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ASSESSMENT REPORT ON NRP SUBTHEME

"ENERGY DEMAND AND SUPPLY OPTIONS TO MITIGATE GREENHOUSE GAS EMISSIONS"

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CONTENTS

Abstract

1. **Introduction**

2. **Energy efficiency improvement**
   - 2.1. The database ICARUS
   - 2.2. The long term potential of improving the energy efficiency
   - 2.3. Energy conservation and investment behaviour of firms

3. **Material efficiency improvement and waste management**
   - 3.1. The production, flow and consumption of materials in the Netherlands
   - 3.2. Organized thrift in waste disposal
   - 3.3. Controlled anaerobic treatment of waste and waste water

4. **Switching to renewables**
   - 4.1. Harvesting the sun using ecosystems
   - 4.2. Conversion routes for energy crops
   - 4.3. Can Dutch agriculture provide clean energy?

5. **Decarbonization of fuels and flue gases, and storage of CO_2**
   - 5.1. Carbon dioxide recovery based on coal gasification
   - 5.2. Chemical absorption and other recovery techniques
   - 5.3. Carbon Dioxide recovery in the manufacturing industry
   - 5.4. Storage of carbon dioxide in aquifers
   - 5.5. Conclusions

6. **Integrated assessments: strategies for CO_2 emission reduction**
   - 6.1. CO_2 emission reduction in the Netherlands energy system
   - 6.2. Integrated emission reduction of CO_2 and non-CO_2 greenhouse gases
   - 6.3. CO_2 emission reduction in the Netherlands energy and materials system
   - 6.4. Conclusions

7. **References**

ABSTRACT

The direct and indirect consumption is responsible for more than half the anthropogenic emission of greenhouse gases, especially. It might well be that within 50 - 100 years countries like The Netherlands should reduce their CO_2 emission with 80% or more. In principle many options can be developed and applied to reduce the CO_2 emission. Focused on The Netherlands, the following ones are investigated within the Dutch National Research Programme on Global Air Pollution and Climate Change, phase I: energy efficiency improvement; material efficiency improvement and waste management; a shift to renewable energy sources, especially biomass; and decarbonization of fuels and flue gases. The

research projects and the results achieved so far are described in this report. Also the set-up and results of an integrated assessment of options to reduce greenhouse gas emissions, especially CO_2, are described. From this assessment one might conclude that technically it seems feasible to reduce the CO_2 emissions in The Netherlands with about 70% between 1990 and 2030. The associated marginal costs are calculated at 250-400 NLG or less per ton CO_2 avoided. Options that are identified as 'robust' to severe CO_2 constraints are:
a) the application of energy saving measures, like thermal insulation in the residential and the commercial sector;
b) the use of selected renewable energy options, like geothermal and solar heat, biogas, hydropower, wood power production and energy from wind turbines;
c) the removal of CO_2 from power plants and other processes, e.g. combined with hydrogen production;
d) the application of heat pumps, for space heating and hot water supply in the residential and the commercial sector;
e) the use of fuel cells, like for automotive purposes in the transport sector;
f) the replacement of fossil fuel use by electricity, like in electric heat pumps;
g) the use of hydrogen, as substitute for natural gas in stationary applications, in fuel cells and as alternative automotive fuel in vehicles and aircrafts.
The implementation of these options requires a strong R, D&D effort as well as policies and instruments to stimulate the introduction.

1. INTRODUCTION

The present way in which we produce and use energy carriers is responsible for more than half the anthropogenic emission of greenhouse gases (GHGs) to the atmosphere. The predominant gas is carbon dioxide (CO_2). Due to the use of fossil fuels to satisfy our energy needs, the emission of CO_2 has increased from the pre-industrial level of zero to about 6 Gigaton Carbon per year (GtC/y) at present. Unless major policy changes occur, this amount might increase further to 20 or 30 GtC/y, maybe even higher, at the end of the next century.
To reduce the risk of a climate change to a level that can be sustained, it might be necessary to reduce these emissions to less than 3 GtC/yr. For countries like The Netherlands this might well imply a reduction with more than 80%. Following this approach the worldwide emissions of CO_2 between the years 1990 and 2100 have to be reduced with an accumulated amount of about 1200 GtC compared to 'business-as-usual' (IPCC Working Group I, 1990; 1994).

To reduce the emission of CO_2 and other greenhouse gases a wide range of options can be applied. Important options in the energy sector are:

a. *Improvement of the energy efficiency,* leading to a reduction of the energy consumption per unit of product or unit of activity. Many technologies to improve the energy efficiency are readily available. New developments can enhance the potential of this option further.
b. *Improvement of the material efficiency.* In modern societies a considerable part of the primary energy consumption is connected with the production of materials and consumer goods. Therefore material efficiency improvement,

including a better treatment and management of waste, can reduce the energy demand and the emission of greenhouse gases.

c. *Development and application of renewable energy sources.* The energy from the sun can be harnessed directly or indirectly and be utilized to replace fossil energy sources. It requires a further development and implementation of options like biomass energy production, hydropower, solar energy conversion systems and wind turbines.

d. *A shift in the use of fuels,* from resources with a high carbon content (like coal) to resources with a lower or even no carbon content (like natural gas and uranium), although aspects like the availability of resources and the acceptability of the conversion technologies involved might restrict its applicability and possible impact.

Table 1.1
Potential contribution of options to reduce CO_2 emissions compared to 'business-as-usual'. Accumulated figures are shown for the period 1990 to 2100, based on a variety of recently published assessment studies. It should be noted that the figures are mutually dependent

- energy and material efficiency improvement	300 - 600 GtC
- application of renewables	200 - 600 GtC
- nuclear fission	100 - 300 GtC
- nuclear fusion	0 - 25 GtC
- fuel shift from coal to natural gas	0 - 300 GtC
- CO_2 recovery and storage	100 - 300 GtC
- afforestation	50 - 100 GtC

e. *Decarbonization of fuels and flue gases,* e.g. by recovering carbon dioxide from energy conversion processes and storing it outside the atmosphere. This option has begun to receive attention only recently. Several research and development programmes have been set up to get a better understanding of this option.

f. *Afforestation,* to remove carbon dioxide from the atmosphere. This option is already applied by some utilities to compensate for CO_2 emissions due to electricity production.

As already mentioned, it might be necessary to prevent the emission of CO_2 between 1990 and 2100 with an accumulated amount of about 1200 GtC compared to 'business-as-usual'. As shown in Table 1.1, the above mentioned options are probably able to reach this goal, provided that enough attention is given to their further development and that implementation barriers are removed.

For some of these options the potential and prospects for The Netherlands are subject of investigation in the Dutch National Research Programme on Global Air Pollution and Climate Change, phase I (NRP-I). An overview of the research projects, togethers with the name of the project coordinators, the project number and the area in interest, is given in Table 1.2.

In this report the results achieved so far are presented.The research is focused on possibilities to improve the efficiency of our energy consumption, to reduce the inefficient use of materials and the production of waste, to utilize biomass and organic waste as an energy source and to sequester and store CO_2 from energy conversion processes.

The results are used in a study of integrated strategies for The Netherlands to reduce the emission of CO_2 and other greenhouse gases in a cost-effective way. In this study the potential and costs of about 500 energy demand and supply technologies to mitigate the emission of CO_2 and other greenhouse gases are assessed and mutually compared using the MARKAL model. Focused on the year 2030 and assuming a continued growth of GDP, the results of this study suggest that in principle it is possible to reduce the net CO_2 emission in The Netherlands with at least 70%, with marginal costs below 400 NLG per ton of CO_2 avoided, depending on the assumptions made (see Section 6).

Table 1.2
List of projects in the NRP subtheme "Energy demand and supply options to mitigate GHG emissions"

Title	Project leader	Number
Programming study Theme Sustainable Solutions	C.J.H. Midden/ C. Daey Ouwens/ E.H. Lysen	850031
Energy and material use scenarios for the limitation of emissions of CO_2 and other greenhouse gases	T. Kram	850028
The long-term potential for improving energy efficiency	K. Blok	853107
Energy conservation and investment behaviour of firms	J.B. Opschoor/ K. Blok	853095
Study on the possibilities of anaerobic fermentation process aimed at the reduction of greenhouse gases	G. Zeeman	852091
Organizing prevention in waste management	E. Tellegen	852090
Harvesting the sun energy using agro ecosystems	J. Goudriaan	853117
Biomass conversion routes for agriculture crops in Europe	H.E.M. Stassen	853108
Sustainability of production and use of biomass for European energy supply (phase I)	E.E. Biewinga	853109
Sustainability of production and use of biomass for European energy supply (phase IIA)	E.E. Biewinga	854143

Management of 4 projects of SOP CO_2 removal and storage	P.W. Renaud	851043
Definition and control of the boundary conditions of the system studies in the SOP CO_2	L.J.M.J. Blomen	851049
CO_2 recovery from industrial processes	K. Blok	851047
Investigations regarding the storage of CO_2 in aquifers in The Netherlands	F.C. Dufour	851048
Evaluation study of SOP CO_2 removal and storage	K. Blok	851046

2. ENERGY EFFICIENCY IMPROVEMENT

An important option to reduce CO_2 emissions is improving the energy efficiency in conversion and end-use processes. Sometimes it is stated that in countries like The Netherlands the ultimate potential of this option might be limited to several ten percents. In the scientific literature, however, it is claimed this potential is much larger, theoretically more than 80% or even 90%. In the literature it is also indicate that already now many technologies can be applied to improve the energy efficiency in a cost-effective way. If this would be true, it raises the question why these technologies have not yet been implemented. As the answer to these questions is of major importance for energy policy making as well as the formulation of policies to mitigate greenhouse gas emissions, the NRP has decided to sponsor research to the potential of energy efficiency improvement as function of time and to barriers that hinder the implementation of energy conservation technologies.

2.1 The database ICARUS

To achieve a better and concrete understanding of the potential of energy efficiency improvement between 1990 and 2000 and between 1990 and 2015, the NRP-I is sponsoring the development of a database called ICARUS-3 on the potential and costs of technologies to improve the energy efficiency between 1990 and 2000/2015 in all sectors of the Dutch economic system. Special attention is given to the industry. In this research the present and future consumption of fuels and electricity (assuming a frozen energy efficiency) is divided in sub-sectors and broken down into major energy consuming processes and unit-operations (e.g. drying, pumping, heating and lighting). Next, an identification is made of (nearly) available techniques to improve the energy efficiency. Then, based on the current efficiency of energy use, an estimation is made of the potential of energy efficiency improvement techniques that can be applied. Also an estimation is made of the associated investment and operation and maintenance costs. The results of this study are contained in a Quattro compatible spreadsheet (Blok et al., 1993).

To improve the energy efficiency, so far more than 400 options have been identified (De Beer et al., 1993a, 1993b; De Beer et al., 1994). The cost-effectiveness of all these options can be presented in a supply curve. The supply curve derived in this study is presented in Figure 2.1 one for the period 1990-2000 and one for the period

1990-2015. The result indicates a technical potential for efficiency improvement of 36% and an economic potential of 29% for the period 1990-2000. The results vary for different sectors. The technical potential for the period 1990-2000 is found to be as high as 42% in the service sector but 'only' 10% in the basic metal industry. For the period 1990-2015 the results show a technical potential of 56% - which is an increase with more than 50% compared to the period 1990-2000 - and an economic potential of 43%. These figures suggest that there exists a considerable potential to improve the energy efficiency, even when all currently available measures are implemented. It should be noted that for the year 2015 also measures were considered that are not readily available, but could come available if adequate actions are taken.

