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COSTS OF CO_2 REDUCTION TECHNOLOGIES FOR THE NETHERLANDS

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This study has been carried out in the framework of the UNEP project 'National Greenhouse Costing Studies' for the Dutch Ministry of Housing, Physical Planning and Environment under coordination of the Institute of Environmental Studies of the Free University of Amsterdam and has been carried out under ECN/ESC project number 7067.

CONTENTS

PREFACE

UNEP (United Nations Environmental Programme) has recently launched a project aimed at establishing a set of methodological guidelines for calculating the costs of limiting greenhouse gas (GHG) emissions, particularly carbon dioxide emissions from the energy sector. The project is being coordinated by the UNEP collaborating centre at Risø National Laboratory in Denmark, with assistance from Caminus Energy (Cambridge, UK) and the Tata Energy Research Institute (New Delhi, India) and with Dr. Michael Grubb of the Royal Institute of International Affairs (London, UK) as consultant.

The Dutch national team is formed by H.M.A. Jansen and T. van der Burg of the Institute for Environmental Studies (IES) of the Free University of Amsterdam, and T. van Harmelen and J.R. Ybema of the unit ESC-Energy Studies of the Netherlands Energy Research Foundation ECN in Petten.

This study is presented as a chapter on 'bottom-up' studies in the IES report 'Costs of greenhouse gas abatement in the Netherlands' by T. van der Burg, T. van Harmelen, and J.R. Ybema.

1. INTRODUCTION

There are many anthropogenic greenhouse gas (GHG) sources. The largest contributing sector at the global level, however, is energy, although agriculture and forestry contribute significantly. Emissions of CO_2 from the energy sector can be reduced by a variety of means such as energy savings, fossil fuel switching, introduction of more efficient technologies, renewable energy, nuclear energy and CO_2 removal.

A number of costing studies have been carried out for various countries and regions. These studies have resulted in estimated costs for greenhouse gas abatement which vary widely, ranging from substantial net savings to costs in trillions of dollars. The differences are at least partly due to differences in assumptions concerning targets for greenhouse gas reduction, baseline projections, allowance of innovative technologies, data on technology costs, and a range of more subtle differences in modelling assumptions and methodologies. In particular the use of 'bottom-up' or 'top-down' modelling approaches tend to give diverging results.

The aim of the UNEP project is to develop a methodological framework for conducting such studies on the basis of a number of authoritative and comparable national studies. Phase I of the project consists of a review of the present situation of greenhouse gas emissions in the participating countries with emphasis on the energy sector. In phase I, an important part will focus on existing national studies on GHG abatement. CO_2 reduction options and their costs will be identified and the national preferences and the ranking of these options discussed. In phase II country studies will be carried out following a common approach which will be worked out in phase I.

The coordinator of the efforts of the Dutch national team is the Institute for Environmental Studies (IES) of the Free University of Amsterdam. In phase I, IES also reviews the current GHG emission situation and existing studies on CO_2 abatement policy instruments and their macroeconomic effects. This paper contains the ECN/ESC-Energy Studies contribution to the first phase of the study. Four important 'bottom-up' technology oriented CO_2 emission reduction studies will be reviewed. Attention will be paid to the methodology, the type of costs, the technological reduction options, and the evaluated CO_2 emission reduction targets. The aim is to explain systematically differences in CO_2 emission reduction technology cost curves for the Netherlands generated by different scenarios for the year 2010.

Chapter two will describe the methodologies used in the studies and the limitations of the formats of the model outputs. In chapter three a characterization of the four studies and a comparison of results will be made. Furthermore, in chapter four, two studies will be described down to the level of separate technologies, in order to draw more detailed conclusions on the costs of CO_2 emission reduction in the Netherlands in the year 2010.

2. ENERGY SECTOR MODELS

In the Netherlands, results from four national 'bottom-up' studies into CO_2 reduction are currently available. In these studies of energy supply and/or end-use large numbers of energy technologies have been investigated on their efficiency, emissions, and also costs. With these inputs the models calculate the total costs and emissions. In the studies either Linear Programming (LP) models or large spreadsheet models are used (see table 1). These energy supply and/or end-use models concern costs from the financial point of view or direct costs for the building and operation of energy technologies. External costs and costs for stimulating policies (implementation costs) have not been taken into account. Since in all four models the energy demand is exogenous and price elasticities are absent, macroeconomic effects are not accounted for.

The spreadsheet models contain large databases with data on technologies. With these data relatively simple calculations were performed to calculate the possibilities for CO_2 reduction in one year. For each technology the yearly costs of the investment including 5% interest were calculated. Also the yearly benefits were calculated from efficiency improvement and fuel price. This resulted in yearly net costs for each technology.

The results of a large study into energy saving technologies [Blok et al, in this paper study 4] show a large energy saving potential at negative costs. This potential has been calculated for several economic sectors. At additional costs additional energy savings can be reached. This way an energy saving cost curve has been derived. The next step in the calculations was to assess not only the amount of saved energy but also the related amount of reduced CO_2.

In general this assessment of CO_2 reduction due to single technological options is problematic in spreadsheet models, due to interaction between measures in supply and demand side. If for instance electricity produced from coal is saved, the effectiveness in terms of Dfl per tonne avoided CO_2 is large. If after this savings coal substitution into natural gas takes place this substitution has a relatively small impact because energy demand has been decreased by savings. But, if the order of introduction of these measures is reversed, the effectiveness of the measures in terms of Dfl per tonne avoided CO_2 will be different. Study 4 'solved' this problem by taking into account only energy saving options on the demand side. Spreadsheet study 1 [Okken et al] postulated a technology penetration order such that CO_2 reduction costs of demand side technologies are calculated before supply side options are introduced.

In relation to the above, a disadvantage of the spreadsheet models is that cost-effectiveness of an option in the total system is not clearly assessed. In both studies the effects of demand side technologies are overestimated. But of course the costs and the emission reduction of all the measures together are correct and the advantage is that CO_2 reduction costs of several economic sectors are available.

The LP model studies [study 2 and 3] are performed to assess technological CO_2 emission reduction potentials in functional categories like transport of goods, high temperature process heat, low temperature steam, and central electricity generation. The model satisfies exogenous energy demands and minimizes national costs of energy supply. This means that it is possible that certain sectors endure a non-optimal solution in their view in order to support an optimal solution from a national point of view. Thus, there is only one economic actor, viz. the nation, which minimizes its costs.

Table 1. Several important properties of CO_2 reduction studies using spreadsheet or LP models

Criteria	Bottom-up models	
	Spreadsheets	LP models
Costs		
financial	yes	yes
implementation	no	no
external	no	no
macroeconomic	no	no
Total emissions	exact	exact
Emission reduction		
penetration of options	arbitrary penetration order	cost optimal penetration order
cost per economic sector	good estimation	difficult
cost per technology	estimation not including interaction	reasonable estimation including interaction

If national CO_2 emissions are constrained, the model chooses a different mix of technologies and energy carriers which respects the CO_2 emission ceiling and results in minimal additional national costs. The model minimizes costs for the total calculation period. Therefore, yearly costs can not be seen without taking into account the total CO_2 reduction path in time. For instance costs from the year 2010 cannot be compared easily between two studies if one study calculates up to 2010 and the other study up to 2030. It is possible that costs from the last study are higher in 2010 because some investments have been made in order to achieve a CO_2 emission reduction target in 2020.

Thus, a strong and a weak point of these LP model studies is the integrated system approach. CO_2 reductions in the supply sector are influencing CO_2 reduction potentials in the demand sector. Therefore, CO_2 emissions and emission reductions can be assessed very well with LP models. Furthermore, the model chooses the cost optimal technology mix, which results in essential information about effectiveness of options in a national energy system. But, yearly costs are not easy to compare with yearly costs from other studies. Also costs are currently not available per economic sector.

3. CO_2 REDUCTION COSTS

From the four studies key parameters and background information are collected and presented in Appendix A. In table 2 a short summary is given. Apart from the model differences as described in chapter two, the time horizon, Reference scenario, considered CO_2 reduction options and fuel prices are different for the four studies. These differences lead to differences in CO_2 emissions in the Reference scenario, CO_2 emission reduction potentials, and CO_2 reduction costs. In this chapter results with respect to CO_2 of the four studies will be analyzed and differences will be explained.

