

Long-term energy and materials strategies for CO₂ reduction

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Abstract

Long-term greenhouse gas emission reduction strategies for the Netherlands were studied, using a MARKAL energy model. The EMS study identifies long-term technological options for greenhouse gas emission reduction and assesses their cost-effectiveness, taking interactions between technologies into account. The project consisted of three parts: carbon dioxide (CO₂) emission reduction in the energy system, integrated reduction of greenhouse gases from the energy system with consideration of upstream emissions and CO₂ reduction in the integrated energy and materials system. 500 energy technologies were assessed for their reduction potential. Significant emission reduction seems possible, but it takes an array of measures to achieve this goal at acceptable costs. Considering the full fuel chain and other greenhouse gases does not significantly affect the optimal solution. CO₂ emission reduction in the materials system proves to be a promising approach, resulting in significant CO₂ emission reduction at lower cost as for the stand-alone energy system.

1. INTRODUCTION

Reduction of anthropogenic greenhouse gas emissions is widely considered an essential measure to reduce the risk of enhanced global warming. The most important greenhouse gas (GHG) is carbon dioxide (CO₂), but other gases like methane (CH₄) and nitrous oxide (N₂O) are also relevant. 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 CO₂ 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 CO₂ intensive, electricity savings become less attractive for CO₂ reduction. The goal of the EMS project (Energy and Materials use Scenarios for reduction of CO₂ and other GHGs) is to assess the potential and cost-effectiveness of reduction options in an integrated approach, taking the whole energy system into account. Three main parts of the project are considered

here:

1. Integrated assessment of CO₂ emission reduction in the Netherlands energy system [1,2],
2. Integrated assessment of GHG emission reduction in the Netherlands energy system [3],
3. Integrated assessment of CO₂ emission reduction in the energy and the materials system [4].

The instrument that is used for this study is the MARKAL (MARKet ALlocation) model. MARKAL is internationally used in IEA/ETSAP (International Energy Agency/Energy Technology Systems Analysis Programme) [5]. This linear programming (LP) model can be used to develop integrated energy strategies, taking environmental restrictions into account (CO₂, NO_x, SO₂). A MARKAL model for the Netherlands has previously been used to support governmental energy policy strategies and national energy technology research programmes. The model contains a database with approximately 500 energy supply and demand technologies. Each technology is characterised 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. Earlier studies with this tool concentrated on emission reduction for SO₂ and NO_x (e.g. [6]). In this project, the model is extended to study the reduction of GHG emissions, especially the reduction of CO₂ emissions.

2. CO₂ EMISSION REDUCTION IN A STAND-ALONE ENERGY SYSTEM

An extended database of energy technologies is evaluated with respect to the cost-effective potential for CO₂ reduction. High (D) and low (G) economic growth scenarios with and without nuclear energy are studied (called DK, DZ and GK, GZ, respectively). Figure 1 shows the CO₂ emission from the energy system in the four base cases (lines). The increase from 2000 to 2030 ranges from 3% to 32%. The increase of baseline emissions of CO₂ is a result of various mechanisms. Energy demand increases and the share of coal in the primary energy mix grows, especially for electricity generation and methanol production. On the other hand the baseline includes significant efficiency improvements and end-use savings. Several CO₂ emission reduction paths were studied, also shown in figure 1 (dashed lines). The CO₂ constraints for the reduction cases follow linear paths from 2000 to 2030 and then stabilize. Reduction percentages imposed for the year 2030 include stabilisation (0%), 20%, 40%, 50%, 60%, 70% and 80%, compared to the emission in 2000.

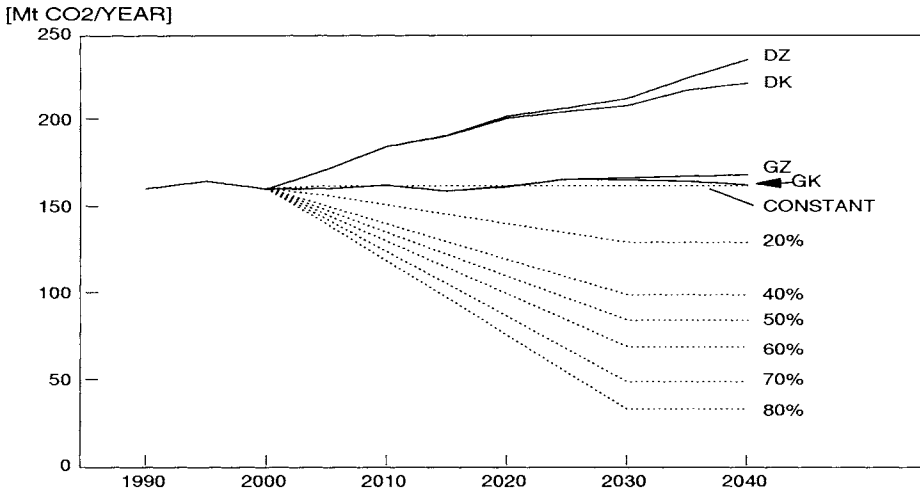


Figure 1: Base case CO₂ emissions and emission reduction constraints [1].