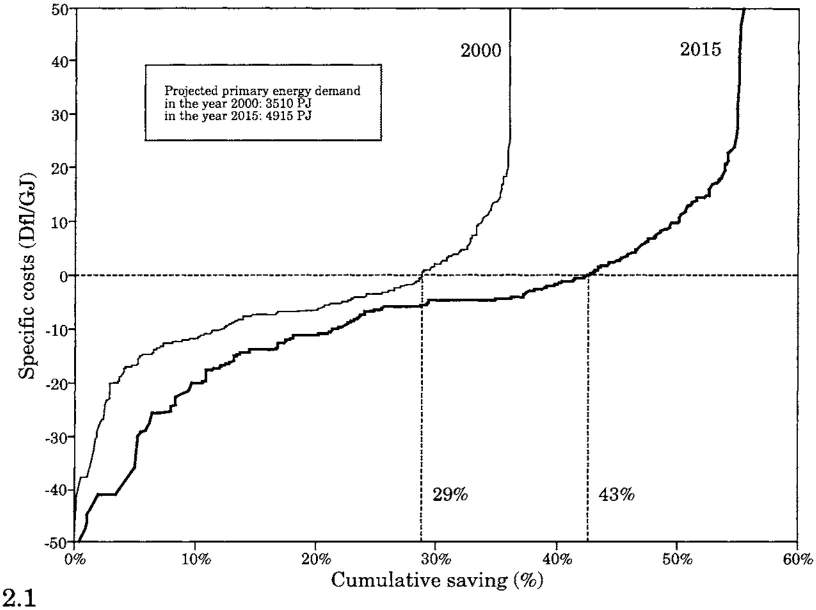

Figure 2.1
Supply curves of energy efficiency improvement measures for the periods 1990-2000 and 1990-2015. On the horizontal axis the cumulative improvement potential is given as percentage of the projected energy demand without efficiency improvements. The European Renaissance scenario is used with physical growth figures.Vertically the specific energy efficiency improvement costs are depicted. The calculations are based on a low energy price scenario, (EZ, 1994). The curves show the results for a discount rate of 5%

2.2 The long term potential of improving the energy efficiency

Assessing the potential in an even longer term, technologies should be considered that are now in a very early stage of development. This brings along problems in analyzing options and gathering information. Co-funded byNRP-I, two research projects addressed the long term potential to improve the energy efficiency, both focused on the industrial sector.

The first research, also sponsored by SYRENE research programme of NOVEM, is directed at making a preliminary survey of technologies that might reduce the end-use demand of industrial process on the longer term (Smit et al., 1994). The technology descriptions are based on accessible literature, supplemented with data provided by experts on a specific sector or technology. The descriptions are divided into two sections. The first one gives a description of the reference technology and of the new, energy efficient technology, together with information about state-of-the-art, ongoing R&D, and applicability of the technology. The second section gives preliminary data about economic and energetic parameters. In Table 2.2 some results of this research are presented. It must be emphasized that the results are based on a limited literature research. A more thorough analysis of the energy efficiency improvement potential is topic of the second research.

The second research focuses on the development of a methodology to make a more accurate analysis of the long term energy efficiency improvement potential. The methodology developed so far starts with the determination of the minimum energy requirement to perform a certain energy function and of the energy losses associated with performing the energy function with the current technology. The question posed is, whether these losses can be reduced without changing the current technology. And if not, can we imagine technologies that can reduce the energy losses. After having compiled a list of potential efficiency improvement technologies, an assessment is made of a possible future development of these technologies. A list of parameters that determine these developments is filled out, based on a review of the literature and a consultation of experts. A study following this line of research has been conducted for the sector 'paper and board' industry (De Beer et al., 1993c). Furthermore, two studies are underway for the sectors 'iron and steel' and 'cement' (De Beer, 1994). Here we present some results of the studies for the paper and board industry and the iron and steel industry.

At present the average primary energy demand to make paper out of wood pulp is about 10 GJ/ton paper. Theoretically this figure can be much smaller. The operation with the largest energy losses appeared to be steam generation (in a CHP-unit or boiler). Steam is mainly required for drying of the paper against steam heated driers. Elimination of these losses is only possible if paper is made without the addition of water, but this would have large negative effects on the characteristics of the product. Therefore five other technologies were selected that have the opportunity to reduce the energy losses. An assessment of the potential development of these technologies, resulted in the selection of two that are most promising: condensing belt drying and impulse drying. These technologies have the potential to reduce the specific steam demand by 60%.

For the iron and steel industry the study has not been finished yet. The specific energy requirement of an efficient steel plant like Hoogovens in The Netherlands is 19.7 GJ/ton crude steel. Between 1990 and 2000 a reduction to 16.8 GJ/ton is technically feasible. Thermodynamically, the minimum energy requirement to reduce iron oxide is only 6.2 GJ/ton. However, an exergy analysis of an integrated steel mill has revealed that the room to improve this process is limited. Larger improvements seems only feasible when other production routes are chosen. Several options are investigated: an increased share of secondary steel making, advanced iron making processes (e.g. plasma processes), direct steel making (in-bath melting of iron, ore-to-powder steel making), near shape casting, and the use of hydrogen as reductant. The largest efficiency improvement can be obtained by an increased share of secondary steel making. Taking into account an improved efficiency of electric arc furnaces and a higher energy demand for scrap bonification, a specific primary energy demand for secondary steel making of about 7 GJ/ton steel seems achievable in the longer term. For primary steel making, by a combination of new technologies, the specific primary energy demand might come down to about 12 GJ/ton steel (see also: Van Wijk et al., 1994).

Table 2.3
Selection of long term energy efficiency improvement technologies. All figures are based on the industrial situation in The Netherlands

Process/ application	**Current technologies**	**Currents SEC (GJ/ton) 1)**	**Long-term technology**	**Long-term SEC (GJ/ton)**
Milk powder	Two-stage drier	3.95	Condi-cyclone	2.3
Paper	Steam heated cylinders	9.9	Impulse drying	7.8 2)
Ethylene	Naphtha steam cracking	61 3)	Selective steam cracking	55
	Cryogenic distillation	61 3)	Membrane separation	56
Chlorine	Membrane electrolysis	9.9 electricity 1.2 steam	Improved membrane electrolysis	7.5 electricity - steam
Bricks	Roller kiln	2.2	Tunnel kiln	1.8
Cement	Standard kiln (dry process)	3.4	Fluidized bed	2.7
Iron making	Blast furnace	17.6 (ton pig iron)	Converted blast furnace	10.6
Steel casting	Casting and rolling	1.64 (ton crude steel)	Strip casting	0.24
Aluminum	Hall-Heroult	51.1 electricity 16.3 fuel	AlCoA	33.1 electricity - fuel
			Inert cathodes and anodes	42.1 electricity - fuel
Cross-cutting technologies	**Current technology**	**Best practice efficiency**	**Long-term improvements**	**Long-term efficiency**
Electric motors	AC induction motor	95.5% (range 40-100 kW)	E.g. permanent magnets; soft magn. materials; moreefficient fan.	98%
Combined generation of heat and power	Gas turbine with waste heat boiler, or combined cycle	η_e = 34-36%	Increase turbine inlet temperature; improvement of gas turbine cycle.	η_e = about 50%
High temp. applications	Furnaces	Energy demand: 200 PJ/year	Heat recovery with ceramic recuperators	Energy demand: 170 PJ/year

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1) SEC = specific energy consumption; in this table normally primary energy is meant.

2) Savings on steam demand are 60%, but as electricity demand increases the savings on primary energy are smaller.

3) Including use of fuel as feedstock (43 GJ/ton)

2.3 Energy conservation and investment behaviour of firms

Apart from studying the potential, the NRP-I also investigates the implementation of technologies to improve the energy efficiency, focused on the investment behaviour of firms. The question is addressed why firms do not implement measures that, according to the database ICARUS, are economically profitable. The project consists of two parts. In the first part the differences between ICARUS and the observed implementation behaviour of firms are analyzed in terms of determinants and barriers to the adoption of Energy Efficiency (EE) technologies. This study should result in an empirically validated implementation model. In the second part of the project the impact of different policy instruments on the investment behaviour of firms with respect to EE-technologies is assessed. The study should provide a simulation model by which the effectiveness of policy instruments to accelerate the adoption of EE-technologies by firms can be assessed.

The project was started with an analysis of the literature on investment decision making and on the application of investment theories to energy conservation measures. From this study the most important theoretical determinants and barriers to the adoption of energy conservation technologies were derived.
In a world without uncertainty about future states of events and cash flows, with free and full information, with independence between technologies, and with unlimited access to capital markets, a profit maximizing firm would implement all available technologies that have a positive net present value. However, if these premises are relaxed one can derive barriers that prevent firms from implementing EE-technologies. The potential barriers can be categorized in the following groups (Gillissen, 1994):

a. *economic barriers:* i) low expected energy prices; ii) uncertainty due to expected fluctuations in energy prices; iii) low expected revenues due to low energy bill; iv) budgetary problems; v) too high required return on investment;

b. *physical/technology barriers:* i) reduction in production quality; ii) bounded rationality; iii) "technology-lock"; iv) information gap;

c. *management barriers:* i) no specialized personnel; ii) no interest in energy conservation; iii) no high priority to conservation (high opportunity costs); iv) present technologies are not fully depreciated; v) lack of pressure.

Potential determinants for the implementation of EE-technologies are for example the number of information sources, the size of the firm (as a proxy for economies of scale), the presence of an energy coordinator, the presence of an R&D department, external pressure and bilateral agreements.

In order to understand why some firms do and others do not adopt EE-technologies that, according to ICARUS, are economically attractive, a conceptual model for the investment behaviour of firms was constructed. The model consists of three "modules". The first module describes the level of information of a firm. Variables are: the number of information channels, the presence of an energy coordinator, the presence of an R&D department and the presence of an environmental care system. Other important variables are: firm size, the energy bill, the complexity of an EE-technology and the costs of this technology. The second module describes how firms evaluate the profitability of an investment. Variables influencing the profitability evaluation are the minimally required return to investment, and a possible bias in perceived return and risk through a low priority for energy conservation in comparison with "core business activities". It should be noted that the profitability as *perceived* by the firm may differ from the profitability as calculated in ICARUS because of uncertainties and firm specific expectations. The third module describes the implementation stage. Rational behaviour theories predict that a firm will implement a technology when it is evaluated as being profitable. In practice, however, there can be barriers that prevent a profitable technology from being implemented, whereas non-economic influences can cause an unprofitable technology to be implemented.

To validate the hypotheses made in this study and the conceptual implementation model, a survey was made of the investment behaviour of more than 300 Dutch firms. The survey focused on the information and implementation of sector specific EE-technologies, and on variables related to the theoretical determinants and barriers (such as firm size, size energy bill, and required return on investment). From this survey, and starting from a set of more than 100 possible influential factors, the most important determinants and barriers were identified. Also indicators for the degree of information and implementation were constructed. Finally information was gathered concerning the influence of policy instruments and firm specific variables.

In another part of the investment behaviour study, the focus is on what actually happened in the Dutch manufacturing industry with regard to energy efficiency improvement. For this study a number a technologies is selected from ICARUS. The actual implementation rate of these technologies in the recent past (1980-1993) is investigated in relation to economic developments and the previously mentioned potential barriers.

The results obtained so far (see Table 2.4) suggest that energy is considered as one of the production factors, and that investments to reduce the use of energy are made largely on the basis of an economic evaluation, taking into account physical and financial constraints. Important determinants are: firm size, return on investment, the availability of capital, the possibility of early depreciation. Barriers that prevail are: uncertainty due to fluctuations in energy prices, budgetary problems, poor financial market expectations, a lack of knowledge of EE-technologies and the complexity of those technologies. Variables that hardly seem to influence the decision making are amongst others the "core business" argument, the size of the energy bill, and the presence of an R&D department. In other words, decisions on EE-investments do not differ basically from the decisions on "core business" investments.