Table 2. Characterization of four CO_2 emission reduction studies for the Netherlands

	Study 1	Study 2	Study 3	Study 4
Commissioned by	Ministry of Environment	Ministry of Economic Affairs/NOP-MLK	Ministry of Economic Affairs/CEC DG XII	Ministry of Environment
Model	spreadsheet	LP model	LP model	spreadsheet
Time horizon	2005	2010-2040	2010	2000
Reference scenario	current GH policy	current GH policy	current GH policy	constant efficiencies
Measures				
supply options	yes	yes	yes	no
nuclear	no	no	no	no
CO_2 removal	yes	yes	no	no
H_2 production	no	yes	no	no
constraints	technical	technical	political	technical
energy savings	yes	yes, not in transport	yes, not in industry	yes
CO_2 emission calculation method	actual and potential, excl. bunkers	actual, excl. marine bunkers	actual, excl. bunkers	potential, excl. bunkers
CO_2 emissions [Mton]	*year 2005*	*year 2010*	*year 2010*	*year 2000*
Reference	159	182	177	242
Maximum Reduction	127	129	136	145
Fuel prices [Dfl/GJ]	*year 2005*	*year 2010*	*year 2010*	*year 2000*
coal	4.52	5.2	4.1	3.9
crude oil	n.a.	13.0	10.5	n.a.
natural gas	9.2-14.2	11.5	6.6	8.4-15.1
electricity	38.6	-	-	27-46

In figure 1 CO_2 emissions according to the Reference and Maximum Reduction (MR-) scenarios are shown in time. The thin solid line shows CO_2 emission development without CO_2 emission limiting policy (based on Kolen Inzet Studie by T. Kram et al, ECN, 1990). The thick solid line shows historical CO_2 emissions up to 1990 and CO_2 emission development according to the current policy from 1990 to 2000. The Reference scenarios of study 1, 2, and 3 follow the CO_2 emission development according to current policy to the year 2000. From the year 2000, study 1, 2, and 3 have calculated Reference scenario CO_2 emissions for different periods (the upper lines of the triangles). The Reference CO_2 emissions of study 2 and 3 in 2010 are in the same range. The difference is explained by the accounting of international flight traffic in study 2. The Reference emissions of study 1 are low compared with the Reference emissions of study 2 and

3. Study 4 has calculated higher emissions than the historical and current policy CO_2 emissions due to two factors. First, study 4 calculates potential emissions from all feedstocks (non-energy use). Second and most important, the Reference scenario of study 4 does not contain any autonomous saving measure.

After the year 2000 additional CO_2 emission reduction has been studied and the CO_2 emissions of the Maximum Reduction scenario of each study are shown (the lower lines of the triangles). In study 1 a set of technological options has been put together to reach the Toronto target for the Netherlands (20% reduction of 1988 CO_2 emissions in 2005). Study 3 reaches in 2010 an equal CO_2 emission reduction (23%) if this reduction is expressed as a percentage of the Reference CO_2 emission. This is an important hold since it is not possible in the time frame of this study to analyze in detail the background of energy demand projections of the studies. In the MR-scenario of study 4 for the year 2000 lower CO_2 emissions than expected according current policies have been calculated. In this MR-scenario also very costly saving measures are introduced but no fuel switch has been assumed. Study 4 calculates on the short term (time horizon is the year 2000) and will not be discussed further.

In study 2 CO_2 emission reduction is much more extreme. This is due to the time horizon of the whole study which allows for more innovative technologies and structural change. For instance hydrogen and CO_2 removal play an important role in this long term study. In the next chapter a more detailed analysis of the two LP studies will follow.

In figure 2 the marginal costs of the studies 1, 2, and 3 are drawn as a function of the yearly CO_2 emissions in the target year. Study 2 and 3 Reference CO_2 emissions are in the same range in 2010. The difference is explained by the accounting of international flight traffic in study 2. The cost curve of study 3 is partly below the X-axis. It has included saving measures (of study 4) in its first reduction scenario, assuming that these measures will be realized autonomously, without implementation costs, if the direct costs are negative. The marginal cost curve of study 2 does not cross the X-axis since all negative costs saving measures have been included in the Reference scenario. This difference can only lead to the conclusion that the energy demand of study 3 is lower than in study 2.

Both in study 2 and 3 strong CO_2 reductions take place at relatively low marginal costs. However, up to 140 Mton CO_2 emission per year costs in study 3 are lower than those in study 2. There are four explanations for this. First, fuel prices, especially for natural gas, are higher in study 2, which leads to higher costs for fossil fuel switch options. Second, study 3 costs are incremental costs, because the marginal costs were not available. In the year 2010 CO_2 reduction takes place in four scenarios or reduction steps. The incremental costs are the costs per ton CO_2 for each reduction step. Marginal costs are expected to be somewhat higher than these incremental costs because the latter are an average value for the marginal costs over each CO_2 reduction step. The differences of incremental costs between both studies are much smaller. Nevertheless marginal costs are presented for study 2 since marginal costs are a more useful indicator. Third, the model calculates the minimum additional costs for the period up to 2040. Therefore, investments that have a longer term effect on CO_2 emissions are made in 2010 which can add to stronger CO_2 reductions for the period after 2010. Fourth, differences in availability of CO_2 reduction options and structure of the energy system can lead to cost differences. Chapter 4 will deal with this issue in more detail.

More drastic reduction than 15% of 1990 CO_2 emissions leads to strongly increasing costs for study 3. Clearly, the model has limited CO_2 reduction potential available in this range and finds only very expensive options. In contrast, the model in study 2 is able to keep its reduction costs relatively low. It has still reduction options potential available. The bow downward is explained by relatively low investments in 2010 due to investments made in 2005 which are (also) effective in 2010.

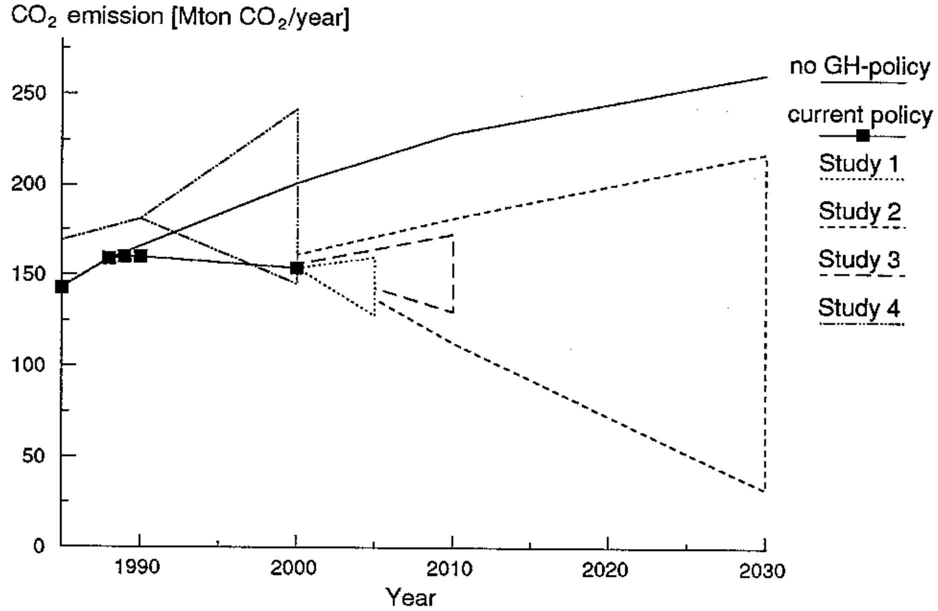

Figure 1. Yearly CO_2 emissions according to the Reference and Maximum Reduction scenarios of several studies

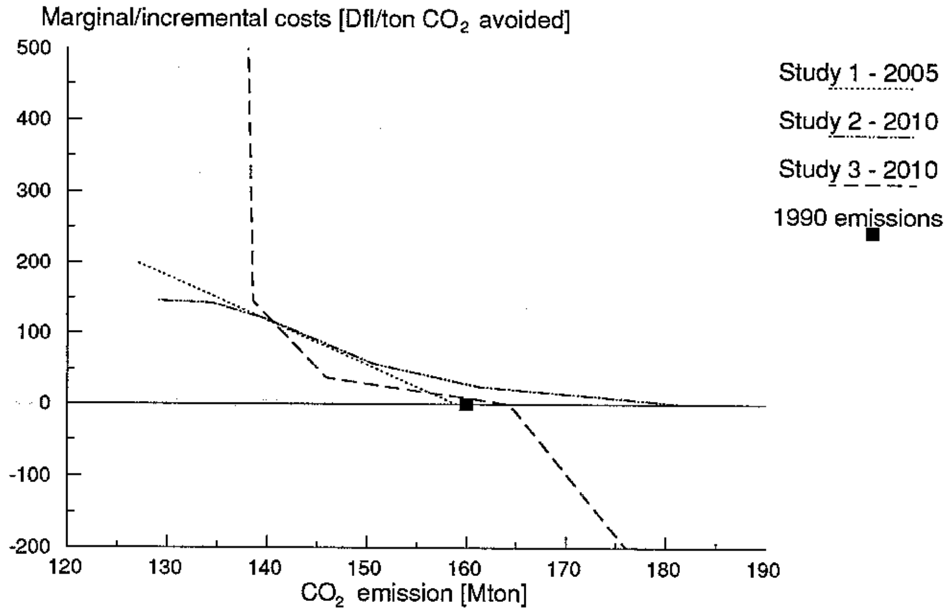

Figure 2. Marginal/incremental costs in the target year as a function of the CO_2 emissions in the target year for several studies