In 2030, significant CO₂ reduction (up to 70%) can be achieved at marginal reduction costs below 400 NLG/t CO₂ (see figure 2). However, as CO₂ removal technologies will hardly be available in 2010, the attainable emission reduction is much smaller and marginal costs increase rapidly in that year, in particular in the D scenarios. Substantial CO₂ reduction proves to be a matter of long-term planning.

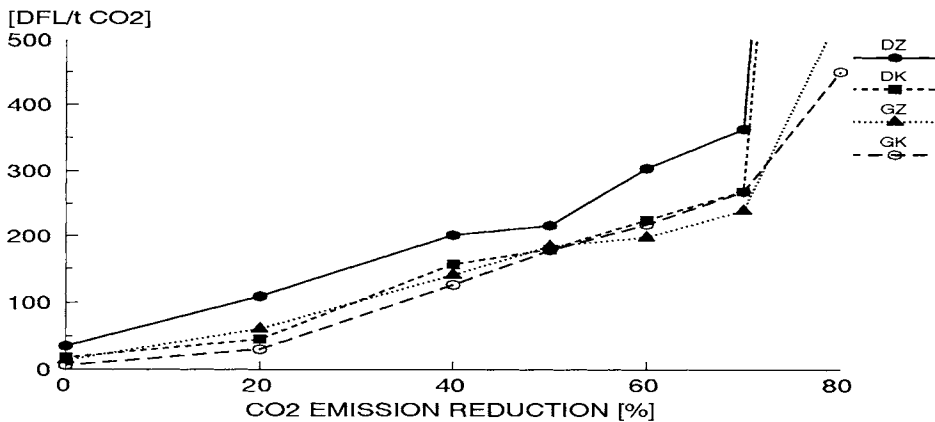


Figure 2: Marginal costs of CO₂ reduction 2030 [1].

The impact of CO₂ reduction on the energy system is very significant. On the energy supply side, the potential for renewable energy is limited due to climate and geographic conditions. Within 15 years it is expected that the Netherlands will have capacity for storage of CO₂ in depleted natural gas fields or aquifers allowing for CO₂ removal options. Such options have been considered for electricity generation and for synfuel production (e.g. hydrogen). CO₂ storage plays a crucial role for achieving significant emission reduction at acceptable costs. At lower emission reduction levels, CO₂ is removed from power plant flue gases. At higher emission reduction levels, synfuels are introduced and a "hydrogen economy" develops. As the Dutch energy system already depends on natural gas to a large extent, the potential for fuel substitution as CO₂ reduction option is limited. On the energy demand and conversion side, significant savings are still achievable, e.g. through better insulation of buildings. Figure 3 shows a breakdown of emission reduction in 2030 in the DZ scenario at increasing emission reduction targets. Most emission reduction can be achieved at the supply side. While the potential for demand side CO₂ reduction is limited, most of these options are already included in the baseline.