Table 2.4
Determinants and barriers for the investment in EE-technologies, clustered to impact (preliminary result)

Very important variables	**Important variables**	**Unimportant variables**
1. Return on investment	1. Size of energy bill	1. Internal opposition
2. Contribution to total profit	2. Environmental image	2. Internal rules
3. Securing working conditions	3. Depreciation status of old equipment	3. External rules
4. Securing production quality	4. Securing production flexibility	4. Low energy prices
5. Availability of own financial sources	5. Market expectations	5. Distance to core business
6. Additional required investment costs	6. Availability external fin. sources	6. Costs collection addit. info.
	7. Uncertainty energy prices	7. Additional time and effort
	8. Degree of competence	8. Uncertainty new technologies
		9. Qualified personnel

As mentioned before, the second part of the project entails an estimation of the effects of energy policies on the implementation behaviour of firms. For that purpose plausible energy policy scenarios for the future (1994-2015) were constructed and evaluated by an expert group. These scenarios consist of a set of economic and regulatory instruments, combined with expectations regarding economic growth and energy prices. In the next phase of the study, the impact of these elements will be evaluated using the newly developed implementation model and the results of the survey concerning the investment behaviour of more than 300 firms. The study will be focused on the impact of energy taxes, energy subsidies, covenants, and information policies to reduce the information gap. Ultimately, these analyses should results in a simulation model by which the impact of different energy policies on the promotion of energy savings can be assessed.

3. MATERIAL EFFICIENCY IMPROVEMENT AND WASTE MANAGEMENT

While CO_2 is generally considered as an energy related problem, this depends on the point of view. For The Netherlands, industrial materials production is responsible for approximately one third of the national CO_2 emissions (50-60 versus 160 Mt). This part of the CO_2 emissions can be influenced by changes in the materials system, especially by improving the efficiency of material use. Options to improve the material efficiency are: good housekeeping; adaption of product designs; substitution of materials; recycling of products; material recycling; and cascade use of materials. A reduced consumption of materials and products as well as an improved management of waste streams will lead to a reduced depletion rate of resources, a reduced consumption of the energy and a reduced emission of CO_2 and other greenhouse gases (especially CH_4) to the atmosphere.

3.1 The production, flow and consumption of materials in The Netherlands

To understand the potential of material efficiency improvement and its impact on CO_2 emissions, within the NRP-I an overview has been made of the production, flow and consumption of materials in the Dutch economic system for the year 1988 and for the year 2000. Also a detailed analysis was made of the associated CO_2 emissions (Blonk et al, 1991, 1993, 1994; Gielen 1994). In the overview all materials are categorized in 22 groups, all products in 8 groups. This division is not very accurate. However, due to constraints in the availability of statistic data and to limitations of the computer model MARKAL that is used to calculate cost-effective routes for GHG-emission reduction based on these data (see Section 6), it does not make sense to strive for a higher accuracy at the moment.

Case studies were made to the material composition of complex products, like paint and cars (Mulder, 1993; Moll, 1993). Also possibilities to change the composition of products were investigated (Gielen, 1994). For several products, i.c. fertilizers and plastics, the potential of material efficiency improvement, without influencing the end function, was analyzed in depth (Worrell, 1994). For The Netherlands the technical potential to reduce the application of nitrogen fertilizers - without loss of services - is found to be nearly 45%. Its realization would lead to energy savings of about 40%. For the use of plastics in packaging these figures are 35% and 30% respectively.

3.2 Organized thrift in waste disposal

One option to increase the efficiency of material use and to reduce the emission of GHG's is the reduction of the amount of waste that is produced and subsequently burned in incinerators or disposed of on landfills. One factor that influences the amount of waste produced and the composition of the waste is the institutional setting of the handling and removal of waste. Consequently it might well be that the amount of waste that is burned or disposed of can be reduced by a change of the institutional structure.

Within the NRP-I research is executed to explore the potential of waste reduction in The Netherlands and to design a structure for organized thrift. The project is divided into five phases:

1. Examination of the structure of the Dutch waste sector.
2. Examination of the waste sector in a number of other countries.
3. Comparative study of demand management in other sectors of society.
4. Design of a waste structure aiming at waste reduction and *ex ante* evaluation of the effects on the size of waste streams.
5. Investigation of possible problems in the implementation of the designed structure.

In the first phase of the project an inventory was made of the structure of the waste sector in The Netherlands. Also its impact on the management of waste streams was investigated. It was found that at some points the present structure does indeed stimulate the growth of waste streams. Also it was found that there are a lot of organizations, both public and private, that try to influence the manner in which and the degree to which solid waste is removed and processed. The following categories of actors are distinguished: (1) waste generators, (2) waste collectors, (3) waste processors, (4) waste disposers, (5) policy makers, (6) organizations that provide data and ideas to support policy makers, and (7) interest groups and umbrella-organizations. The study has shown a number of structural impediments for waste reduction. They can be summarized as follows (De Jong and Wolsink, 1993):

a. Organizations that collect and provide data about size and composition of waste streams sometimes have interests in the outcome of the data collection. This could hinder the provision of objective and reliable data.
b. Public authorities that are simultaneously waste collectors and waste processors can pass on the corporate risk of an incineration plant to residents by changing the tariffs for the collection of domestic waste. This opportunity means that the former can accept such risks more readily than private institutions, which stimulates overcapacity of incineration facilities.
c. Owners of incineration capacity are able to force waste collectors and waste processors to deliver collected waste to them. Long-term contracts and political influence and extension of waste processing activities are among their means of influence on waste collectors.
d. Incineration plants that are in accordance with the present strict environmental standards require large investments. The financial necessity to use these plant at full capacity could hinder investments in waste prevention, recycling of waste or other waste reducing activities.
e. The long write-off periods of incineration plants are an obstacle to waste minimization policies of governments. For public authorities that are owners of such plants, waste minimization damages their own financial interests.
f. The responsibility of public authorities dealing with waste in general is limited to either the local, regional, provincial, or national level. Private waste organizations often cannot be forced to implement the policy of a public authority because they operate at another scale.
g. It is beneficial to private waste collectors not to sign long-term contracts with waste processors. In that way they remain free to search for the cheapest processing option. This often results in discrepancies between predicted and actual amounts of waste in a certain area. This can lead to a too low supply to the incinerators which implies an increase of the tariffs for contractees. In this situation, private collectors who are not contractually tied can offer "extra" waste to processors who want to see their remaining capacity utilized. The price is agreed by negotiation and is far lower than that to the contractees.
h. Private collectors have vested interests in the continuity of the existing waste structure and in the existence of uncertainty among public authorities about quantities of waste that will be offered for incineration. Therefore they try to avoid common decision-making with public authorities.
i. Waste producing enterprises are interested in:
   - Continuity of the existing waste structure and uncertainty about quantities of waste that will be offered for incineration. Overcapacity will lead to lower instead of higher tariffs for the processing of industrial waste.
   - Avoidance of exchange of information that could lead to a better insight is size, weight and composition of waste streams. More information and better planning of facilities will limit bargaining opportunities of enterprises and lead to higher processing tariffs.

Possible solutions to structural impediments are:

1. Changes in contracts between participants in the waste market.
2. Improved exchange of information, cooperation and decision-making between participants in the waste sector.
3. Revised division of tasks and competencies of authorities.
4. Creation of an independent institution that can force organizations within the waste sector to give correct information and is able to interpret and to report about these data.
5. Better use of available policy instruments by authorities.

In the second phase of the project the waste sector in other countries is examined. Based on criteria derived from the first phase, the following states were selected: Denmark, France, Nordrhein-Westfalen (Germany), California (USA), New Jersey (USA) and Massachusetts (USA). A further selection will be made later on.
New Jersey became the state of the first case study. The state was visited in May-June 1994. Interviews were held with key persons in the waste structure of this state and written documents were collected. The oral and written information is sorted out and will be published at a later date.

Nowadays in many different sectors of the Dutch society, and for quite a number of reasons, the need is felt to limit the use of existing (semi) collective facilities. Ideas are formulated and organizational experiments are put in practice to limit the demand of these facilities. Possibly the ways in which other sectors of society put preventive measures in practice, and in particular the organizational structures they develop to do so, may be of interest in designing a waste structure that aims at waste minimization. This is investigated in the third phase of the project.
Case studies were made of demand management in energy supply, housing, psychiatric hospitalization and social security in The Netherlands. The results will be published in a book (in Dutch) which is in preparation now. Work on phase 4 and 5 of the project has yet to be started.

3.3 Controlled anaerobic treatment of waste and waste water

Biological degradation of waste and waste water containing degradable organic substances can generate large quantities of CH_4 and/or CO_2. The actual quantity and composition of the produced gas depends on the amount and the composition of waste produced but also on the way the waste is discharged, stored, and treated. Focused on waste water, aerobic degradation as conventionally applied in most treatment systems leads to the production of mainly CO_2, water and a considerable amount of biomass or sludge. Most of the potential energy present in waste water, therefore, ends-up in biomass, the disposal of which is becoming a serious problem. Furthermore, aerobic treatment is rather energy consuming since this process depends on a more or less intensive aeration. An interesting alternative is formed by anaerobic treatment (Lettinga & Van Haandel, 1993). Anaerobic degradation occurs when no or insufficient oxygen is available for (complete) aerobic degradation. Under anaerobic conditions organic material can be completely degraded into CO_2, CH_4, water, a small amount of biomass, and traces of other components. The produced biogas contains the largest part of the potential energy present in waste water, and can be used as a fuel. By doing so, anaerobic degradation has the following advantages over aerobic degradation: 1)

Production of a valuable fuel, the use of which can lead to a reduction of the amount of fossil fuel consumed, 2) no energy requirement for aeration, and 3) significantly less sludge production. On the other hand, if anaerobic degradation occurs in an uncontrolled way, CH_4 can be emitted to the atmosphere where it enhances the greenhouse effect even more than CO_2.

Global atmospheric CH_4 emission from the treatment, storage, and discharge of all waste water is roughly estimated to be about 26-40 Tg/y, thereby representing about 8-11% of the total anthropogenic CH_4 emissions (Thorneloe, 1993). The contribution of the Food & Beverage (F&B) and the Pulp & Paper (P&P) industry, the main contributors to the organic pollution load, is estimated to be 12-18 Tg/y. The contribution of domestic waste water is estimated to be only about 2 Tg/y.
In the NRP-I research is done to investigate the potential of applying controlled anaerobic processes for the treatment of both domestic and industrial (F&B and P&P) waste water in order to reduce the global atmospheric emission of both CH_4 and CO_2. In this project the present day emission of CH_4 and CO_2 from waste water treatment is estimated. Furthermore, the potential production and use of CH_4 from waste water treatment and its impact on the emission of CH_4 and CO_2 emissions is analyzed (Lexmond and Zeeman, 1993).

In the estimations the following cases are considered:

1) *Complete anaerobic treatment:* Calculated emissions are energy related CO_2, and CH_4 from anaerobic degradation. Three options are regarded:
   - All CH_4 is flared.
   - CH_4 is partly used for the maintenance of the treatment plant. The excess is flared.
   - CH_4 is completely used for energy production.

   It is assumed that a certain percentage of the produced CH_4 is lost due to leakage and to amounts that are too small to collect.
2) *Complete aerobic treatment:* Calculated emissions are CO_2 from the use of fossil fuels, and CH_4 from uncontrolled anaerobic degradation also occurring in aerobic systems (Czepiel et al., 1993). CH_4 produced in aerobic systems is assumed to be emitted to the atmosphere.
3) *Current situation:* Calculated emissions are the energy related CO_2 emission and the CH_4 emissions from controlled treatment systems and from uncontrolled degradation in the environment.

Relevant data concerning waste water (amount, composition, degraduability) and treatment systems (efficiency, sludge growth, energy demand, methane emission factors, frequency of operation) were collected from literature and queries. Models were developed to be able to estimate the CH_4 and CO_2 emissions (Lexmond and Zeeman, 1994).
Due to scarcity of information, amongst others an assumption had to be made about the current use of different waste water treatment systems. As this figure has a strong influence on the final results, the assumption is given in 3.1. Especially the percentage of uncontrolled aerobic and anaerobic degradation of discharged waste water in developing countries is an important parameter. It is assumed that a large part of the waste water is discharged on surface waters.