The marginal costs of study 1 were not available. On the basis of information given by the authors, a rough estimation of the marginal costs has been made by the authors of this paper. This estimation in figure 2 will not be discussed in detail. The costs of study 1 for 2005 seem in line with the costs of study 2 in 2010. One needs to take into account that study 2 calculates for the year 2010 and therefore has a higher energy demand due to a larger population and economic activity than study 1. On the other hand, study 2 has more CO_2 reduction options and potential available, due to the turn over of existing energy technology and technological improvements.

The studies are based on very different assumptions and were calculated for different time periods, troubling the comparison of results. However, cost estimates from stabilization up to circa 15% reduction of 1990 emissions are in line for the three studies. At the extremes of the curves costs are not in line. According to study 3, a negative costs CO_2 reduction (energy saving) potential exists that can almost stabilize CO_2 emissions at the 1990 level. According to study 2, costs of more extreme reductions are lower than calculated in the other studies. This is mainly caused by assumptions about new technologies and structural changes in the energy system.

The main conclusions about CO_2 emission reduction costs in 2010 are:
- Study 2 and 3 Reference CO_2 emissions in 2010 are in the same range;
- Study 3 describes a CO_2 reduction potential of 13 Mton by energy saving measures at negative costs;
- Up to 15% CO_2 emission reduction (compared with 1990 level) costs in study 3 are lower than in study 2 although they are in the same range;
- In contrast with study 2, stronger reductions than 15% of 1990 CO_2 emissions lead in study 3 to strongly increasing costs.

4. CO_2 REDUCTION OPTIONS

In this chapter fuel mix and technology penetration potentials of study 2 and 3 will be analyzed for the year 2010 in order to draw more specific conclusions concerning CO_2 reduction potentials and their costs. Study 2 and 3 are selected because they executed an integrated energy system analysis, including cost-effectiveness of CO_2 reduction. CO_2 reductions by a penetrating technology are highly dependent from the technology that is substituted for, e.g. the 'moment' of penetration or its cost-effect ratio. Furthermore, study 3 has 2010 as target year, study 2 has a long term view up to the year 2040, with the year 2010 as intermediate target year.

Methodological factors like the use of incremental costs versus marginal costs and optimization up to 2010 versus 2040 and their influence on CO_2 emission reduction costs were discussed in the previous chapter. The technological assumptions are another important factor that affect CO_2 emission reduction costs. With the help of the primary energy by fuel figures in figure 3 these conclusions will be discussed now.

The level of Reference CO_2 emissions in 2010 is similar for the two studies. This is a result of balancing impacts. The higher primary energy demand in study 3, resulting from a higher GDP growth rate and less energy savings in the Reference scenario, leads to higher CO_2 emissions. However this effect on CO_2 emissions is neutralized by the higher share of coal (relative to natural gas) in study 2, due to a high gas price in study 2.

The difference in the primary energy use in the Maximum Reduction scenarios is even larger. Primary energy use in the Maximum Reduction scenario in study 3 is lower than in the Reference scenario, due to energy savings and efficiency improvements in conversion. Unlike study 2, study 3 included additional energy savings in the transport sector (note the decrease in oil use). In study 2 some additional energy savings in industry and tertiary/domestic sector are included, but these are more expensive than in study 3. Although study 2 reaches a more drastic CO_2 reduction in the Maximum Reduction scenario than in study 3, primary energy use is not lower in study 2. This is due to the large role of CO_2 removal and H_2 producing technologies (gas reforming) in achieving this reduction. These options cause a loss in net efficiency, neutralizing the primary energy decrease by energy savings in conversion and end-use.

Also the fuel mix of the Maximum Reduction scenarios of both studies are completely different. In study 3 coal has been substituted by natural gas and renewables as much as possible. The strategy of study 2 is dominated by electricity generation with CO_2 removal and H_2 production with CO_2 removal. Therefore, unless a higher coal and oil use, emission reduction is larger than in study 3.

In table 3 contributions of CO_2 emission reduction of groups of technologies are estimated for both studies. This table is an aggregation of more detailed calculations of reduction contribution of technologies. These are listed in the Appendix. As discussed before, the exact CO_2 reduction of a penetrating technology is highly dependent on the technology that is substituted for, e.g. the 'moment' of penetration. This is the reason why an integrated energy system analysis with cost optimization is preferred above simulation and single technology analysis. However, this is also the reason why these contributions can only be estimates, since the optimization process of the model can not be determined precisely. Most often a mix of technologies is replaced by another mix of technologies. Furthermore, options come and go if CO_2 reduction becomes more drastic. Thus, contributions cannot be simply added. Although CO_2 reduction contributions have to be treated carefully, they are very useful in comparing CO_2 reduction scenarios at technology level.

Study 3 reduces CO_2 mainly by advanced natural gas technologies in electricity generation and energy savings in end-use. Study 2 uses mainly CO_2 removal, H_2 production and advanced natural gas technologies. Clearly, the CO_2 reduction potential is larger in study 2 than in study

3. This explains the lower reduction costs for more drastic CO_2 emission reductions (more than 15% reduction compared with 1990 level) in study 2 compared with study 3.

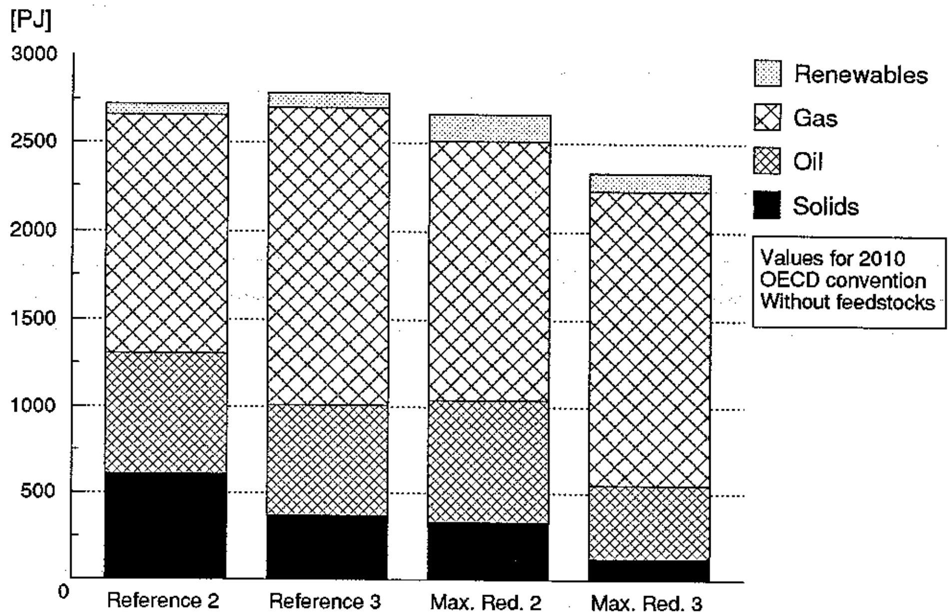

Figure 3. Primary energy by fuel without feedstocks in 2010 for Reference and Maximum Reduction scenarios of study 2 and 3

Table 3. CO_2 emission reduction contribution by groups of technologies in the Maximum Reduction scenarios compared with the Reference scenarios in the year 2010 of study 2 and 3

Emission reduction technologies in the Maximum Reduction scenarios in the year 2010	CO_2 reduction per year [Mton CO_2] Study 2	Study 3
Electricity generation gas	6.2	9.5
Electricity generation renewables	3.2	2.7
Advanced heating	1.2	5.0
Oil sector measures	0.0	6.0
Industrial sector measures	4.4	0.6
Savings tertiary/domestic sector	2.3	7.9
Savings in transport sector	0.0	8.5
Electricity production with CO_2 removal	19.6	0.0
H_2 production with CO_2 removal	10.4	0.0
Non-energy recycling	1.3	0.0
Biogas	2.1	0.0
Total CO_2 emission reduction	52.6	40.9

5. CONCLUSIONS

From the comparison of different CO_2-emission reduction studies for the Netherlands, it can be concluded that:

- Direct costs for CO_2 emission reduction in the year 2010 rise gradually up to circa 150 Dfl or 85 \$ per tonne avoided CO_2 for CO_2 emission reduction up to 15% compared with 1990 emissions;
- The CO_2 reduction potential is strongly dependent on the allowed penetration of (new) low CO_2 emitting technologies;
- Depending on the availability of H_2 production and CO_2 removal technologies more drastic reductions are possible at the same marginal costs;
- Energy saving potentials at negative costs are described, but must be carefully examined, since cost-effectiveness from a private or national point of view is not a guarantee for implementation in some economic sectors that have other investment criteria;
- The costs for CO_2 emission reduction by a technology can only be calculated precisely if the reference energy technology that is substituted is known. Therefore, an integrated cost effectiveness analysis of the national energy system is preferred above simulation and single technology analysis.