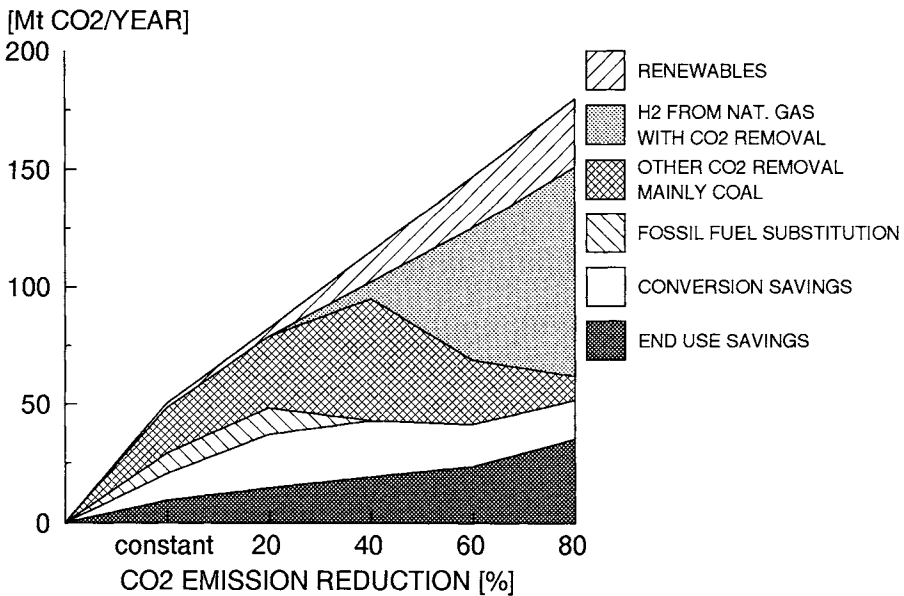


Figure 3: Emission reduction allocation for the stand-alone energy system (DZ 2030) [1]

As the model contains a whole array of reduction options, a detailed discussion of the attractiveness of specific options is beyond the scope of this paper.

Table 1
Attractiveness of major reduction options in different scenarios (60% reduction case 2030).

Option	Potential [Mt/year]	Performance ¹			
		DZ	DK	GZ	GK
Marginal costs [DFL/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	+	+	+	-
Heatpumps	10-25	++	++	++	++
Efficient appliances	< 5	++	++	++	
Industry					
More CHP	5-10	++	-	-	-
More natural gas	5-10	-	-	+	+
Heatpumps	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 1 shows an overview of reduction options in different scenarios. A general cost figure in DFL per tonne CO₂ for each option is not available, as the costs and the CO₂ reducing potential depend on the scenario conditions. For example the reducing potential for electricity generating or consuming technologies and for combined heat and power generation (CHP) are largely determined by reference technologies and load patterns. As these conditions vary between scenarios, the attractiveness varies accordingly. Cost figures per tonne CO₂ in the literature should thus be considered with care, as scenario conditions determine their validity.

The general picture from table 1 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 section 4). Conversion savings like e.g. CO₂-free hydrogen and methanol production are in table 1 allocated to final consumption. The potential in table 1 is only an indication; these figures cannot be added straightforward as reduction options show interaction (e.g. through limited CO₂ storage potential, see figure 3).

3. INTEGRATED REDUCTION OF GREENHOUSE GASES

The sensitivity of emission reduction results from consideration of non-CO₂ GHGs (CH₄, N₂O, CO and halocarbons), was studied with an extended MARKAL database. Emissions of GHGs which occur outside the Netherlands, but which are related to the Dutch final energy use were also included. The upstream GHG emissions include 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 warming impacts of emissions of different GHGs were compared using the Global Warming Potential (GWP) concept.

Incorporation of non-CO₂ GHGs and upstream GHG emissions in the analysis appears to affect the effectiveness of reduction options. Total upstream CO₂ emissions and non-CO₂ GHG emissions account for 10-15 % of total energy-related GHG emissions. Upstream CO₂ emissions and CH₄ emissions are dominant. The impact of other greenhouse gases on the optimisation was analysed, using a CO₂ "penalty". In the penalty concept, CO₂ emissions are valued externally with a fixed sum per tonne CO₂. CO₂ emissions are minimised again in a cost-effective way. Table 2 shows the contribution of groups of options to emission reduction in two approaches. In the 'only direct CO₂' approach the non-CO₂ GHG emissions and the upstream emissions have been neglected, while in the 'all GHG' approach these emissions were included. At two emission penalties (100 and 200 DFL/tCO₂), CO₂ removal at coal-fired facilities appears to reduce less direct CO₂ 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-CO₂ GHG and upstream GHG emissions.

Table 2

Contribution of options to reduction of direct CO₂ emissions in cost-optimal emission reduction strategies in 'all GHG' approach and in 'only direct CO₂' approach (DZ scenario, 2030).