Table 3.1
Assumptions concerning the treatment of waste water and the division in aerobic and anaerobic degradation a)

	treated (%)			untreated (%)		
	total	**aerobic**	**anaerobic**	total	aerobic	**anaerobic**
developing countries						
* domestic	10	70	30	90	75	25
* industrial	50	85	15	50	75	25
developed countries						
* domestic	90	90	10	10	80	20
* industrial	95	85	15	5	80	20

a) Assumptions are partly based on a query held among students from the International Institute for Hydraulic and Environmental Engineering, The Netherlands, 1993

The results of the study are shown in Table 3.2. The estimated CH_4 and CO_2 emissions for F&B and P&P industry waste water and domestic sewage treatment are presented as calculated for the five cases described earlier. In the calculations two values for the loss of CH_4 were used, 5% and 10%. As shown, the current CH_4 emission from the investigated waste water streams is estimated at 5 Tg/y. This is considerably lower than the value of 14-20 Tg/y, estimated by Thorneloe (1993).
Also it has been calculated that the present contribution of waste water treatment and disposal to the enhanced greenhouse effect is mainly determined by the emission of CH_4 from uncontrolled disposal of domestic waste water in developing countries. So, not only from the point of view of human health, but also from the greenhouse point of view, it is of great importance that in these countries waste water treatment is stimulated. The results show that anaerobic treatment of waste water should be stimulated in order to reduce the emissions of greenhouse gases, provided that the loss of CH_4 is minimized and the produced CH_4 is optimally used.

Table 3.2
Estimated emissions from industrial and domestic waste water treatment and disposal

	industrial emission (Tg/y)				**domestic emission (Tg/y)**				
CH_4 loss	**5%**		**10 %**		**5%**		**10 %**		
	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2	
Cases									
*** only flaring**	0.8	2.8	1.6	2.8	0.9	2.5	1.8	2.5	
*** partial reuse**	0.8	0.0	1.6	0.0	0.9	0.0	1.8	0.0	
*** complete reuse**	0.8	- 32.8	1.6	- 31.0	0.9	- 36.9	1.8	- 34.8	
*** aerobic**	0.1	17.0	0.1	17.0	0.1	15.3	0.1	15.3	
*** current situation**	1.2	12.1	1.3	12.1	3.6	3.9	3.6	3	9

It should be noted that the treatment method and the disposal of waste water are the most important parameters for the estimated emissions in the current situation. For most countries very little data is available about these subjects. Within the calculations the most important parameter is the amount of anaerobic degradation in the case of untreated waste water in the developing countries. If we, for instance, would assume that this amount is not 25% but 50%, the total CH_4 emission would increase from 5 to about 11 Tg/y. Therefore more data should become available to be able to estimate the present emissions more accurately.

In the next phase of the project, a similar study is planned for the treatment of sludge produced during waste water treatment. During aerobic waste water treatment about 4 times as much sludge is produced as during anaerobic treatment. This sludge has to be disposed of and treated. In The Netherlands sludge of aerobic installations is often digested, resulting in biogas which is normally used or flared. Anaerobic sludge contains less organic material and is therefore less suited for digestion. In order to obtain a complete picture of the emissions from waste water treatment, a comparison will be made of the most common sludge treatment systems and their related CH_4 and CO_2 emissions

4. SWITCHING TO RENEWABLES

An important option to reduce CO_2 emissions is switching to renewable sources of energy. In 1990 the contribution of renewables to the world energy supply was about one-fifth. Several studies have indicated that it might be possible to increase this figure to one-quarter or one-third in the year 2025 and to about one-half in the second half of the next century (UNSEGED, 1992; World Bank, 1992; WEC Study Group on Renewable Energy Resources, 1993; World Energy Council, 1993; T.B. Johansson et al, 1993). In the coming decades, apart from hydro power and wind energy, especially the use of biomass to produce fuels and electricity seems attractive. In the longer term a major contribution is expected also from energy production by solar cells.

In The Netherlands the current consumption of primary energy resources is about 2750 PJ. About 1% of it is obtained from renewables. The potential, however, is much higher. It is estimated that the exploration of renewable energy sources in The Netherlands that can replace about 700 PJ of our fossil fuel consumption, with major contributions from solar cells, wind turbines and the production of fuels and electricity from biomass including organic waste (Van Wijk et al., 1994). There are however many uncertainties. Some of these uncertainties are addressed in a research project initiated by the NRP-I, focused on the potential and attractiveness of biomass energy production in The Netherlands.

4.1 Harvesting the sun using ecosystems

The agricultural production in Western Europe and the US has risen enormously in recent decade. As an example, in The Netherlands the wheat yields per hectare have doubled since 1950. This has led to a reduction in land area needed for food production, meaning that there is land that could be used to grow energy crops. The objective of energy plantations is a high sustainable yield at low cost with minimal adverse impact on the environment.

The demands placed on biomass are different from those for regular agricultural crops. Mainly, an energy crop must produce a great deal of material, containing little moisture, and easy to harvest. In this context much attention is given to fast growing wood (e.g. poplar and willow) and some grassy species (e.g. reed and miscanthus). However, there is a great deal of vagueness about what the possible yields of such crops might be, whereas these yields are in fact a key factor in all evaluations of the attractiveness of biomass energy production. Therefore, within the NRP-I, a simple crop growth simulation model is developed to improve the yield estimates of (presently often unknown) energy crops (Nonhebel, 1994).

As an example the calculation of the energy yield of a poplar plantation is given. In The Netherlands the poplars begin to sprout at the beginning of May, losing their leaves in October. The amount of solar radiation that is received during this period is 1.5 GJ/m^2. Under optimal circumstances (sufficient water, etc.) 1.4 g of plant material is produced for every MJ of radiation. This would result in a biomass production of 21 ton per hectare. As the optimal circumstances seldom occur, in practice the production will be less. Also not all of the biomass can be harvested for energy production (leaves, young twigs, etc.). Therefore, in the year 2000 the annual yield might be 10-12 ton dry matter per hectare.

It should be noted that other studies have indicated yields of about 15 ton/ha. These studies were based on field experiments. In practice, yields will generally be lower.

Also it should be noted that the growing conditions vary enormously throughout Europe. Thus great differences occur in the potential productivity between different regions. Therefore the simple simulation model will now be used to calculate the maximum yield of a variety of biomass crops in different European regions. This will give an insight into which crops can where best be grown with what productivity.

4.2 Conversion routes for energy crops

There are several conversion routes for the transformation of energy crops into heat, fuels and/or electricity. Within the NRP-I ten conversion routes have been analyzed with respect to technical, financial and environmental characteristics (Van den Heuvel et al., 1994). The options considered include: cogeneration of heat and power with combustion technology; co-combustion in a pulverized coal fired power plant; electricity production with an integrated gasifier combined cycle plant of 50 MW_e; combustion of gasified biomass in a conventional natural gas fired power plant; fermentation of wheat to ethanol using wheat straw for combined heat and power generation; fermentation of sugar beet to ethanol; and RME production from rape seed followed by esterification. All these technologies are technically mature, with the exception of the integrated gasification combined cycle plant.

The lowest electricity production costs are found for the large-scale gasification option and for co-combustion. The production costs are calculated at 0.15 NLG/kWh. This figure is much higher than current electricity production costs with conventional power stations.

In this study also the specific costs to avoid the emission of CO_2 have been analyzed. The lowest figure is found for the BIG-CC plant of 50 MWe. The costs are calculated at about 75 NLG per ton CO_2 avoided. Much higher costs are calculated for the investigated production of fuels. It is concluded that future research should concentrate on large scale gasification of biomass and on co-combustion of biomass in existing power plants.

4.3 Can Dutch agriculture provide clean energy?

By generating energy from vegeTable fibers (biomass) the emission of greenhouse gases can be reduced. As well as an ecological advantage, the cultivation of crops for the supply of energy could also improve the moderate to bad economical results of Dutch arable farms. Energy crops can also create new problems, such as an environmental burden due to their cultivation.

So far research into the use of biomass as a source of energy has been focused mainly on its technical and economic feasibility. Therefore, within the NRP-I also research was set up to assess the ecological sustainability of the cultivation and use of energy crops (Zeijts et al., 1994).

Can the Dutch agricultural sector provide clean energy? Elements of this question are: how harmful to the environment is the cultivation of energy crops; what are the direct and indirect environmental effects of fitting energy crops into the cropping plan; what indirect effects are to be expected at a regional level; how much energy is produced in the entire cultivation, transport end processing chain and what effect does this have on the emission of greenhouse gases; and what is the overall conclusion for the various crops with regard to sustainability.

In this research the following effects of the cultivation and use of energy crops have been assessed: the emission of minerals; the emission of pesticides; the use of energy and the emission of greenhouse gases, the fixation of carbon from CO_2; the use of by-products and waste products; desiccation; erosion; the contribution to natural values; the contribution to scenic values; and the use of space. Nine crops and their processing chains have been studied: rape (to bio-diesel oil), sugar beet and winter wheat (to ethanol), and maize, hemp, reed, miscanthus, poplar and willow (to electricity and/or heat).

First the direct effects of the cultivation of energy crops have been assessed. The results are compared with those of cultivation on fallow land and cultivation of cereal. The direct effects are found different for each energy crop, but in general the conclusions are as follows:

- If cereal is replaced by energy crops, the emission of minerals deteriorates because the cultivation of cereal leads to low mineral losses. If energy crops are grown on fallow land, the emission remains the same.
- For most energy crops, the emission of pesticides reduces if they replace cereal. If they are grown on fallow land, there is no difference on average.
- If annual energy crops are grown on fallow land or replace cereal, the risk of erosion increases.
- Cereals contribute considerably to natural values; replacing them by energy crops leads to lower natural values. Compared with cultivation on fallow land, the average effect is neutral.
- Fallow land and land on which cereal is grown require little water, so that the risk of desiccation increases if energy crops are grown there instead.

Effects that are not directly related to the cultivation of energy crops are known as indirect effects. Indirect effects on environmental pollution and on natural and scenic values are found at the level of the individual farm as well as at a regional and national level. A few examples are given here. At the level of the individual farm, perennial crops are likely to have a cleaning effect on the soil as regards persistent weeds and a number of soil pathogens and nematodes. However, the annual crops in the cropping plan will follow each other faster. It is expected that the positive effect (clean soil) is only of interest during the first years after the cultivation of the perennial crop, and that the negative effect (faster rotation of annual crops) will predominate. On balance, this means greater mineral and pesticide emissions and a greater risk of erosion.
An indirect effect at a national level is related to the national mineral surplus. Energy crops will first be grown on fallow land, but will also replace cereal, which is normally used to produce animal feed. If the livestock population remains the same, replacement of cereal leads to an increase in the import of animal feed and/or the use of artificial fertilizers (for more intensive cultivation of animal feed). Negative effects on the national mineral surplus can be compensated by: 1) processing byproducts and waste products (such as byproducts from the fermentation of sugar beet and wheat) in animal feed, so that imports will not increase as much; 2) exporting the waste product ash as a fertilizer as it contains almost all the phosphate from the biomass; 3) using animal manure rather than fertilizers for energy crops.

In this study the following net avoided emission of greenhouse gases are calculated for the various processing and conversion routes:
- 2 to 3 tons of CO_2-equivalent per hectare per year in the production of rape diesel oil by means of extraction;
- 3 to 7 tons of CO_2-equivalent per hectare per year in the production of ethanol by means of fermentation;
- 8 to 24 tons of CO_2-equivalent per hectare per year in the production of electricity by means of burning and gasification.

The differences are caused by differences in crops, regions, processing and conversion routes. Rape extraction produces the lowest score on the emission of greenhouse gasses, followed by fermentation of sugar beet and winter cereal. Crops that are burnt or gasified score the highest.

Based on these results, and giving all evaluation criteria equal weight, the following order for the attractiveness of biomass energy production from an environmental point of view is derived:

1. winter wheat;
2. hemp and reed;
3. miscanthus, poplar and willow;
4. rape and maize;
5. sugar beet.

Winter wheat scores very high. Its cultivation produces hardly any mineral losses, it has positive natural and scenic values and it limits the risk of erosion and desiccation. A great disadvantage, however, is the low score on the emission of greenhouse gasses.

Hemp and reed score relatively high. A great advantage is that the net avoided emission of greenhouse gasses is high. A disadvantage of both crops is that they use a great deal of water, which increases the risk of desiccation. Few pesticides are required for the cultivation of both hemp and reed. Reed presumably uses minerals very efficiently, but this effect is countered by the above mentioned negative effects of perennial crops on the emission of minerals and pesticides in the other crops in the cropping plan. Fitting hemp into the cropping plan has a positive indirect effect on the use of pesticides for the other crops.