The technological mix of options for CO_2 reduction in study 2, with the focus on electricity generation with CO_2 removal and H_2 technology with CO_2 removal, is assessed by the long term emission target. These new technologies are already relatively sound with respect to information on efficiencies and costs. However, the exact moment of introduction (somewhere between 2000 and 2020) is less certain, due to uncertain Research, Development & Demonstration funding and uncertain institutional and market barriers. Also social and political developments can influence the introduction of CO_2 removal technologies. Study 3 calculates up to 2010 and focuses primarily on energy saving technology and does not reach drastic emission reductions. Moreover, in litarature cost-effectiveness has appeared to be an imperfect indicator for implementation of energy saving measures in end-use sectors.

If developments in energy saving, CO_2 removal and H_2 production are disappointing, the marginal costs will be substantial higher. However, if energy saving, CO_2 removal and H_2 production options can be introduced simultaneously, marginal costs might be somewhat lower than estimated above. E.g. the reduction potential will be larger, although the CO_2 reduction effectiveness of savings will be decreased. CO_2 reduction costs as described in this paper give an indication of the range of possible reduction cost developments.

The conclusions of the studies are sensitive for variations in assumptions on future economic growth, population growth and life style.

Macroeconomic effects, implementation and external costs are not taken into account in this CO_2 emission reduction cost curve assessment. One could decide to express uncertainties about development and implementation of options in implementation and external costs. Cost results awarded to sectors, years and components (investment, operation & maintenance, fuel) can be fed into economic oriented models.

APPENDIX A: Characterization of studies

Several aspects of the four studies that have been analyzed in this report are presented as follows.

Studies

1. Een uitwerking voor Nederland van de Toronto doestelling, een CO_2-reductie van 20% in 2005, (An investigation of the Toronto target for the Netherlands, 20% CO_2 reduction in 2005. In Dutch), P.A. Okken, P.G.M. Boonekamp, M. Rouw en J.R. Ybema, ECN-C--91-045, ECN, Petten, augustus 1991.
2. The challenge of drastic CO_2 reduction, future energy systems under CO_2 constraints in the Netherlands, P.A. Okken, J.R. Ybema, D. Gerbers, T. Kram, J. van Doorn and P. Lako, under preparation, ECN, Petten.
3. Cost-effectiveness analysis of CO_2-reduction options, the case of the Netherlands, F. van Oostvoorn and T. van Harmelen, ECN-C--91-024, Petten, December 1990.
4. Data on energy conservation techniques for the Netherlands, K. Blok, E. Worrell, R.A.W. Albers and R.F.A. Cuelenaere, University of Utrecht, April 1990 (to be updated in December 1991).

Commissioned by

1. Ministry of Housing, Physical Planning and Environment.
2. Ministry of Economic Affairs/National research program on global air pollution and climate change (NOP-MLK).
3. Ministry of Economic Affairs/CEC DG XII.
4. Ministry of Housing, Physical Planning and Environment.

Methods

1. Spreadsheet.
2. Linear Programming: CO_2 reduction ceilings are set for every year in the CO_2 reduction cases. Discounted costs are minimized for the complete system for the whole calculation period. Costs that are made in a certain period can be a result of a CO_2 constraint in latter years. Costs that are made in the supply sector can reflect the implementation of a CO_2 reduction option in a demand sector.
3. Linear Programming, see point 2.
4. Spreadsheet.

Sectors

1. Residential, Industry, Transport, Other (Services, Commercial, Agriculture, Greenhouses, and Construction), Waste, and Energy Conversion (Electricity, Refineries, and Cokes).
2. Residential, Commercial, Industry, Transport, Feedstocks, International Bunkers.
3. Residential & Commercial, Industry Large, Industry Small, Iron & Steel, Transport, Oil, Gas, Coal, Central Electricity, Industrial Cogeneration Large and Small, and Urban Cogeneration.
4. Twenty energy demand sectors according to the Netherlands Central Bureau of Statistics.

Categories of measures

1. Energy end-use (volume), Carbon management, Energy savings, Renewable energy, Fuel switch, and CO_2 removal.
2. Savings on end-use, Savings on conversion, Renewable energy, Fuel switch, Recycling, Hydrogen technologies, and CO_2 removal.
3. Focus on Fuel switch, Renewable energy, and Savings in tertiary/domestic and transport sector.
4. Distinction has been made between Efficiency improvement in end-use, Renewables, and Cogeneration.

CO_2 emission calculation method

Potential emissions are theoretical emissions assuming that all carbon from fuels for non-energetic use (feedstocks) is emitted as CO_2. Actual emissions are CO_2 emissions which take place if fossil fuels or feedstocks are combusted. Thus, since not all feedstocks are combusted, actual emissions are lower than potential emissions.

1. Both potential and actual emissions, excluding international bunkers.
2. Actual emissions, excluding international marine bunkers.
3. Actual emissions, excluding international bunkers.
4. Potential emissions, excluding international bunkers.

Reference scenario

1. Economic growth projections of 3% per year up to the year 2005. All measures on energy conservation, combined heat and power, and renewables, to the year 2000, from the National Energy Conservation Plan and the Electricity Plan 1991-2000 have been included. Between the year 2000 and 2005 a continuation of this policy at a slightly lower level has been assumed. Energy consumption in 2000 is 2874 PJ.
2. Economic growth is 2.2% per year on average in the so called Continuing Growth scenario. The Reference scenario contains increasing energy efficiency in conversion, large detail in savings on end-use, and fuel switch. Energy consumption in 2000 is 2815 PJ.
3. MEDEE energy demand projections (DG XII) based on Conventional Wisdom scenario (Energy 2010, DG XVII) have been used. Economic growth rates are circa 2.6% per year. The Reference scenario contains increasing energy efficiency in conversion, savings in end-use, and fuel switch. Energy consumption in 2000 is 2812 PJ.
4. The Netherlands Central Planning Bureau growth rates have been applied on energy consumption figures of 1985. Centrally produced electricity is produced with an efficiency according to the Electricity Plan. No change in fuel mix or savings on energy has been assumed. The resulting energy consumption in 2000 is 3640 PJ.

Year/Periods

1. One year: 2005
2. Period 2000, 2005, 2010, 2015, 2020, 2025, 2030, 2035, 2040
3. Period 1985, 1990, 1995, 2000, 2010
4. One year: 2000

Energy prices/tariffs [Dfl/GJ]

1. Current fuel prices (excluding taxes) in 2005:

Coal	4.52
Fuel oil	14.3
Gas large	9.2
Gas small	14.23
Electricity	38.6

2. The Continuing Growth scenario:

	2000	2010	2020	2030
Coal	4.25	5.2	5.95	6.55
Crude oil	10.3	13	15.9	18.5
Natural gas	9.3	11.5	13.9	16.5

Electricity, gasoline prices etc. are calculated by the model, excluding taxes.

3. EC-DG XVII price projections (Energy 2010 study, Conventional wisdom scenario, year 2010):

Coal	4.1
Crude oil	10.5
Natural gas	6.6

Electricity, gasoline prices etc. are calculated by the model, including taxes.

