual</td>
</tr>
<tr>
<td>Netherlands</td>
<td>61.4</td>
<td>47.5</td>
</tr>
<tr>
<td>Switzerland</td>
<td>39.9</td>
<td>40.3</td>
</tr>
<tr>
<td>OECD-Europe</td>
<td>1882.0</td>
<td>1844.6</td>
</tr>
<tr>
<td>OECD Total</td>
<td>5030.9</td>
<td>4916.9</td>
</tr>
</tbody>
</table>

It must be noted that the CO$_2$ levels reported for the Netherlands are calculated as actual emissions. Other cases relate to potential emissions, except the USA where all oil products used as feedstocks are assumed to yield no CO$_2$. 
APPENDIX D. CO₂ REMOVAL AND STORAGE

Fossil fuels are mainly composed of carbon and hydrogen in the form of (mixtures of) various carbohydrates (CH₄). When burnt, thermal energy is produced by oxidation of the carbon and hydrogen, see the formula below:

\[ CH₄ + (1 + \frac{9}{4})O₂ \rightarrow CO₂ + \frac{9}{2}H₂O + \text{Energy} \]  

Normally the carbon dioxide (CO₂) and water vapour (H₂O) from the chemical reaction are released to the atmosphere, together with other combustion gases. In principle the CO₂ can be removed from the flue gases by application of chemical or physical absorption or cryogenic ('freezing') processes, or membranes. When burning fossil fuels with ambient air, the relatively low concentration and low partial pressure of the CO₂ imply that removal from the flue gas is not easily accomplished. High additional costs and substantial internal energy consumption make this option less favourable. Some improvement is possible when using pure oxygen instead of air or flue gas recycling to raise the concentration and partial pressure of the CO₂.

More attractive technical solutions exist when the CO₂ is removed before burning, so during a preceding fuel conversion stage. Examples are production of synthetic hydrogen or methanol from coal, oil products or natural gas and integrated coal gasification combined cycle (IGCC) power plants. In all these processes the fossil fuel is first converted into a gas mixture, mainly consisting of carbon monoxide (CO) and hydrogen (H₂). Adding a so-called shift reactor, the composition of the gas mixture is adjusted to become richer in CO₂ and hydrogen and leaner in CO:

\[ CO + H₂ + H₂O \rightarrow CO₂ + 2H₂ \]  

This leads to a higher concentration and partial pressure of CO₂ and thus to cheaper, less energy consuming and more effective removal, using similar processes as above. Depending upon the end product desired and the process route chosen, larger or smaller fractions of the carbon in the input fuel can be removed. Per unit of CO₂ removed such processes show far better cost and energy characteristics than scrubbing of flue gases. Similar technologies are currently in use in the fertilizer industry (hydrogen for ammonia synthesis from coal, natural gas or oil products) and in refineries to obtain hydrogen for oil products upgrading (higher yield of light products) and desulphurisation.

Other concepts are also considered, in which a mixture of solid biomass (wood) and fossil fuels is converted to solid carbon and e.g. methanol, examples are the HYDROCARB processes studied in the USA. The solid carbon can be marketed as carbon black for e.g. rubber production, or burnt e.g. for power production. In the latter case those plants are to be equipped with CO₂ removal technologies.

Complex, integrated systems are being studied, combining nuclear and fossil energy inputs to produce electricity, heat, hydrogen and methanol. Into such concepts, referred to as Integrated Energy Systems (IES, see Vol.II/Japan), recovered CO₂ may be fed as input to produce synthetic fuels like methanol.
In principle the formula \{1\} for burning fossil fuels is reversed in this process, with the energy requirements being met by high-temperature nuclear reactors.

Of course the CO₂ or carbon removed must be stored for periods of at least several centuries, a major problem being the large volumes involved if CO₂ removal is to make a sizeable contribution to the goal of reducing emissions to the atmosphere. Several storage reservoirs are suggested and currently investigated in research programmes: deep ocean water, depleted gas and oil reservoirs, and aquifers (sealed water containing underground layers). If CO₂ is compressed to a sufficiently high pressure and then transported by pipelines to sufficiently deep ocean water, it will remain a liquid of higher density than water. Apart from diffusion into the surrounding water body and the chance of being dragged along by deep ocean currents, it is assumed that the CO₂ will stay basically in place for at least centuries. Most probably, however, it will eventually return to the surface and escape to the atmosphere. Large uncertainties still exist, including the ecological impact of raising the acidity of the ocean water around the CO₂ 'bubbles'. Alternative modes of transport to the bottom of the ocean are also suggested, such as dumping of large, frozen CO₂ blocks or 'torpedos'. Depleted gas and, to a lesser extent, oil fields offer storage space for large volumes of CO₂, that needs to be injected at high pressure into the geological formations. The largest uncertainties here are possible slow leaking through recent cracks in the caprock covering the reservoirs and risks of a sudden release of large quantities of CO₂, comparable to the infamous 'blow-outs' in gas and oil drilling. Nevertheless storage in gas fields seems to offer the most favourable perspectives for the time being.