Miscanthus, poplar and willow have moderate scores as regards environmental impact. The net avoided emission of greenhouse gasses is fairly high. The mineral losses in cultivation are not likely to exceed the levels for nitrate in ground water, the use of pesticides is relatively small and erosion is prevented fairly effectively. On the other hand, however, there are negative effects of fitting perennial crops into the cropping plan. Because these crops use a relatively great amount of water, there is a risk of desiccation.

Rape and maize have a slightly negative score. A great disadvantage of rape is the low score on the emission reduction of greenhouse gasses and the use of space. Rape does, however, contribute considerably to natural and scenic values; maize does not. Both crops have a fairly low score on the emission of minerals and pesticides and for the risk of desiccation. The main reason for the low score of rape in the field of pesticides is that rape has the same crop rotation problems as sugar beet. Extra rape or sugar beet in the cropping plan will lead to an increase in the need for pesticides.

The cultivation of (extra) sugar beet has many ecological disadvantages and no obvious advantages. It scores low as regards pesticides (also because of the negative effects on soil health), erosion and scenic values. Cultivation of sugar beet also has a low score on minerals, desiccation, natural values and the use of space. An important disadvantage is that it contributes relatively little to decreasing the greenhouse effect.

It should be noted that miscanthus, reed, willow and poplar do not only score high from the point of view of environmental impact. They are also economically the most feasible, in view of the results of other studies. There are possibilities for these perennial crops especially at extensive farms with fallow land. Studies of the economic feasibility have shown that in The Netherlands energy from biomass can be profitable in the near future, if the set-aside scheme is continued and an environmental tax on non-renewable energy or a subsidy per ton of CO_2 avoided is introduced. Hemp is somewhat less feasible from an economic point of view. For the mainly intensive Dutch arable farming, however, hemp is interesting because it is easier to fit into the cropping plans. It could be grown on fallow land or it could replace cereal. Also from the point of view of environmental impact, hemp scores high.

In other European countries energy from biomass is already being generated on a limited scale. If a European subsidy for avoided CO_2 emissions or a European environmental tax on energy is introduced, the cultivation of energy crops will sooner commence in these other countries than in The Netherlands. In other European countries ground prices are lower and more land will probably be set aside. Also, in many European regions sustainable cultivation will be easier to realize than in The Netherlands.
In the long term, energy from biomass will receive competition from two sides. Firstly, agricultural land will be claimed for other purposes, such as nature development. Secondly, there may be more cost-effective ways of reducing the emission of greenhouse gasses by then.

5. DECARBONIZATION OF FUELS AND FLUE GASES, AND STORAGE OF CO_2

In the longer term, decarbonization of fuels and flue gas is the only possible GHG mitigation option allowing large-scale use of fossil sources. It can only be done practically in large scale conversion facilities. Till the beginning of the nineties, the potential of this option was hardly investigated. Therefore, in 1991 an explorative research program was set up with a number of research institutes in The Netherlands. The objective of this program was to get a better understanding of Carbon Dioxide Removal (CDR) option and to investigate its potential for The Netherlands. The research was carried out in 1991 and 1992. The program was sponsored from various sources, the main ones being the Ministry of Housing, Physical Planning and Environment, VROM and the Dutch National Research Programme on Global Air Pollution and Climate Change (NRP-I). The total budget amounted to about 1.5 million Netherlands guilders (NLG).
Before the research program started, several publications on carbon dioxide recovery and storage in The Netherlands had already been issued, with special emphasis on carbon dioxide removal from ICGCC power plants and on storage of carbon dioxide in depleted natural gas fields. In the new program the main emphasis was on studying a range of techniques to recover carbon dioxide from gas streams in detail. Some studies were devoted to the recovery of CO_2 from industrial processes. One study explored the possibilities of CO_2 storage in aquifers. A separate study was conducted to calculate the impact of CO_2 removal on the conversion efficiency and costs of complete power plants. The findings have been presented in a final report , published in 1993 (Blok, 1993). A summary of this report is given here. Table 5.1 presents some conclusions.

5.1 CO_2 recovery based on coal gasification

It was confirmed that carbon dioxide recovery based on coal gasification shows the smallest decrease in efficiency of electricity production. A detailed analysis carried out by the research institute of the electric utilities, KEMA, showed that due to

CO_2 recovery the conversion efficiency of the power plant might be reduced from 42-43% (reference value) to about 36%.

Two widely differing CO_2 recovery technologies have been investigated:

In the first approach, a water-gas shift reaction is applied after gasification of the coal, resulting in a fuel gas mainly consisting of hydrogen and carbon dioxide. For separation of hydrogen and carbon dioxide a number of options were studied: freezing out the CO_2, membrane separation, hydrogen recovery, physical absorption and chemical absorption.

The best option is physical absorption (using Selexol). By freezing out the CO_2 the required high degree of CO_2 recovery (to less than about 120 g/kWh) can probably not be attained. When this limitation would not be set, freezing out the carbon dioxide should certainly be taken into consideration. The use of membranes at low temperatures is not attractive, mainly due to the high hydrogen loss. Combined with high-temperature gas clean up the application of membranes may become of interest, although the membranes with the required high H_2/CO_2 selectivity are still under development. Chemical absorption systems have a too high energy demand. Hydrogen recovery techniques are showing considerable hydrogen losses.

The components for the favored shift/Selexol concept are commercially available. It is concluded that the technology is ready for demonstration.

In the second approach, the ICGCC makes use of a gas turbine in which the fuel is combusted in a mixture of oxygen and recycled CO_2. The combustion products (mainly CO_2 and water) are expanded through the turbine section. After cooling in a heat recovery steam generator and removal of the water, the CO_2 is recycled to the gas turbine compressor. Part of the compressed CO_2 is recycled to the gas turbine combustion chamber, the remainder is exported. As CO_2 is the main working fluid in the gas turbine, the properties differ strongly from a conventional gas turbine. The results of an analysis focused on the integration of such a gas turbine in an ICGCC power plant are given in Table 5.1. The main bottleneck for the application of this scheme is the fact that a CO_2-gasturbine is required which is not available at present. Its development could be costly. Starting such a development process is only justified if this recovery technology gives clear advantages above the ICGCC/shift/Selexol-process already mentioned.

5.2 Chemical absorption and other recovery techniques

As the future of coal gasification is still uncertain it is advisable to develop other CO_2 recovery techniques as well. In the research program, a number of other options for CO_2 recovery has been evaluated. It was found that in most cases chemical absorption, using amines, is the most attractive alternative.

Table 5.1
The impact of Carbon Dioxide Removal on the performance of power plants, as calculated by KEMA (Koetsier et al., 1992) *)

Type of plant + method of recovery	**Net conversion efficiency (%)**	**Specific CO_2 emission (g/kWh)**
ICGCC + CO_2/O_2 combustion (Texaco)	34.8	5
ICGCC + CO_2/O_2 combustion (Shell)	36.0	30
ICGCC + shift & physical absorption (Texaco)	36.4	139
Pulverized coal + chemical absorption (retrofit)	29.7	105
Natural gas fired combined cycle + chemical absorption	44.9	86
Reference coal fired power plant	42-430	800-820
Reference natural gas fired power plant	52	390

*) *Also some preliminary costs analyses were made. It was found that the recovery costs might range from 60 - 80 NLG per ton of CO_2 avoided, being the lowest for the ICGCC options. Electricity production costs in decarbonized power plants are estimated at 0.14 - 0.15 NLG/kWh for coal and 0.095 NLG/kWh for natural gas.*

For the recovery of CO_2 from the flue gas of a conventional coal fired power plant the use of gas *separation* membranes is more expensive than chemical absorption. This is mainly due to the high power requirements for the compression of the flue gases. When chemical absorption is applied, the use of gas *absorption* membranes is of interest. Gas absorption membranes are used in conjunction with chemical absorption liquids where the conventional absorption column is replaced by a membrane contactor. This modification might reduce the loss in conversion efficiency of the power plant with approximately 0.5%. This improvement is mainly due to a reduction of the pressure drop over the absorber. Gas absorption membrane systems, however, are still under development.

Also in the case of a natural-gas fired combined cycle power plant the most cost-effective option is chemical absorption. As shown in Table 5.1, it reduces the overall conversion efficiency from 52% (reference value) to approximately 45%. An alternative is a power plant based on a gas turbine using combustion in a CO_2/O_2-mixture.

Also a system based on methane reforming of natural gas (to a large extent similar to an ICGCC plant) was investigated. However, it showed a low conversion efficiency: about 37%.

5.3 CO_2 recovery in manufacturing industry

Twenty plants in manufacturing industry with the largest CO_2 emissions in The Netherlands together are responsible for about 20% of the total CO_2 emission of

The Netherlands. Main sectors are: refineries, and the iron and steel, petrochemical and fertilizer industries. The potential of CO_2 recovery in these sectors has been investigated.

Carbon dioxide recovery can be accomplished in refineries equipped with a residue gasification unit. Residue gasification is expected to be a good solution in the development towards low sulfur oil products and deeper conversion. The gasification product is fed to a shift reactor in order to produce hydrogen for other refinery processes. The carbon dioxide that is co-produced can be recovered easily. In this way about one quarter of the CO_2 emissions in future refineries can be avoided.

Another attractive option is available in the fertilizer industry. In producing ammonia, which is one of the main feedstocks for fertilizer production, approximately 50% of the CO_2 output of the fertilizer industry is already recovered. At present, the recovered CO_2 is partly utilized. The remainder is vented to the atmosphere. In this case CO_2 recovery can simply be achieved by compressing this stream to transportation pressures. Both for the refineries and the fertilizer industry, the estimated mitigation costs are in the order of 20 NLG per ton of CO_2 avoided.

More costly options were identified in the iron and steel industry: recovery of CO_2 from blast furnace gas; and in the petrochemical industry: the use of low-temperature waste heat (100 - 150 °C) for supplying the reboiler duty of a chemical absorption process.

5.4 Storage of carbon dioxide

According to one of the studies, CO_2 storage in deep aquifers is technically feasible. When injecting CO_2 in an aquifer part of the water already present will be displaced. The main mechanisms for this displacement will be gravity segregation and viscous fingering. Extended simulations of the behavior of CO_2 have been carried out for sample reservoirs. In one of these 15,000 tons of carbon dioxide per day could be injected during 8 years. After this period CO_2 breakthrough was observed at the spill point. The subsurface of The Netherlands contains a large number of aquifers that are potentially suitable. Taking into account a number of constraints, a prudent estimate of the total storage capacity of these aquifers was made. The resulting figure was 1.2 gigaton CO_2.

The main chemical influence of carbon dioxide in aquifers is its effect on carbonate chemistry. The decrease of the pH due to the dissolution of carbon dioxide will cause solution of carbonates. This effect is so small that weakening of the porous structure is not expected. However, significant changes in permeability may occur. If the seal of the structural trap is a clay layer, drying of this layer could reduce its tightness.

Departing from a CO_2 delivery pressure of 110 bar, the injection costs are estimated to be 0.7 to 1.2 NLG per ton of CO_2, depending on the storage depth.

5.5 Conclusions

As far as CO_2 recovery from power plants is concerned, options based on coal gasification with CO_2 recovery turn out to be most energy-efficient. Of the remaining recovery options chemical absorption from flue gases, using amines seem most promising. A number of recovery options based on membrane technologies have been identified, but most of them still require considerable development. Storage of CO_2 in aquifers seems to be technically feasible, but assuming very strict conditions the total storage capacity might be smaller than the storage capacity in exhausted natural gas fields.

More than at present, attention should be paid to possibilities for CO_2 recovery that are not directly related with electricity production, e.g. in manufacturing industry.

It is felt that storage of carbon dioxide will pose most problems. These problems are not only of a technical and environmental character. Also legal questions arise, e.g should storage of 'waste' in the underground be allowed?