4. 1995 price projections Ministry of Economic affairs (including taxes for motor fuel) for 2000:

Coal	3.9
Uranium	2.5
Gasoline	45
Diesel fuel	20
Gas large	8.4
Gas small	15.1
Electricity s	46.4
Electricity l	38.0
Electricity v	26.9

Technologies/potentials

1. This study was carried out to assess the measures that are required to reach the Toronto CO_2 target. CO_2 reduction potentials are derived from current policies. In some cases measures are advanced. Additionally, technological CO_2 reduction potentials of new technologies are used. In short, this CO_2 reduction study is quite optimistic, and for a large part of the measures it is not clear yet how they are going to be implemented.
2. This study uses technological potentials that are optimistic, since the goal of the study is to assess long term technological and structural changes which can contribute to the reduction of CO_2. Not only proven technologies but also promising technologies under development are in the model. This study considers, unlike the other studies, CO_2 removal and hydrogen technology. Furthermore the end year of the study is 2040 and not 2010.
3. This study is less optimistic than the other studies because energy savings are not introduced for all sectors. Besides, in some cases constraints that reflect economic actors' behaviour are used.
4. The maximum CO_2 reduction of this study represents an optimistic technological view. Potentials are technological, not micro-economical. The fact that fuel switch in the energy supply is not an option, is compensated by severe energy efficiency improvements on the energy demand side. Therefore, energy savings are very effective from a CO_2 reducing point of view.

CO_2 emissions [Mton]

	Year	1985	1989	2000	2005	2010	2020	2030	2040
1.	Reference	143	160		159				
	MR-Case				127				
2.	Reference	143		161	169	182	199	219	239
	MR-Case			*161	*140	*118	75	32	32
3.	Reference	140	148	159		177			
	MR-Case			*146		136			
4.	Reference	169		242					
	MR-Case			145					

* A lower CO_2 emission target has not been applied

The difference between potential (study 4) and actual emissions (other studies) in the Reference in the year 1985 is circa 15 Mton. In study 4 growth rates and savings are also applied on feedstocks.

CO_2 reduction costs

1. Cost estimates are calculated with an average life time of 10 year. Yearly exploitation costs (including interest) are assumed to be 12% of the investment cost. CO_2 reduction cost reflects the cost in the year 2005. No indications are given about a reduction path in time, or reduction costs for lower reductions in 2005. Reduction costs figures are available per sector and per option category, but for the latter an order of introduction had to be assumed. Costs per Mton CO_2 reduced are average costs in the year 2005, undiscounted and including

interest. Costs for lower CO_2 reduction targets can not be derived easily, due to the fact that the options per category have to be evaluated on a cost-effectiveness basis again. A reduction cost curve like in study 4 is difficult to estimate because supply side reduction options influence cost-effectiveness of end-use options.

2. CO_2 reduction costs are calculated by the model for a CO_2 reduction path from 2000 to 2040. Total period costs are without interest and available in discounted (5% discount rate) and undiscounted format for different supply and demand sectors. However, reduction options in end-use can have cost-effects in supply sectors, which can not be determined explicitly. Optimization for several CO_2 reduction targets (thus paths) resulted in an incremental reduction cost curve where the costs are for the period 2000 to 2040. For this period average reduction costs per Mton CO_2 are derived as well. Yearly costs can be derived, but it must be realized that costs for a certain year may be spent for reduction in latter years and thus costs show a large variation in time.

3. As in study 2 CO_2 reduction costs are calculated for a period, viz. 1985 to 2010. Total period costs are with 5% interest and discounted (5% discount rate). Undiscounted costs can be derived. Costs are available for several supply and demand sectors. However, reduction options on the demand-side can have cost-effects in supply sectors, which can not be determined explicitly. Optimization for several reduction targets resulted in a discounted system cost curve. Again, the costs are calculated for the whole period. However, by chance the most substantial CO_2 reduction costs are in the period 2000 to 2010. Because this period is represented by one year, 2010, it is possible to derive average undiscounted yearly costs for 2010, which show no large deviation due to CO_2 reduction paths.

4. As in study 1 yearly CO_2 reduction costs are calculated for one year, 2000. No indications are given about a reduction path in time, but a cost-effective order of saving options in end-use resulted in a marginal CO_2 reduction cost curve for 2005. This is possible due to the fact that no CO_2 reduction options in the energy supply have been considered. Marginal and average reduction costs can also be derived per option per end-use sector.

APPENDIX B: Study 2 reporting

CO_2 EMISSION REDUCTION TECHNOLOGIES AND COSTS IN 2010 IN THE MARKAL/EMS STUDY
- CONCEPT -

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ESC-Energy Studies
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B1. GENERAL BACKGROUND

Since the MARKAL study for the period 2000-2040 is not yet finalized, results are not yet reported extensively. Since part of the results of this study are used for the UNEP national cost comparison study it was decided to inform briefly about the scenario, technologies and results connected to this study.

The study is part of the project EMS (Energy and Material Scenarios to reduce emissions of CO_2 and other greenhouse gases). This project aims to assess the prospectiveness of energy technologies [1] in the medium and long term for CO_2 emission reduction using the MARKAL (MARKet Allocation) LP-model of the Netherlands energy system. The MARKAL model minimizes the total discounted system costs over nine time periods of 5 years. In comparison with an earlier study [2] which focused on the period until 2020 various new technologies were added or modified in accordance with latest knowledge.

In first instance the EMS project focuses on technologies in the period around the year 2030. Most of the additional new energy technologies which are allowed for this time frame (CO_2 removal, hydrogen technologies, solar electricity from the Sahara) are already relatively sound with respect to information on efficiencies and costs. However their exact moment of the introduction somewhere between 2000 and 2020 is less certain, due to uncertain technology Research, Demonstration & Development funding and institutional and market barriers. As this study focuses primarily on technology evaluation within the framework of CO_2 emission reduction there is second priority for the reduction possibilities regarding political constraints (which are anyhow less relevant on the long term). This results in the enforcement of few of such barriers, resulting in an optimistic technology introduction moment (2005/2010) for most of the new technologies.

B2. THE REFERENCE SITUATION IN 2010

The energy system in the reference case in 2010 of the MARKAL model differs significantly from the current energy system. The differences are due to various factors. The LP-model calculates an energy system which is organized in the most rational way by minimizing the national costs. The national energy policy towards the year 2000 aims for the stimulation of energy conservation, combined heat and power, and renewables. The considerable time gap between 1992 and 2010 allows for a high penetration of efficient and cost-effective technologies and the introduction of some new technological innovative technologies.

Energy demand in the reference case is determined by two groups of factors: social and economic (scenario) parameters and energy and technology related parameters. The most important scenario indicators are economic growth (2.2% per year towards the year 2010) and the increasing number of households (1.3% per year until 2010). A detailed description of the scenario is given in [3]. The energy and technology factors can be disaggregated by sector:

The Dutch industry (iron & steel, petrochemicals) ranks among the most efficient in Europe and is dominated by the use of natural gas. The official government policy aims at further efficiency improvements (2% per year, 20% in the year 2000). It is generally assumed that the remaining conservation potential for the medium time horizon (2010) is small, as the short term policy will exhaust the larger part of overall efficiency improvements estimated at around 1%/year.

Similar to the situation in industry, the residential and the commercial sectors needs to achieve ambitious goals for energy conservation which are set by the government. Newly built houses will need only 900 m^3 natural gas per year for space heating; existing dwellings will need 1500 m^3 natural gas per year (this is 20% less than now). Most houses will have a condensing gas boiler [4]. High efficient light bulbs, tubes, and medium efficient appliances will have the highest possible mid term penetration [5]. The increased penetration of new electricity consuming appliances results however in a net increase in demand for electricity in the residential and the commercial sector.

In the base case demand for transportation increases considerably. However since the assumed autonomous efficiency improvement are significant the final demand is similar compared to the current situation. Additional options for saving (beyond the government targets for energy improvements) are expensive.