	100 DFL/tCO ₂ penalty		200 DFL/tCO ₂ penalty	
	all GHGs	only direct CO ₂	all GHGs	only direct CO ₂
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
<i>Renewables</i>	8.4	5.8	18.7	14.9
Total Reduction	84.2	86.7	132.4	122.7

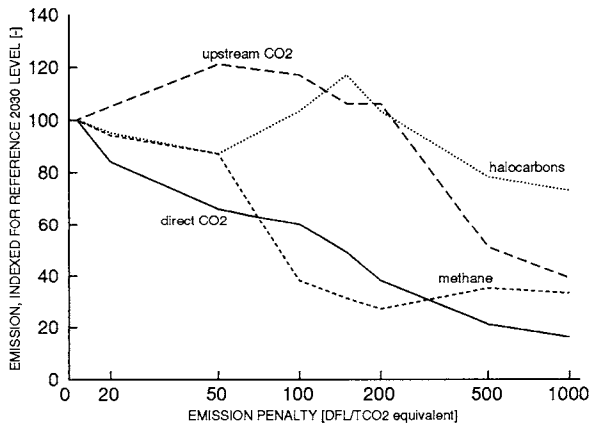


Figure 4: Indexed emissions for various greenhouse gases at different emission penalties (DZ 2030).

The emission levels which resulted from the enforcement of penalties are shown in figure 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 levels of direct CO₂ emissions decrease with rising emission

penalties. The gradual reduction is achieved by a mix of options, with prominent roles for energy saving, savings in conversion, CO₂ removal and renewables. Upstream CO₂ emissions show an initial increase, but decrease at emission penalties above 200 DFL/t CO₂. The increase is caused by shifts towards more coal with CO₂ removal for power generation at emission penalties between 100 and 200 DFL/t CO₂. Coal production shows relatively high upstream CO₂ emissions.

The path of the CH₄ emissions is partly a result of specific CH₄ abatement measures, such as technical measures at offshore gas production, and the path is partly a result of changes in the fuel mix. At the lowest penalties (20 and 50 DFL/tCO₂) CH₄ emissions will be reduced by measures at gas production facilities and by a reduced coal consumption. The strong emission decrease at 100 DFL/tCO₂ is a result of a move away from certain coal types and natural gas imports which are linked with high production emission levels. The alternatives, surface-mined coal and natural gas transported through high technical standard pipelines, have lower CH₄ emission levels. Replacement of cast-iron natural gas distribution networks is attractive at 200 DFL/tCO₂. The increase of CH₄ emissions at 500 DFL/tCO₂ results from the increased consumption of natural gas which is mainly used for hydrogen production. The emissions of halocarbons show a peak at 175 DFL/tCO₂, caused by an increased use of heatpumps. This is offset at higher penalty levels by improvements in cooling devices that reduce halocarbon emissions.

4. CO₂ EMISSION REDUCTION IN THE INTEGRATED ENERGY AND MATERIALS SYSTEM

While CO₂ 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 CO₂ emissions (50-60 vs. 160 Mt). This part of the CO₂ 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 CO₂ emissions with lower costs. The existing energy system model was extended to represent the materials system. The model describes the whole Dutch materials system, and it includes all processes "from cradle to grave"; figure 5 shows the materials system model structure. All material flows are modeled that are related to end-use of materials in products in the Netherlands.

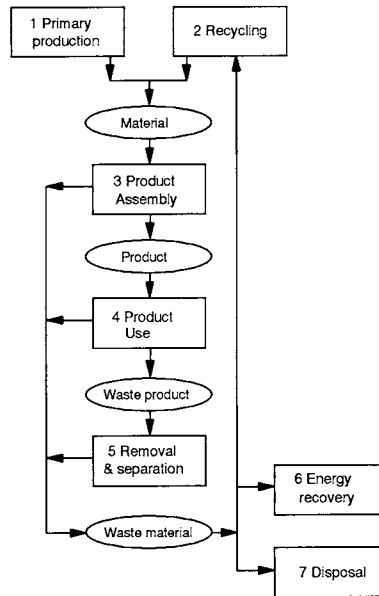


Figure 5: Materials system model structure.

A large effort was put into the characterisation of 29 materials, 20 product groups and 30 waste materials and some 200 processes which link the material flows. Appendix 1 shows the relation between materials and products. CO₂ reduction options in the materials system include:

- industrial energy savings;
- CO₂ 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 shows the model results for CO₂ emissions in the base-case (no CO₂ reduction). The materials system that is defined on the end-use principle is again responsible for approx. one third of the CO₂ emissions from the energy system (with national boundaries). This is important, as large Dutch industrial CO₂ emissions are generally dismissed as being related to exports. These results prove however that these export-related CO₂ emissions are offset by import-related CO₂ emissions. The emissions from the materials system (M) are stabilised in time, while the total emissions from the energy system (E) increase. On one hand, this stabilisation is caused by improved efficiency and recycling; on the other hand dematerialisation plays an important role.