6. INTEGRATED ASSESSMENTS: STRATEGIES FOR CO_2 EMISSION REDUCTION

Most GHG emissions in The Netherlands are related to the use of fossil energy carriers. An array of technological measures is available to reduce these emissions, ranging from fuel shifts and renewable energy sources to improved waste management or shifts in materials use. Beforehand, it is unclear how much CO_2 reduction can be achieved and at what cost. The assessment of emission reduction options is complicated because technologies are linked in the energy system (i.e. the total of energy supply, conversion, distribution and use). If e.g. the electricity production becomes less CO_2 intensive, electricity savings become less attractive for CO_2 reduction.

Sponsored by the NRP-I and the Department of Economic Affairs of the Government, the so-called EMS project was set up to assess the potential and cost-effectiveness of reduction options in an integrated approach, taking the whole energy system into account. EMS stands for Energy and Materials use Scenarios for the reduction of CO_2 and other GHG emissions.

Three main parts of the project are considered here:

1. Integrated assessment of CO_2 emission reduction for The Netherlands energy system (Okken et al., 1993; 1994).
2. Integrated assessment of GHG emission reduction for The Netherlands energy system (Ybema and Okken, 1993).
3. Integrated assessment of CO_2 emission reduction for The Netherlands energy and the materials system (Gielen and Okken, 1994).

The instrument that is used for this study is the MARKAL model (MARket ALlocation model). MARKAL is internationally used in IEA/ETSAP (International Energy Agency/Energy Technology Systems Analysis Programme) (Kram, 1993). This linear programming (LP) model can be used to develop integrated energy strategies while environmental targets are taken into account. The model contains a database with approximately 500 energy supply and demand technologies. Each technology is characterized by technical, financial and environmental parameters. The model is used to calculate the least-cost system configuration for the period 2000 - 2040, meeting exogenously defined national energy service demands and emission reduction targets. The outcomes strongly depends on the inputs in the database. These inputs were derived from many specific studies. Assumptions with respect to the costs, potentials, and performance of technologies and with respect to scenario characteristics such as fuel price paths and energy demand projections have been extensively reported. As an example, Table 6.1 gives some key data for a limited set of electricity generating technologies for the year 2030.

6.1 CO_2 emission reduction in The Netherlands energy system

The database of energy technologies has been used to analyze the potential of cost-effective CO_2 emission reduction. The analyses was done for a high (D) and a low (G) economic growth scenario, with and without nuclear energy. The scenarios are indicated by DK, DZ and GK, GZ respectively.

First the base case emissions in these scenarios were assessed. Figure 6.1 shows the results (solid lines). The increase from 2000 to 2040 ranges from 3% to 32%. The increase is due to various mechanisms. On one hand the demand for energy services increases as well as the share of coal in the primary energy mix. On the other hand already in the base case significant efficiency improvements and end-use savings are taking place.

Next, several CO_2 emission reduction paths were studied, also shown in Figure 6.1 (dashed lines). The imposed constraints are such that the CO_2 emissions 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%, compared to the emission in 2000.

It is found that, on the longer run, significant CO_2 reduction (up to 70%) can be achieved at marginal reduction costs below 400 NLG/t CO_2, as shown in Figure 6.2. Many of the implemented CO_2 removal technologies at present hardly or not available. Therefore the attainable emission reduction on short terms, e.g. in the year 2010, is much smaller. For this year also the marginal costs as function of reduction percentage will increase rapidly. It is concluded that significant CO_2 reduction are a matter of long-term planning and requires a high attention for technological innovation.

Table 6.1
Key data for some selected electricity generating technologies in 2030, used in the MARKAL studies (NLG of 1992)

Technology	**Investment cost (NLG/kWe)**	**Life (year)**	**Potential (GWe)**	**Generation costs (NLG/kWh)**
ICGCC power plant	2400	25	no limit	0.090
ICGCC + CO_2 removal	3000	25	no limit	0.106
Light Water Reactor	4775	25	12.0	0.101
PV systems on rooftops	2000	20	12.5	0.177
Wind turbines offshore	3000	20	12.5	0.115
Biomass power plant	3140	20	1.5	0.130
MCFC industrial cogeneration	2300	20	no limit	0.109

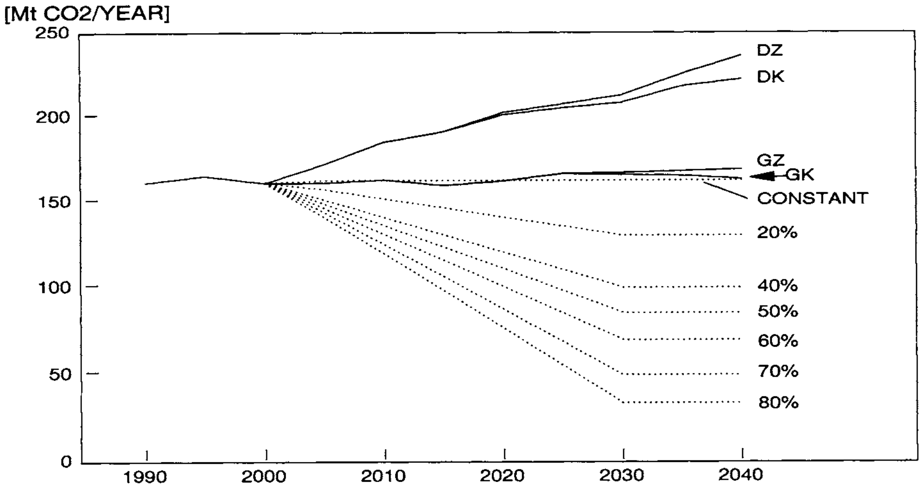

Figure 6.1
Base case scenarios for the emission of CO_2 in The Netherlands and emission reduction constraints (see text)

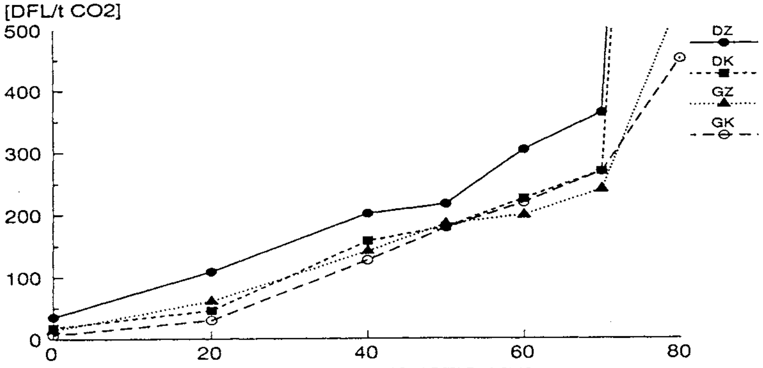

Figure 6.2
Marginal costs of CO_2 emission reduction in The Netherlands in the year 2030 assuming scenario GK, GZ, DK and DZ, taking into account the emission of CO_2 from the energy system only (Dfl = NLG)

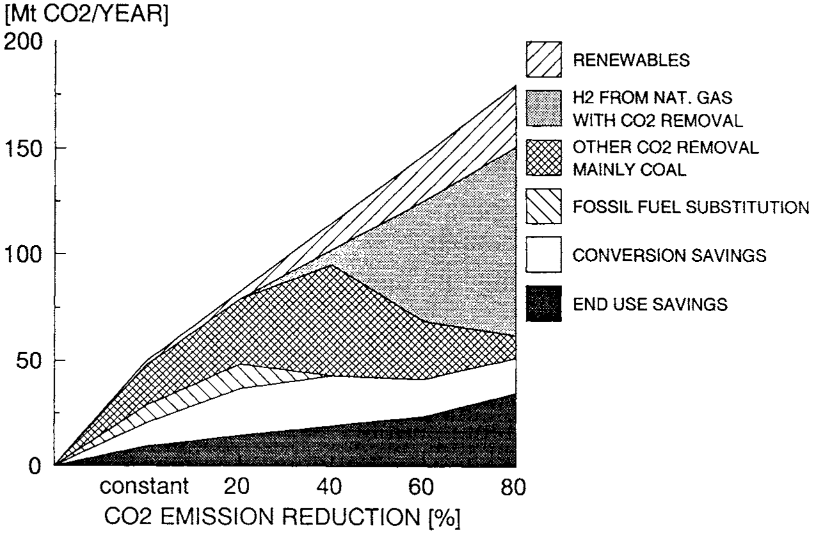

Figure 6.3
The allocation of CO_2 emission reduction for the stand-alone energy system in the year 2030, starting from base case scenario DZ

The impact of the required CO_2 emission reduction on the configuration of the energy system is significant. On the energy demand and conversion side, further savings will be realized, e.g. through better insulation of buildings. On the energy supply side, the potential for renewable energy is limited due to climate and geographic conditions. CO_2 recovery and storage plays a crucial role for achieving significant emission reduction at accepTable costs. At lower emission reduction levels, CO_2 is removed from power plants. At higher emission reduction levels, synfuels are introduced and a "hydrogen economy" combined with CO_2 removal develops. In these analyses it is assumed that within 15 years The Netherlands will have capacity for CO_2 storage in depleted natural gas fields or aquifers. As The Netherlands already now rely to a large extent on natural gas, the potential for fuel substitution as CO_2 mitigation option is limited.

Figure 6.3 shows a breakdown of the CO_2 emission reduction in 2030 in the DZ scenario for different emission reduction targets. Most reduction is achieved at the supply side. The potential for demand side emission reduction is limited, as most energy conservation options were already implemented in the base case.

As the model contains a whole array of reduction options, a detailed discussion of the attractiveness of each options is beyond the scope of this report. An overview of the attractiveness of major options in each scenario is given in Table 6.2, assuming a reduction target of 60% in the year 2030. A general cost figure for each option, in NLG per ton CO_2 avoided, is not available as this figure depends on scenario conditions. Cost figures presented in the literature should thus be considered with care, as scenario conditions determine their validity.
The general picture from Table 6.2 shows the greatest cost-effective potential in electricity generation and in the residential and commercial sector. Shifts in the transportation sector prove to be very costly, while the potential for shifts in the industry is limited (at least concerning energy related options in the industry, integrated chain management shows a very different picture, see paragraph 6.3). Conversion savings like CO_2-free hydrogen and methanol production are allocated in Table 6.2 to final consumption. It should be noted that the potentials presented in Table 6.2 should be used only as an indication. Also it should be noted that these figures cannot be added straightforward, as reduction options show interaction (e.g. through the assumed limited capacity of CO_2 storage, see Figure 6.3).

6.2 Integrated emission reduction of CO_2 and non-CO_2 greenhouse gases

In a separated study the cost-effectiveness of CO_2 emission reduction has been compared with the reduction of non-CO_2 GHGs (CH_4, N_2O, CO and halocarbons). For this study an extended MARKAL database was used. In this study emissions of GHGs which occur outside The Netherlands but are related to the Dutch final energy use were also included. Also upstream GHG emissions were included; these are emissions from mining, processing and transport of energy carriers. Such system boundaries differ from the ones commonly used for national emission accounting, but they coincide with emission definitions in full fuel cycle analysis and life cycle analysis. The greenhouse effect of emissions of different GHGs were compared using the Global Warming Potential (GWP) concept.

The incorporation of non-CO_2 GHGs and upstream GHG emissions in the analysis appears to affect the cost-effectiveness of reduction options. Total upstream CO_2 emissions and non-CO_2 GHG emissions account for 10-15 % of total energy-related GHG emissions. Upstream CO_2 emissions and CH_4 emissions are dominant.
The impact of non-CO_2 GHGs on the optimization of CO_2 emission reduction strategies was analyzed assuming a penalty on GHG emissions. In the penalty concept, the GHG emissions are valued externally with a fixed sum per equivalent ton CO_2. In the calculations all GHG mitigation options cheaper than this penalty are assumed to be implemented.