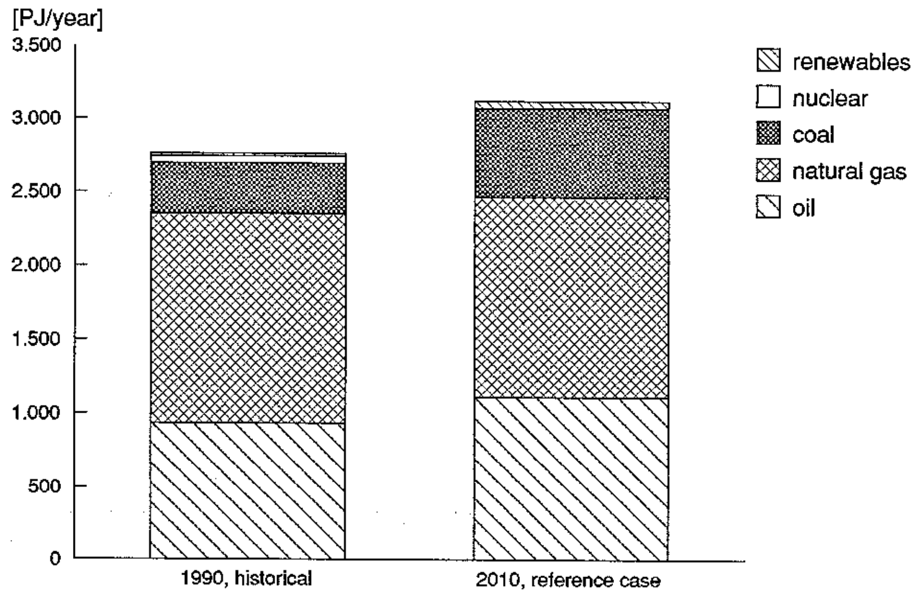

Figure B1. Primary energy mix in 1990 and in the reference case 2010

Based on the above mentioned developments energy use increases slightly compared to the 1990 situation. Total primary energy use increases 13.2%. In the primary energy mix the role of natural gas becomes less dominant; the share of coal and renewables (wind turbines, solar heat) increases. Such results in an increase of national (actual) CO_2 emissions from 161.4 Mton in 1990 to 181.7 Mton in 2010 (12.6% increase).

Electricity generation in 2010 (Table B1) is mainly dominated by decentral combined production of heat&power (mainly in industry) and advanced coal fired electricity generation (IGCC (integrated coal gasification combined cycle)). The role of coal in electricity production has increased from 40% in 1990 to 48% in 2010. Nuclear energy was not allowed as an option in this study. In the base case biomass is not a cost-effective energy source.

Table B1. Electricity production and CO_2 emissions by technology base case 2010

	[PJ_e]	[Mton CO_2]
Blast furnace gas combi power plant	8	1.0
Gas turbine / ind. cogeneration	54	4.6
Gas engine / residential & commercial cogeneration	11	0.9
MCFC (molten carbonate fuel cell) / ind. cogeneration	13	0.9
MCFC / coal gas fired / ind. cogeneration	14	1.7
Wind turbines (small and medium)	6	0.0
STAG (steam and gas turbine) power plant	45	4.7
IGCC (integrated coal gasification cog.) power plant	139	27.5
Coupled production gas combined cycle	33	3.4
Conventional coal power plant	10	2.2
Other	14	1.6
Total	347	48.5

As a consequence of the increased share of high efficient technologies and the small shift towards the use coal for electricity generation the average specific CO_2 emission (140 kg CO_2/GJ_e) for electricity production is close to the current value (167 kg CO_2/GJ_e).

B3. CO_2 REDUCTION: THE CONCEPT

In order to detect strategies for emissions reduction the reference scenario was recalculated with various maximum allowable annual CO_2 emissions (see figure B2). This appendix only presents the results for the cases with emission reduction up to 20% relative to the 1990 emission level in the year 2010 (maximum emission 129 Mton CO_2) corresponding to a maximum reduction of 60% in 2030 and 2040. In the EMS study calculations have been performed with CO_2 reductions up to 26.7% (maximum emission 118.5 Mton CO_2) in 2010 and 80% in 2030/2040 (32.3 Mton); the results of these more extreme cases have not been reported in this appendix.

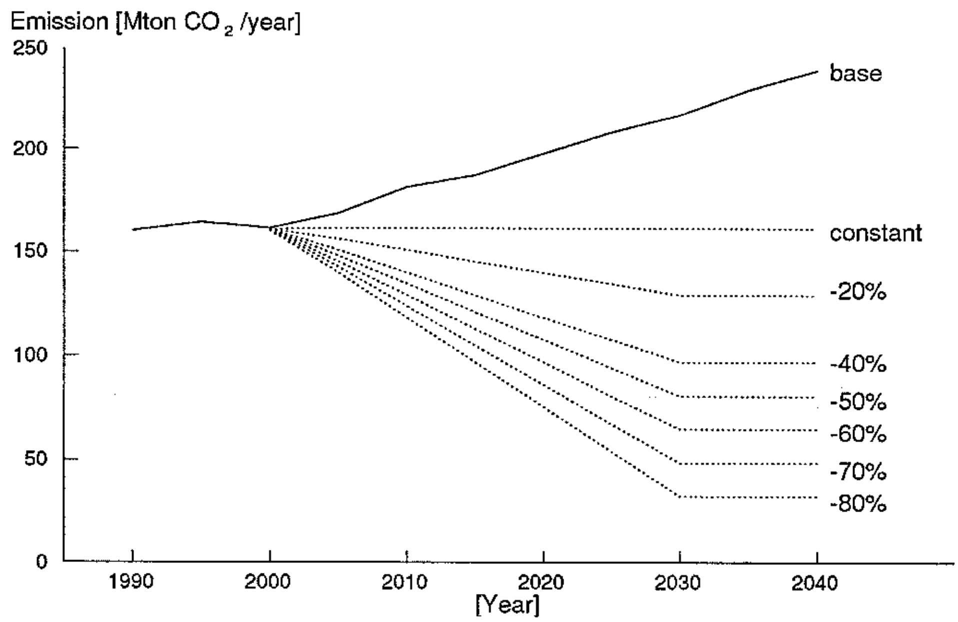

Figure B2. Yearly CO_2 emissions; reference case and CO_2 constraints

Under CO_2 constraints the MARKAL model replaces technologies with relative high CO_2 emissions by technologies with lower CO_2 emissions. The lower the emissions the more effective is the technology in reducing CO_2 emissions. If the costs are only slightly higher than the technologies in the reference case the technology is also a cost-effective option. In the Netherlands (as in most other countries) only a limited potential for cost-effective CO_2 free technologies (e.g. wind turbines and hydro electric in favourable conditions) exists. In general technologies tend to be more expensive when the technology related CO_2 emissions are lower.

Most often at modest CO_2 constraints the technologies with high CO_2 emissions are replaced first at relatively low additional costs. At more severe CO_2 constraints the technologies with high CO_2 emissions have already been replaced, consequently the 'CO_2 benefits' for replacing a technology decrease. Simultaneously the additional costs of CO_2 reduction technologies increase since the cheaper options are already installed. Increasing CO_2 reduction costs (expressed per ton CO_2) is the result.

The assessment of the CO_2 emission reduction costs of some technology can only be regarded if the replaced (or reference) technology is known. The CO_2 emission reduction costs of the technology can vary considerably when different technologies are being replaced.

B4. CO_2 REDUCTION IN 2010: THE TECHNOLOGIES

Table B2 shows the total national CO_2 emissions in 2010 in the reference case and the cases with reduced CO_2 emissions; the numbers are in accordance with figure B2.

Table B2. CO_2 emission constraints for the year 2010 (actual CO_2 emissions, excluding marine bunkers)

Scenario	Base	Con	-20%	-40%	-50%	-60%
Emission [Mton/y]	181.7	161.4	150.6	139.9	134.5	129.1

In section 2 the limited short term potential for energy saving after the execution of the government plans was explained. Saving options contribute typically 10-15% to CO_2 emission reduction (see also table B4, B5, B6 and B7). As a result the model decides to achieve its emission reduction in the year 2010 mainly by measures at the supply side of the energy system.

Regarding the results for an emission stabilisation (161.4 Mton CO_2 in 2010) the largest reduction comes from the removal of CO_2 at nitrogen fertilizer plants. The production of fertilizers in the Netherlands is relatively high. In a N-fertilizer plant CH_4 is transformed with atmospheric N_2 into NH_3. This option is relatively inexpensive since no recovery of CO_2 from flue gases needs to take place since the CO_2 is already available in its pure form. After compression it can be stored in depleted natural gas field or aquifers.

Most of the other CO_2 reduction for emission stabilisation takes place in electricity generation. The remainder of this section will focus on electricity production technologies.

Table B3 shows the specific CO_2 emission factors of important electricity producing technologies in the data base. These have been calculated from emission factors of input fuels, efficiencies and have been corrected for the combination with the production of heat. The numbers refer to the expected technological situation in the year 2010. Natural gas is assumed to be the input fuel for gas-fired technologies, not hydrogen.