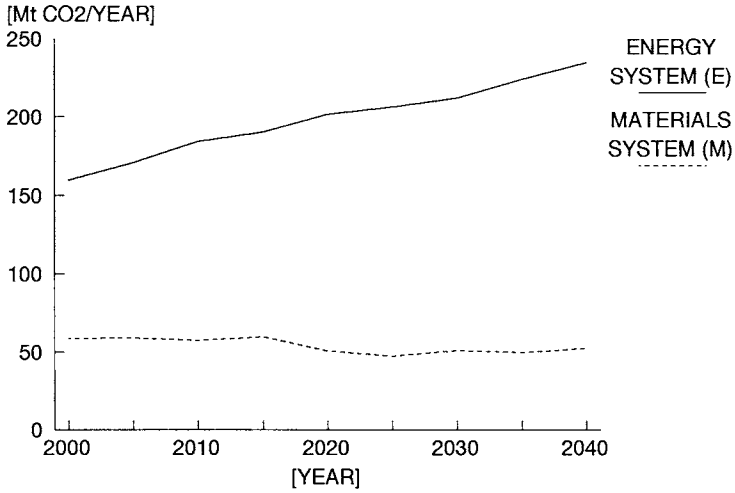


Figure 6: Base case CO₂ emissions for the energy system (E) and the materials system (M) (DZ).

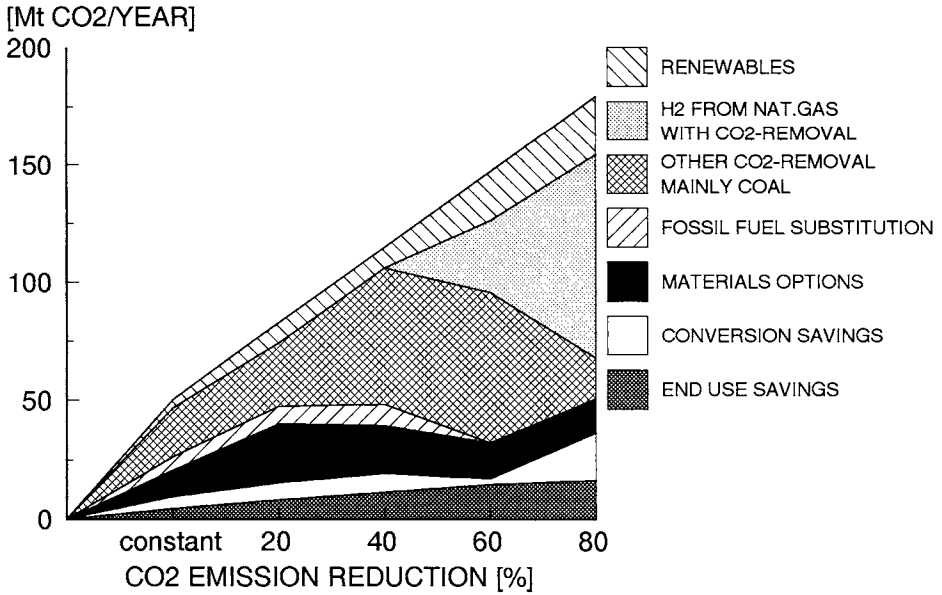


Figure 7: Emission reduction allocation for the integrated energy and materials system (DZ 2030).

Considering emission reduction in the materials system results in significant cost reduction. The long term marginal CO₂ reduction costs decrease by NLG 50-100 as costly reduction options in the energy system can be avoided. Figure 7 shows the structure of emission reduction options in the integrated energy and materials system.

Comparing figures 3 and 7 shows what type of CO₂ emission reduction options in the energy system can be avoided at certain reduction targets. Generally speaking, savings in conversion and end use are reduced. The largest shift is however related to CO₂ storage. The storage capacity is limited. As more CO₂ reduction can be achieved in the integrated energy and materials system at certain costs without storage, less storage per PJ is required. The consequence is that the limited storage capacity can be used less effectively, but at lower costs. The 'hydrogen economy' (hydrogen from natural gas with CO₂ removal) is introduced later, while CO₂ removal at coal fired power plants is still used at higher reduction targets compared to the results for the stand-alone energy system.