Table 6.2
Attractiveness of major reduction options in different scenarios if the CO_2 emission should be reduced with 60% in 2030

Option	**Potential**	**Performance** 1)			
	(Mt/year)	**DZ**	**DK**	**GZ**	**GK**
Marginal costs (NLG/t CO_2)		300	225	200	220
Electricity generation:					
- CHP	5-10	++	+	++	+
- CO_2 removal	>50	++	+	++	+
- Nuclear 2)	>50	n.a.	++	n.a.	++
- Renewables	10-25	++	+	+	+
- More natural gas	5-10	+	-	-	-
Transportation:					
- Hydrogen	10-25	+	+	-	-
- Methanol	10-25	-	-	-	-
- Ethanol	5-10	-	-	-	-
- Electric vehicles	10-25	+	+	-	-
- RME	5-10	-	-	-	-
Residential & commercial:					
- Insulation	10-25	++	++	++	++
- Hydrogen	10-25	+	+	+	-
- Heat pumps	10-25	++	++	++	++
- Efficient appliances	< 5	++	++	++	++
Industry:					
- More CHP	5-10	++	-	-	-
- More natural gas	5-10	-	-	+	+
- Heat pumps	5-10	-	-	-	-
- Hydrogen	5-10	++	+	+	+
- CO_2 removal	5-10	++	++	++	++
- Savings	5-10	++	++	++	++

1) ++ = achieves maximum potential
\+ = achieves limited potential
\- = not applied
2) n.a.= option is not available in this scenario

Table 6.3 shows the contribution of different groups of options to the emission reduction for two penalties (100 and 200 NLG/t CO_2 eq.). The analysis was done for two approaches. In the 'only direct CO_2' approach, the non-CO_2 GHG emissions and the upstream emissions are neglected. In the 'all GHG' approach these emissions are included.

At the investigated emission penalties, CO_2 removal at coal fired facilities appears to reduce less direct CO_2 emissions than in the 'all GHG' approach. On the other hand, renewables play a more important role in the 'all GHG' approach. For most other options, such as end-use savings and efficiency improvements, the results are less sensitive to the inclusion of non-CO_2 and upstream GHG emissions.

Table 6.3
Contribution of options to the reduction of direct CO_2 emissions in The Netherlands in cost-optimal emission reduction strategies, assuming an 'all GHG' approach and an 'only direct CO_2' approach (DZ scenario, 2030)

	penalty = 100 NLG/t CO_2 equiv.		**penalty = 200 NLG/t CO_2 equiv.**	
	reduction of all GHG emissions (Mt CO_2 eq)	reduction of direct CO_2 emissions only (Mt CO_2 eq)	reduction of all GHG emissions (Mt CO_2 eq)	reduction of direct CO_2 emissions only (Mt CO_2 eq)
Savings on end-use	16.0	15.3	20.7	20.1
Savings in conversion	21.5	22.5	22.1	22.9
Fossil fuel substitution	10.7	9.1	0.0	0.0
CO_2 removal, coal-fired	27.5	33.9	30.9	35.1
CO_2 removal, natural gas-fired	0.0	0.0	39.9	29.7
Renewables	8.4	5.8	18.7	14.9
Total reduction	**84.2**	**86.7**	**132.4**	**122.7**

The emission levels which result from an enforced emission penalty are shown in Figure 6.4 for the year 2030, indexed to the emission level in the reference case. Note that the horizontal axis has a logarithmic scale. As expected, the level of direct CO_2 emissions decreases with rising emission penalties. The gradual reduction is achieved by a mix of options, with prominent roles for energy saving, savings in conversion, CO_2 removal and renewables. Upstream CO_2 emissions show an initial increase, but they decrease at emission penalties above 200 NLG/t CO_2 equivalent. The increase is caused by shifts towards more coal with CO_2

removal for power generation at emission penalties between 100 and 200 NLG/t CO_2 equivalent. Coal production shows relatively high upstream CO_2 emissions.

The path of the CH_4 emissions is partly a result of specific CH_4 abatement measures, such as technical measures at offshore gas production, and partly it is a result of changes in the fuel mix. At the lowest penalties (20 and 50 NLG/t CO_2 eq.) the CH_4 emissions is reduced by measures at gas production facilities and by a reduced coal consumption. The strong emission decrease at 100 NLG/t CO_2 eq. is a result of a move away from certain coal types and imports of natural gas which are linked with high production emission levels. The alternatives, surface-mined coal and natural gas transported through high technical standard pipelines, have lower CH_4 emission levels. Replacement of cast-iron natural gas distribution networks is attractive at 200 NLG/t CO_2 eq. The increase of CH_4 emissions at 500 NLG/t CO_2 eq. results from an increased consumption of natural gas which is mainly used for hydrogen production. The emissions of halocarbons show a peak at 175 NLG/t CO_2 eq., caused by an increased use of heat pumps. This is offset at higher penalty levels by improvements in cooling devices that reduce halocarbon emissions.

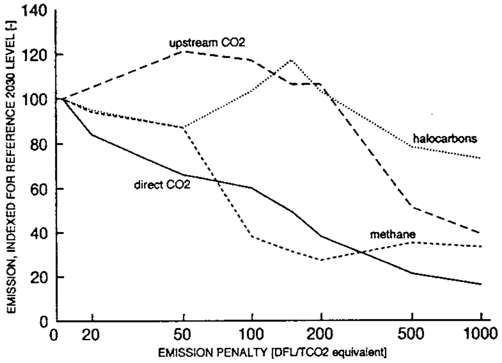

Figure 6.4
Indexed emissions in the year 2030 for various greenhouse gases at different emission penalties as calculated for the DZ scenario (Dfl = NLG)

6.3 CO_2 emission reduction in The Netherlands energy and materials system

The emission of CO_2 is generally considered as an energy related problem. Whether this is correct depends on the point of view. For The Netherlands, the industrial manufacturing of materials and products is responsible for approximately one third of the national CO_2 emissions (50-60 Mt versus 160 Mt). This part of the CO_2 emissions can be influenced by changes in the materials system. The environmental impacts of energy systems (energy production and consumption) and materials systems (materials, products and waste materials) are closely related. Oil is used as feedstock for plastics, waste is incinerated for energy recovery. Wood can either be used as construction material or energy carrier or in a sequence of both applications.

An integrated approach for both systems should enable the identification of ways to reduce CO_2 emissions with lower costs. Therefore the existing energy system in

the MARKAL model was extended to represent the materials system also. The new model describes the whole Dutch materials system, and it includes all processes "from cradle to grave". Figure 6.5 shows the materials system model structure. All material flows have been modeled that are related to end-use of materials in products in The Netherlands (see also Section 3 of this report). A large effort was put into the characterization of 29 materials, 20 product groups, 30 waste materials and some 200 processes which link the material flows. CO_2 reduction options in the materials system include:
- industrial energy savings;
- CO_2 removal from industrial plants and storage;
- reduction of materials consumption (e.g. re-usable packaging);
- materials substitution;
- biogenous fibre materials;
- improved waste collection and separation systems;
- waste recycling, cascading and energy recovery.

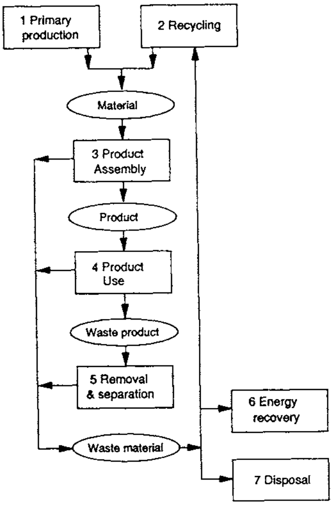

Figure 6.5
Materials system model structure

Figure 6.6 shows the CO_2 emission from our energy system and from our material consumption as calculated for the base case scenario DZ (so high economic growth, no nuclear, no CO_2 reduction policy). As shown, the emission of CO_2 due to our material use is at present equal to approximately one third of the CO_2 emissions from our energy system (with national boundaries). This notion is important, as large Dutch industrial CO_2 emissions are generally dismissed as being related to exports. These results show, however, that these export-related CO_2 emissions are offset by import-related CO_2 emissions. Figure 6.6 also shows that in the base case scenario DZ the emissions from the materials system (M) are stabilized in time, while the total emissions from the energy system (E) increase. On one hand, this stabilization is caused by improved efficiency and recycling; on the other hand dematerialization plays an important role.

If options to change the materials system are taken into account when looking for cost-effective CO_2 emission reduction strategies, significant savings in costs can be achieved. The long term marginal CO_2 mitigation costs decrease by NLG 50-100 per ton CO_2 avoided, as costly reduction options in the energy system can be avoided. Figure 6.7 shows the structure of emission reduction options in the integrated energy and materials system. Comparing Figures 6.3 and 6.7 shows what type of CO_2 emission reduction options in the energy system can be avoided at certain reduction targets. Generally speaking, energy savings in conversion processes and in end-use are reduced. The largest shift is however related to CO_2 recovery and storage. The storage capacity is assumed to be limited. As at a certain cost more CO_2 reduction can be achieved in the integrated energy and materials system without decarbonization, less CO_2 storage per PJ is required. The consequence is that the limited storage capacity is used less effectively, but at lower costs. In the MARKAL simulations, the 'hydrogen economy' (hydrogen from natural gas with CO_2 removal) is introduced later, while CO_2 removal at coal fired power plants is still used at higher reduction targets.

The simulation also shows that substitution of materials in products is an attractive option in CO_2 emission reduction strategies. Some options for reduced materials consumption (e.g. in packaging) are already included in the baseline, due to other environmental policies.

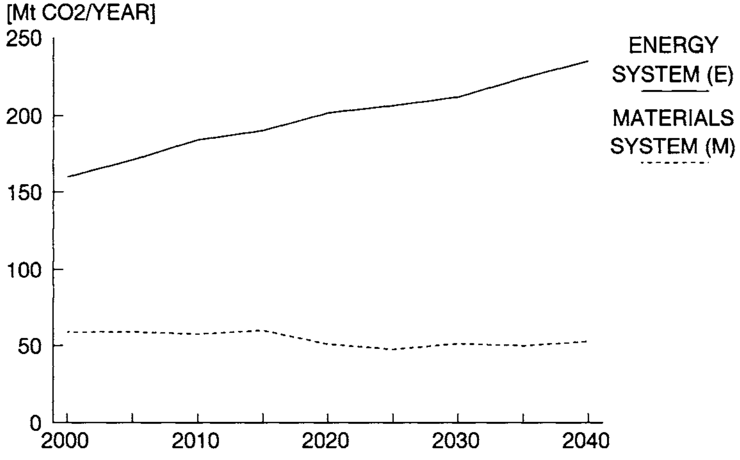

Figure 6.6
Base case CO_2 emissions for The Netherlands energy system (E) and the materials system (M) as function as time in the DZ scenario

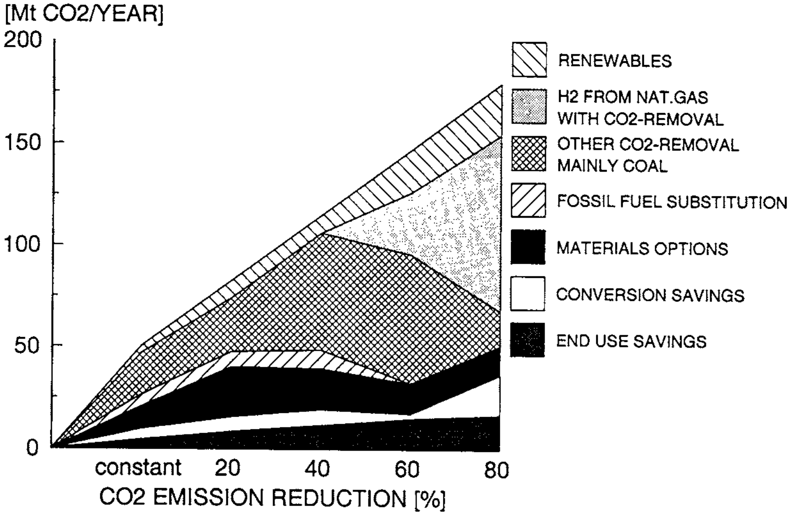

Figure 6.7
Allocation of CO_2 emission reduction in an integrated energy and materials system as calculated for the DZ scenario. The allocation is presented as function of the CO_2 emission reduction target for the year 2030