Table B3. Specific CO_2 emission factors for electricity production of selected technologies in the MARKAL database for the year 2010

Technology	Specific CO_2 emission [kg/GJ$_e$]
Wind turbines (small, medium, large, offshore)	0
Wood fired power plant	0
Solar Photovoltaic cells (domestic or Sahara)	0
Hydro power plant	0
STAG power plant with CO_2 removal	27
IG-MCFC with CO_2 removal	27
IGCC with CO_2 removal	51
MCFC cogeneration natural gas (industry, R&C)	73-83
Gas turbine cogeneration (industry)	78-98
STAG power plant	104
Coupled production gas combined cycle	104
MCFC coupled production plant	104
Back pressure turbine	117
MCFC cogeneration /coal gas (industry)	122
Mixed fossil power plant	132
Coal IG-MCFC power plant	192
IGCC power plant	197
Conventional coal power plant	227

In the case with constant emissions (table B4) relative to 1990 emissions a mix of electricity generating technologies disappears, primarily the IGCC power plant (76 PJ$_e$ replaced). This plant has a high specific CO_2 emission (see table B3) and the capacity build-up is scheduled for after 2000. The small amount of electricity generation by conventional coal power plants is less flexible to be replaced (in operation or planned) and accelerated depreciation will only take place at more stringent emission constraints.

Table B4. Technical options for CO_2 emission reduction from 181.7 towards 161.4 Mton in 2010

Nr.	CONSTANT EMISSION CO_2 reduction measure	CO_2 reduction [Mton]	Additional production [PJ$_e$]	Total production [PJ$_e$]
1	Wind turbines (large)	1.14	5.9	12.4
2	Gas turbine industrial cogeneration	3.01	26.5	64.4
3	Back pressure turbine	0.60	5.5	13.9
4	Coupled production gas comb. cycle	1.53	17.1	49.6
5	IGCC with CO_2 removal	3.65	25.5	25.5
6	Advanced gas reformer (H_2 prod.)	0.87	12.4	12.4
7	CO_2 removal at N-fertilizer plant	4.2	-	-
8	Re-refining of lubricants	1.3	-	-
9	Industrial savings	0.80	-	-
10	Absorption heatpump small offices	0.10	5.4	9.6
11	Compression heatpump small offices	0.18	8.4	9.6
12	Minimum energy office	0.11	-	-
13	Absorption heatpump greenhouses	0.46	20.4	20.5
14	District heat for greenhouses	0.15	7.7	9.4
15	Other residential savings	0.59	-	-
	Not accounted for	0.61	-	-
	Total	18.69		

The new electricity producing technologies emit 10 Mton CO_2 less per year (compare with CO_2 emissions from electricity production in the reference case/table B1). Among the new technologies gas turbines for industrial cogeneration (specific CO_2 emission ±85 kg/GJ_e) and IGCC with CO_2 removal (specific CO_2 emission 52 kg/GJ_e) are most important (see table B4).

The changes in electricity generation result in a decrease of the average CO_2 emission factor for electricity generation from 140 to 110 kg/GJ_e.

Table B5. Additional technical options for CO_2 emission reduction from 161.4 Mton to 150.6 Mton in 2010

Nr.	-6.7% EMISSION CO_2 reduction measure	CO_2 reduction [Mton]	Additional production [PJ_e]	Total production [PJ_e]
16	Blast furnace gas combi	0.08	1.2	9.3
17	Gas turbine industrial cogeneration	0.40	3.9	68.3
18	Gas engine R&C cogeneration	0.16	1.5	12.8
19	IGCC with CO_2 removal	6.54	50.0	75.0
20	Wood fired power plant	0.39	3.8	3.8
21	Advanced gas reformer (H_2 prod.)	0.03	0.5	12.9
22	Gas boilers for coal boilers (ind.)	0.22	-	-
23	Wood furnace	0.72	-	-
24	Industrial savings	1.36	-	-
25	Floor insulation / new dwellings	0.04	-	-
26	Absorption heatpump greenhouses	0.35	-	-
27	Other residential savings	0.23	-	-
	Not accounted for	0.28	-	-
	Total	10.8		

To achieve the next emission reduction step more coal fired plants can be replaced (45 PJ_e IGCC and 10 PJ_e MCFC/coal gas). Apparently the remaining potential for additional industrial cogeneration is small after the stabilisation case, since only limited extra amounts are generated in this way. The main substitution is by the IGCC with CO_2 removal. The average CO_2 emission factor decreases towards 89 kg/GJ_e.

In the third step for CO_2 emission reduction (towards 139.9 Mton CO_2) the average emission factor decreases further towards 74 kg/GJ_e. The remaining IGCC's are replaced and the depreciation of the existing conventional coal capacity is accelerated. In addition to the IGCC with CO_2 removal the STAG with CO_2 removal and the IG-MCFC power plant with CO_2 removal are the additional electricity producers.

Table B6. Additional technical options for CO_2 emission reduction from 150.6 Mton to 139.9 Mton in 2010

Nr.	-13.3% CO_2 EMISSION CO_2 reduction measure	CO_2 reduction [Mton]	Additional production [PJ_e]	Total production [PJ_e]
28	Blast furnace gas combi	0.08	1.3	10.6
29	Wind turbines offshore	0.26	1.4	1.4
30	Gas engine R&C cogeneration	0.12	1.1	13.9
31	IGCC with CO_2 removal	2.09	15.9	90.9
32	IG-MCFC with CO_2 removal	2.22	14.2	14.2
33	STAG with CO_2 removal	0.86	5.6	5.6
34	Wood fired power plant	1.41	13.6	17.4
35	Advanced gas reformer (H_2 prod.)	0.84	12.0	24.9
36	Gas boilers for coal boilers (ind.)	0.93	-	-
37	Industrial savings	0.37	-	-
38	PU foam + heat recovery (ex. dwel.)	0.28	-	-
39	Other residential savings	0.22	-	-
40	Gas from manure	0.22	-	-
41	Gas from biocell	0.56	-	-
	Not accounted for	0.24	-	-
	Total	10.7		

In the fourth and the fifth step (towards 134.5 Mton respectively 129.1 Mton CO_2) less drastic changes in electricity generation take place. Most striking is the replacements of IGCCs with CO_2 removal by STAGs with CO_2 removal. The resulting decrease in the average CO_2 emission reduction is small.

The fourth and the fifth step are mainly achieved by the production of hydrogen (through reforming of natural gas) in combination with CO_2 removal. The H_2 is mainly used for the production of process heat in the industry. Smaller amounts are used in the transport sector and for fuel cells.

Table B7. Additional technical options for CO_2 emission reduction from 139.9 Mton CO_2 to 134.5 Mton CO_2 in 2010 and from 134.5 Mton to 129.1 Mton

Nr.	-16.7% CO_2 EMISSION CO_2 reduction measure	CO_2 reduction [Mton]	Additional production [PJ_e]	Total production [PJ_e]
42	Gas engine R&C cogeneration	0.09	2.0	15.9
43	STAG	0.10	1.5	41.0
44	Advanced gas reformer (H_2 prod.)	4.46	63.7	88.6
45	Gas from manure	0.45	-	-
46	Coated glass/ ex. dwel.	0.38	-	-
	Total	5.48		

Nr.	-20.0% CO_2 EMISSION CO_2 reduction measure	CO_2 reduction [Mton]	Additional production [PJ_e]	Total production [PJ_e]
47	Molten carbonate fuel cell/ind.cogen	0.05	1.6	1.6
48	STAG with CO_2 removal	0.87	36.3	40.4
49	Advanced gas reformer (H_2 prod.)	4.20	60.0	148.6
50	Coated glass/ ex. dwel.	0.37	-	-
	Total	5.49		

B5. CO_2 REDUCTION IN 2010: THE COSTS

MARKAL reports the marginal costs for CO_2 emission reduction. Incremental and average costs can be extracted from the differences in CO_2 emissions and system costs of successive reduction cases. The marginal reduction costs in 2010 are given in figure B3. They must be used carefully because they do not necessarily reflect the emission reduction costs in 2010 only. This is due to the fact that 2010 is not the end year of the studied time period, neither is it the year where some ultimate reduction goal is achieved. Since the MARKAL model has perfect foresight it anticipates on more drastic emission reduction targets in coming years (see figure B2). As a result part of the investments in 2010 contributes to the later reduction target. Most probably the mix of technologies would have been different with a different reduction path (e.g. if the emissions would stabilize from the year 2010 onwards).

The shadow prices (marginal costs) for CO_2 presented in figure B3 increase with more drastic constraints from 25 to 150 Dfl/ton CO_2. Marginal costs increase only modestly in the fifth reduction step. This is due to the dynamic concept of the model. In the fourth step the marginal cost level of CO_2 limiting technologies in 2010 is relatively high in comparison with the cost level in 2005 and 2015; many investments occur in 2010 which also serve the longer term targets. On the other hand in the fifth step the marginal cost level in 2010 is relatively low compared to the adjacent time periods.