At varying depths in the underground aquifers occur, porous water containing formations, sealed off by impermeable layers of rock above and underneath. CO₂ may be fed into these aquifers, where it is partially dissolved in the water. As yet large uncertainties exist regarding suitable storage volumes, risks of slow leaking (the rock cover may be impermeable for water, but not for gases) and possible 'squeezing': sideways transport of the water bodies following the injection of CO₂.

Economies of scale restrict application of CO₂ removal, recycling and storage to large, centralized units.

All in all CO₂ removal and storage has evolved in recent years from a purely theoretical idea to a seriously considered candidate on the menu of CO₂ abatement options, reflected by e.g. an IEA Implementing Agreement being in execution besides national research programmes in i.a. Norway, Japan and the Netherlands. The attractiveness lies in the continued use of fossil fuels, in particular abundant coal reserves, while avoiding or drastically reducing CO₂ emissions. Removal is technically speaking perfectly feasible, drawing upon common practice in chemical industry, and not very costly per unit of CO₂ removed. For the longer term it must be regarded at best, so even if health and ecological risks could be contained, as an intermediate solution because of the storage issue. The largest potential reservoir, the ocean, will return the gas sooner or later to the atmosphere at an uncertain rate, and gas fields and aquifers have a limited, exhaustible storage capacity.
Table D.1. contains the data assumptions for electric power plants with CO₂ removal included in the Netherlands’ analysis.

Table D.1:  
**Technology Characterisation of New Central Power Plants with CO₂ Removal in the Netherlands in 2030**

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<td>1245</td>
<td>58.0</td>
<td>50.4</td>
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<tr>
<td>(no CO₂ removal)</td>
<td>(740)</td>
<td>(38.5)</td>
<td>(58.1)</td>
<td>(347.4)</td>
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<tr>
<td>Coal Combined Cycleᶜ)</td>
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<td>71.9</td>
<td>43.1</td>
<td>93.9</td>
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<tr>
<td>(no CO₂ removal)</td>
<td>(1320)</td>
<td>(57.7)</td>
<td>(49.0)</td>
<td>(690.5)</td>
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<tr>
<td>Coal MCFCᵈ)</td>
<td>1800</td>
<td>101.7</td>
<td>49.5</td>
<td>19.9</td>
</tr>
<tr>
<td>(no CO₂ removal)</td>
<td>(1455)</td>
<td>(90.7)</td>
<td>(55.0)</td>
<td>(616.0)</td>
</tr>
</tbody>
</table>

ᵃ) Net, incl. internal use for compression of CO₂ to 60 bar and transport (100 km)
ᵇ) Flue gas scrubbing through chemical absorption (MEA, mono-ethanol amine)
ᶜ) CO₂ captured from synthesis gas (shifted to H₂/CO₂) through physical absorption (Selectol)
ᵈ) IGMCFC: Integrated Coal Gasification Molten Carbonate Fuel Cell. The fuel cell serves as (partial) pre-shift reactor, the off-gas is shifted further with the H₂ fed back to the fuel cell and the CO₂ captured through physical absorption or membrane gas separation.

In addition, costs are incurred with injecting the CO₂ in underground reservoirs. These are estimated at US$ 5.5 and US$ 11 per tonne of CO₂ stored in depleted gas fields and aquifers.
APPENDIX E. BACKSTOP OPTIONS

E.1 Concept

Typically, prevailing energy resources are limited in size. At one point in time they will run out, or become too expensive, and alternative forms of energy will inevitably be called upon to meet a continuing demand for energy services. In order to ensure continued supply, such alternatives must be available in virtually unlimited quantities. Moreover they must be produced in a form which enables practical conversion, transport and distribution chains that comply with various applications (heating, stationary and mobile driving power, lighting and communication). Technological options offering these prospects are often referred to as backstop options.