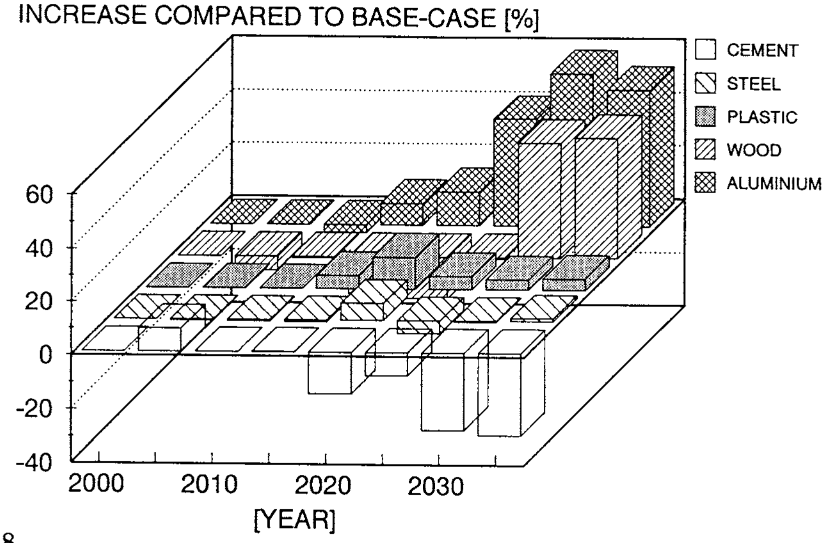

Figure 6.8
Shifts in materials consumption in the DZ scenario as function of time, assuming a CO_2 *emission reduction target for the year 2030 of 60%*

Figure 6.8 quantifies the material substitution effects. The main shifts are in the construction and transportation areas. Traditional brick/concrete buildings are

replaced by wooden skeleton buildings. The energy consumption per ton for brick and cement production is relatively low, compared to other materials. The relatively high CO_2 emission for traditional buildings is caused by the large amount of materials that is required per house and because of inorganic CO_2 emissions from cement production. In the transportation sector, cars and trucks shift towards more aluminum and plastic is used instead of wooden pallets and crates. The fuel savings due to lighter constructions are in this area the main drive. The net result of materials substitution is a decrease in the use of cement, while the use of wood and aluminum increase after 2015. The use of steel and plastics remains constant.
It should be noted that for different products these results prove to be very sensitive to assumptions concerning assembly costs.

Other shifts in the materials system occur in materials production as a result of shifts from one production technology to another. Shifts also occur as a result of changes in waste management. For some materials recycling is favoured (e.g. plastics), while for others (elastomers, biogenous fibre materials) incineration seems the best solution. These shifts are not discussed in further detail in this report.

6.4 Conclusions

The model calculations for The Netherlands 'stand alone' energy system indicate that significant CO_2 emission reductions are possible. Changes in the residential and commercial sectors (reduction is end-uses, high efficiency equipment such as heat pumps, etc.) and in electricity generation (fuel switching, cogeneration, etc.) appear more cost effective than those in industry and transport. CO_2 recovery and storage options are relatively cost effective, but are to be considered probably as transient towards more sustainable configurations. Biomass and wind provide relatively cheap renewable energy, but have limited potential. In The Netherlands photovoltaic solar energy could serve as backstop technology only; it has a large potential but most probably also high costs, even in the year 2030.
In The Netherlands it seems feasible to achieve drastic CO_2 emission reductions (up to 70%) in the period 1990-2030 at marginal costs of NLG 250 till 400 per ton CO2 avoided. The following strategies are identified as 'robust' to severe CO_2 constraints:

a) the application of energy saving measures, like thermal insulation in residential and commercial sector;
b) the use of selected renewable energy options, like geothermal and solar heating, biogas, hydropower, wood power stations and wind turbines;
c) the removal of CO_2 from power plants and in other sectors, e.g. combined with hydrogen production;
d) the application of heat pumps, for space heating and hot water supply in the residential and commercial sector;
e) the use of fuel cells, like for automotive purposes in the transport sector;
f) the replacement of fossil fuel use by electricity, like in electric heat pumps;;
g) the use of hydrogen, as substitute for natural gas in stationary applications, in fuel cells and as alternative automotive fuel in vehicles and aircrafts.

The preferred measures are not significantly influenced by taking upstream CO_2 and other greenhouse gas emissions into account. Including upstream CO_2 and methane emissions makes a noticeable difference when assessing options to reduce GHG emissions from The Netherlands energy system. Nitrous oxide, carbon monoxide and halocarbons, however, are far less important.

The manufacturing of materials and products is associated with considerable energy use. Today it constitutes approximately one third of The Netherlands CO_2 emissions. Changes in material flows and material technologies can contribute importantly to cost effective CO_2 mitigation strategies. Interaction between the materials system and the energy system at large are shown to be of importance and require further attention. The integrated assessment of energy and materials systems reveals more cost effective mitigation options than were found in the energy system alone, especially at higher reduction percentages. The reduction is achieved through shifts in material production and waste handling and through materials substitution in products. The impact on materials consumption seems most significant for cement (reduced), timber and aluminum (both increased). For steel and plastic, the net effect is balanced, but shifts between applications do occur.

International trade issues complicate the design and implementation of integrated chain management policies, especially for open, trade oriented economies like The Netherlands. Therefore, extending the coverage of this type of studies to the European level is required. This would also provide valuable extra insights into the interactions between a broader array of energy system configurations and materials systems.

7. REFERENCES

Blok, K. 1993. Final Report of the Integrated Research Program on Carbon Dioxide Recovery and Storage. Utrecht University.

Blok, K., E. Worrell, R. Cuelenaere and W.C. Turkenburg, 1993. The cost-effectiveness of CO_2 emission reduction achieved by energy conservation. Energy Policy 21: 158-175.

Blonk, T.J. and R. van Duin, 1992. Materiaalverbruik in Nederland (material use in the Netherland). Bureau B&G, Rotterdam.

Blonk, T.J. and R. van Duin, 1994. Verkenning van de ontwikkelingen in materiaalverbruik tussen nu en 2000 (Analysis of developments in the use of materials between now and 2000). Bureau B&G, Rotterdam.

Blonk, T.J., R. van Duin and P.A. Okken, 1991. CO_2 en materialen (CO_2 and materials). Netherlands Energy Research Foundation, Petten.

Czepiel, P.M., P.M. Crill, and R.C. Harriss, 1993. Methane Emissions from Municipal Waste water Treatment Processes. Environmental Science and Technology 27, (nr. 12): 2472-2477.

De Jong, P. and M. Wolsink, 1993. De structuur van de Nederlandse afvalsector (the structure of the Dutch waste sector). Onderzoeksreeks nr. 69. Interfacultaire Vakgroep Milieukunde, University of Amsterdam.

De Beer J.G., 1994. Long term energy efficiency improvement in the industry. IIASA, Laxemburg, Austria (in press).

De Beer, J.G., E. Worrell and K. Blok , 1993a. Energiebesparing in de Nederlandse industrie op de lange termijn (Energy conservation in The Netherlands industrry in the long term). Utrecht University.

De Beer, J.G., E. Worrell, K. Blok and R. Cuelenaere, 1993b. ICARUS-2.1; het potentieel van energiebesparing in Nederland tot 2000 en 2010 (ICARUS-2.1; the potential of energy conservation in The Netherlands till 2000 and 2010). Utrecht University.

De Beer, J.G., E. Worrell and K. Blok, 1993c. Energy conservation in the paper and board industry. Utrecht University.

De Beer, J.G., E. Worrell and K. Blok, 1994. ICARUS-3, potentials for energy efficiency improvement in The Netherlands till 2015. Utrecht University (in press).

Gielen D.J. and P.A. Okken, 1994. Optimization of integrated energy and materials systems. Netherlands Energy Research Foundation, Petten, The Netherlands.

Gillissen M. and H. Opschoor, 1994. Energy conservation and investment behaviour: an emperical analysis of influential factors and attitudes. Free University, Amsterdam, (in press).

Houghton, G.J. Jenkins and J.J. Ephraums (eds.), 1990. Climate Change; the IPCC Scientific Assessment. IPCC Working Group I, Cambridge University Press, Great Britain.

IPCC Working Group I, 1994. Report on Radiative Forcing and Global Warming Potentials (in press).

Johansson, T.B., H. Kelly, A.K.N. Reddy and R.H. Williams (eds.), 1993. Renewable Energy, Sources for Fuels and Electricity. Island Press, Washington.

Koetzier, H., S.P.N. van Rijen and H. Bresser, 1992. Calculations on Some Complete Systems for Electricity Production with CO_2 recovery, Transport and Storage. KEMA, Arnhem, (In Dutch).

Kram, T., 1993. National energy options for reducing CO_2 emissions; Volume 1: the international connection. Report of ETSAP/Annex IV. Netherlands Energy Research Foundation, Petten.

Lettinga, G. and A.C. Van Haandel, 1993. Anaerobic Digestion for Energy Production and Environmental Protection. In: T.B. Johansson et al. (eds.). 'Renewable Energy: Sources for Fuels and Electricity'. Island Press, Washington, USA, p. 817-839.

Lexmond M.J. and G. Zeeman, 1994. Potential of controlled anaerobic waste water treatment in order to reduce the global emissions of methane and carbon dioxide. In: J. van Ham et al. (eds). Non-CO_2 Greenhouse Gases. Kluwer Academic Publishers, p. 411-419.

Moll, H.C., 1993. Energy counts and materials matter in models for sustainable development. Thesis, Groningen University.

Mulder, H.A.J., 1993. Werkdocument metalen en verf (Working document metals and paint). IVM, Groningen University.

Nonhebel, S., 1994. A simple method to estimate regionally average yields of biomass crops. Dept. of Theoretical Production Ecology, Wageningen Agricultural University, (in press).

Okken, P.A., T. Kram, P. Lako, J.R. Ybema, J. van Doorn and D. Gerbers, 1992. Drastische CO_2 reductie - hoe is het mogelijk? (drastic CO_2 reduction - how can it be achieved?) Netherlands Energy Research Foundation, Petten.

Okken, P.A., J.R. Ybema, T. Kram, P. Lako, D. Gerbers, 1994. Energy systems and CO_2 constraints. Netherlands Energy Research Foundation, Petten.

Smit, R., J. de Beer, E. Worell and K. Blok, 1994. Long term energy efficiency improvement: technology descriptions. Utrecht University.

Thorneloe, S.A., 1993. Waste water treatment, from A.R. van Amstel (ed.). 'Methane and Nitrous Oxide, National Institute of Public Health and Environmental Protection (RIVM), Bilthoven, p. 115-130.

UNSEGED, 1992. United Nations Solar Energy Group on Environment and Development. Solar Energy: a Strategy in Support of Environment and Development. United Nations, New York.

Van Zeijts, H., E.B. Oosterveld and E.A. Timmerman, 1994. Kan de landbouw schone energie leveren? (Can Dutch agriculture provide clean energy?). Centrum voor Landbouw en Milieu, Utrecht.

Van den Heuvel, E.J.M.T., H.E.M. Stassen and F.S. Feil, 1994. Conversieroutes voor energiegewassen (Conversion routes of energy crops). BTG Biomass Technology Group BV, Enschede.

Van Wijk, A., B. Meuleman, J. de Beer, K. Blok, W. Turkenburg and E. Worrell, 1994. Sustainable Energy System; Technologies to Reduce the CO_2 Emission. Utrecht University.

WEC, 1993. World Energy Council, Energy for Tomorrow's World. St. Martin's Press, London, U.K.

WEC Study Group on Renewable Energy Resources. 1993. Renewable Energy Resources: Opportunities and Constraints 1990-2020. World Energy Council, London, U.K.

World Bank, 1992. Development and the Environment. World Development Report 1992, Oxford University Press, U.K.

Worrell, E., 1993. Potentials for improved use of industrial energy and materials. Thesis, Utrecht University.

Ybema J.R. and P.A. Okken, 1993. Full fuel chains and the basket of greenhouse gases. Netherlands Energy Research Foundation, Petten.