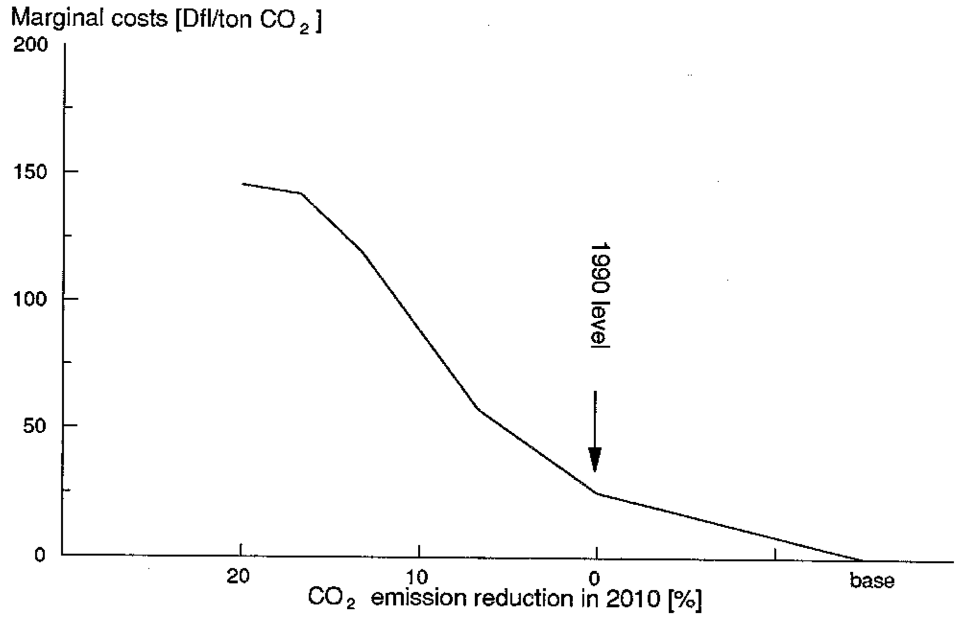

Figure B3. Marginal costs for CO_2 emission reduction in 2010

The costs for CO_2 emission reduction consist of additional investments, additional costs for operation and maintenance and additional fuel costs. Typically additional fuel costs are negative due to energy savings. Additional investments are in general the larger part of reduction costs. At high marginal costs the impacts of large investments in CO_2 reduction technologies will have drastic impacts on capital resources which could effect indirectly slow down economic growth. New investigations into CO_2 reduction costs should focus stronger on such investment related issues.

More information on the scenarios, technologies involved and results of the EMS-study which was the source of the presented information will come forth in [6]. In [6] also more detail will be given about CO_2 reduction costs on the long term; the costs will be awarded to sectors, years, technologies and components, allowing for relatively easy soft-linking with macroeconomic models.

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APPENDIX C: Study 3 emission reduction cost curve

In table C1 CO_2 reduction technologies and their CO_2 reduction contribution are listed for each scenario. The numbers of the technologies correspond with the numbers in the CO_2 reduction cost curve on the next page (figure C1). The first scenario step is called the MURE scenario and consists of the Reference scenario including additional cost-effective energy saving measures (no CO_2 constraint). In the other scenarios CO_2 constraints are applied.

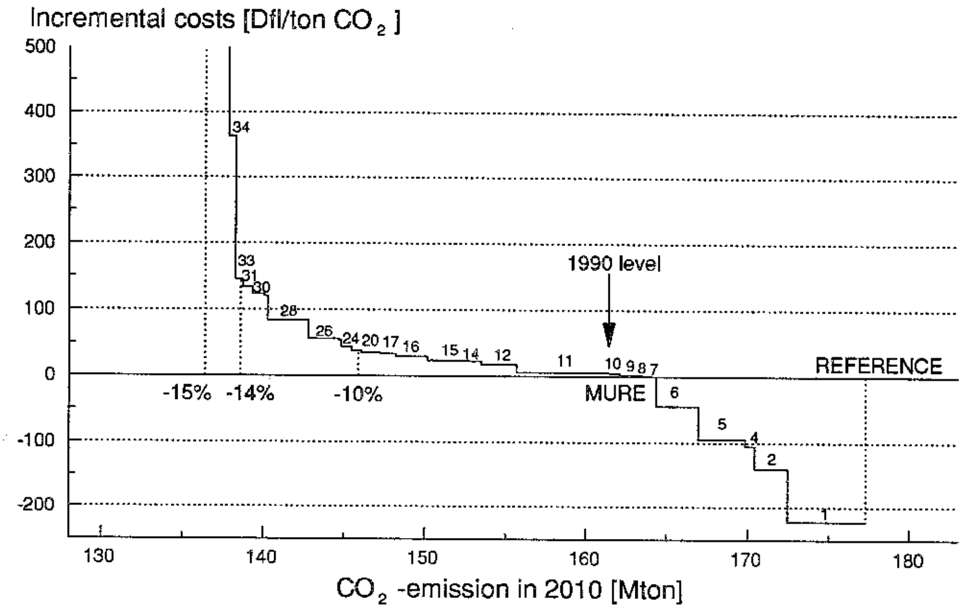

Figure C1. Incremental cost curve in the year 2010 for study 3 including estimated CO_2 reduction contribution and costs per technology

Note: The CO_2 emission reduction costs for each scenario are given by the model. The intermediate costs per technology are estimated costs linearly interpolated on the basis of the CO_2 emission reduction achieved by that option.

Table C1. CO_2 emission reduction technologies in order of penetration for 2010 in the EFOM-ENV model study 3

Nr.	CO_2 reduction measure	CO_2 reduction [Mton]	Additional production [PJ]	Total production [PJ]
MURE or saving scenario (177.3 to 164.3 Mton)				
1	Gasoline cars Maximum Power Speed Limit	4.8		
2	Traffic/Tune/Tax measures on passenger cars	2.0		
3	Gas sector measures	0.0		
4	Oil sector measures	0.6		
5	Savings on Lighting/Fridges/Freezers	2.9	18.0	
6	Insulation measures 1 for single/multi family houses	2.6	43.0	
	SUBTOTAL	13.0		
CONSTANT 1988 emission scenario (164.3 to 145.9 Mton)				
7	Fuel-cell electricity only	0.4	2.8	7.8
8	Steam and gas turbine (STAG) heat and electricity	0.5	3.1(elec.)	17.0
9	Wind farms onshore	1.4	5.8	16.2
10	New topping gas fired power plant	0.7	6.0	125.3
11	Steam and gas turbine (STAG) electricity only	5.7	50.4	69.2
12	Gas fired heat pump for comm., coll. and single houses	2.2	53.0	53.0
13	Hydro energy	0.2	0.7	1.6
14	Industrial sector	0.6		
15	Oil sector measures	2.6		
16	Insulation measures 2 for single family houses	2.0	36.0	
17	Solar boiler domestic hot water, gas back-up	0.6	8.6	8.6
18	Future vans on gasoline (including 1&2)	0.4		
19	Conventional gas power plant	0.1	0.9	5.3
20	Gas turbines for peak power production	1.1	17.9	27.1
21	Future passenger car on gasoline >1.4 l	0.1		
22	Gas fired high pressure boiler/back pressure turbine	0.1	0.2 (elec.)	6.8
	SUBTOTAL	18.4		
-5% 1988 emission scenario (145.9 to 138.6 Mton)				
23	Insulation measures 2 for multi family houses	0.4	9.0	
24	Steam and gas turbine (STAG) electricity only	0.6	6.0	75.2
25	Conventional gas power plant	0.1	1.4	5.3
26	Gas fired heat pump greenhouses, comm., single houses	1.9	71.0	124.0
27	Gas sector measures	0.0		
28	Oil sector measures	2.5		
29	Future vans on gasoil (including 1&2)	0.2		
30	Wind farms offshore	0.7	3.3	3.3
31	Future truck on gasoil	0.6		
32	Gas turbines for peak power production	0.2	3.0	30.1
	SUBTOTAL	7.3		
-6.5% 1988 emission scenario (138.6 to 136.4 Mton)				
33	Electric heat pump greenhouses, multi/single houses	0.3	2.8	2.8
34	Grid connected photovoltaics	0.4	1.8	1.8
35	Future ships for freight transport	0.4		
36	Future passenger car on gasoline <1.4 l	0.6		
37	Oil sector measures	0.3		
	SUBTOTAL	2.2		
	TOTAL	40.9		