A typical example is production of synthetic liquid and gaseous fuels from coal to replace oil products and natural gas. However, in light of concerns over potential climate impacts from using fossil fuels, production of synthetic fuels from coal may have to be constrained, or even forgone altogether. Thereby ruling out its potential to serve as backstop option in CO₂ emission constrained cases. Instead, non-fossil backstop options are to be considered, among which conversion of solar radiation into secondary energy carriers such as electricity, or high-quality synthetic fuels such as hydrogen, etc.

E.2 Marginal Reduction Cost

Except for dispersed energy uses in remote areas, a minor part of the world energy consumption, and limited potentials in the vicinity of major energy consuming areas, solar based energy is more expensive than currently prevailing, largely fossil fuel based alternatives. As a general rule the price of exhaustible resources like fossil fuels will rise with time. At the same time ongoing R, D and D programmes and the prospect of large scale deployment is expected to lead to lower costs for e.g. solar photovoltaic cells (PV). Hence fossil fuels will sooner or later become more expensive to use than solar energy alternatives and subsequently be pushed out of the market. In view of the vast coal reserves this process may not take place within the next century. In other words coal, and synthetic liquid and gaseous fuels manufactured from it, would replace oil products and natural gas rather than renewable resources.

So, if external costs associated with burning of ever growing volumes of fossil fuels are not accounted, a large-scale transition to renewables is unlikely to occur on economic grounds alone. Precise estimates of external costs, in particular those relating to potentially disruptive climate change, are very hard to make. Alternatively the point at which backstop technologies become viable can be assessed by imposing exogenous bounds on the CO₂ emission level or by imposing CO₂ taxes or fees.

When it comes to the marginal cost associated with reducing CO₂ emissions through introduction of suitable backstop options, timing and technological detail are decisive factors.
If one makes an assessment for a more distant future period (say around 2100) using a highly aggregated approach (just distinguishing electric and non-electric demands, each to be served by a limited number of supply options), relatively low marginal reduction costs emerge. By 2100, it is assumed that crude oil and natural gas reserves are exhausted and, without constraining CO₂ emissions, synfuels from coal are the reference supply to meet non-electric demands. To reduce CO₂ emissions a non-electric backstop option is available, say hydrogen produced from solar energy in desert areas.

Including upgrading and transport cost, the price of coal synfuels is estimated at US$ 12 GJ. At a net conversion efficiency of 65%, around 150 kg CO₂ are emitted to produce one GJ. The cost of solar hydrogen as delivered, including storage facilities to level out the supply pattern, is estimated at US$ 27 per GJ. Now the extra cost to avoid 150 kg of CO₂ is US$ 15, leading to US$ 100 per tonne of CO₂ reduced.

If, however, a shorter time horizon is considered (say 2030), and a more detailed analysis is made (distinguishing various applications and a wealth of technological supply and end-use options), quite different results are obtained.

First, oil and gas supplies are probably not yet exhausted. Their price may have risen to around US$ 40 per barrel of oil equivalent (or US$ 7 per GJ and thus still cheaper than coal synfuels). The CO₂ emission reduction from introducing the backstop option is thus around 56 (gas) to 75 (oil) kg per GJ. Instead of a single marginal cost figure, two can now be distinguished. Replacing natural gas will cost US$ 360, replacing oil products US$ 265 per tonne of CO₂ reduced.

Moreover, these numbers only apply if the solar hydrogen were used in otherwise similar technologies (same cost and performance). However, new hydrogen fueled technologies can be introduced. On the one hand such technologies may suppress the reduction cost level through a higher efficiency. On the other hand, using hydrogen may be much more costly (e.g. hydrogen cars replacing gasoline cars), pushing up the reduction cost level.

In technology rich models like MARKAL, a backstop option will be evaluated against the "second-best" option per application (see also Appendix A), the number of applications typically amounting to several dozens. If, for instance, solar hydrogen would compete with hydrogen from natural gas with CO₂ removal (say at US$ 10 and a net CO₂ emission of 2 kg per GJ), the reduction cost is no less than US$ 8,500. Also, a fuel burning device may be replaced by an electric device (e.g. an electric heat pump for house heating instead of a gas boiler). This opens up a whole range of new competitors for the backstop option considered.

In summary, CO₂ reduction costs associated with a single backstop option in a MARKAL model are not easily estimated and and are typically much higher than those emerging from more aggregated very long-term models.