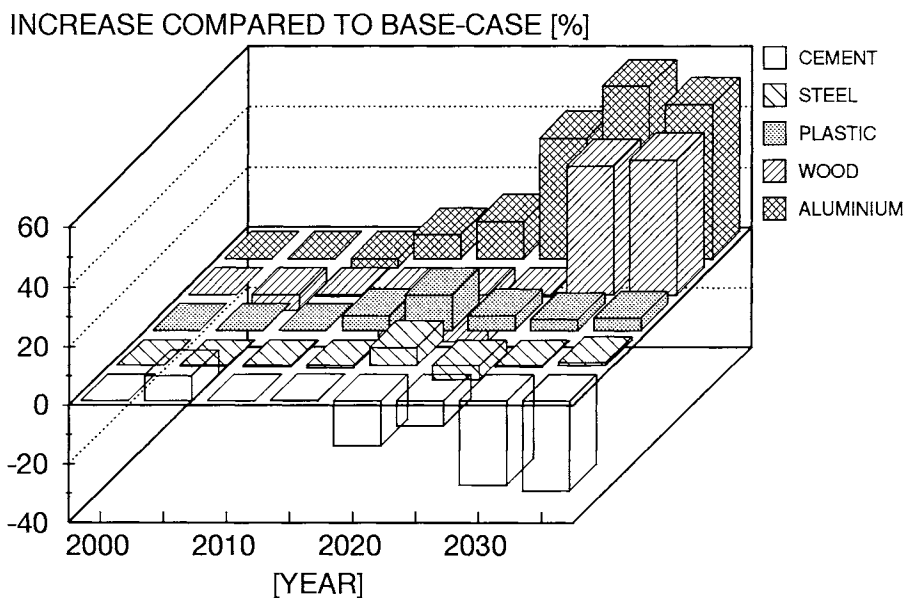


Figure 8: Shifts in materials consumption due to CO₂ emission reduction (DZ -60%).

As a result of CO₂ reduction, materials in products are substituted. Some options for reduced materials consumption (e.g. in packaging) are already included in the baseline; other environmental policies may cause such a shift.

Figure 8 quantifies material substitution effects due to CO₂ reduction. The main shifts are in the construction and transportation areas. Traditional brick/concrete buildings are replaced by wooden skeleton buildings. The energy consumption per tonne for brick and cement production is relatively low, compared to other materials. The relatively high CO₂ emission for traditional buildings is caused by the large amount of materials that is required per house and because of inorganic CO₂ emissions from cement production. In the transportation sector, cars and trucks shift towards more aluminium and plastic is used instead of wooden pallets and crates. The fuel savings due to light weight 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 aluminium increase after 2015. The use of steel and plastics remains constant.

These results prove to be very sensitive to assumptions concerning assembly costs for different product options. The impact of 60% CO₂ reduction on product life cycle costs is generally below 10 %. If e.g. assembly costs for an aluminium car are 15% higher as for a steel car, the shift from steel to aluminium is not cost effective. The uncertainty range in future production costs is however in this order of magnitude. This problem occurs for most products.

Other shifts in the materials system occur in materials production due to shifts from one production technology to another and occur also in waste management. For some materials recycling is favoured (e.g. plastics), while for others (elastomeres, biogenous fibre materials) incineration seems the best solution. These shifts are not discussed in further detail in this paper.

5. CONCLUSIONS

The model calculations for the stand alone energy system indicate that significant CO₂ emission reduction is possible. Changes in the residential and commercial sectors (conservation, high efficiency equipment such as heatpumps, etc.) and in electricity generation (fuel switching, cogeneration, etc.) appear more cost effective than those in industry and transport. Significant savings, mainly in the residential and commercial sectors, are still possible but will need to be supplemented by measures in the supply sectors to reach more ambitious targets. CO₂ removal and storage options are relatively cost effective, but are to be considered as transient towards more sustainable configurations only. Biomass and wind provide relatively cheap renewable energy, but have limited potential. Photovoltaic solar energy could serve as backstop technology only: large potential but high costs.

The preferred measures are not significantly influenced by taking upstream CO₂ and other greenhouse gases into account. Including upstream CO₂ and methane emissions makes a noticeable difference, but nitrous oxide, carbon monoxide and halocarbons are less important when assessing future Netherlands energy systems.

Production of materials is associated with considerable energy use. Today it constitutes approximately one third of the Netherlands CO₂ emissions. Changes in material flows and material systems technologies appear important

contributors to cost effective CO₂ reduction strategies. Model calculations indicate an increased use of aluminium and wood, while the use of cement decreases. This is caused by changes in the construction and transportation sectors. 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 options than were found in the energy system alone. Moreover, options within the materials system are often truly sustainable, an important feature supporting current long term policy strategies.

International trade issues complicate the development 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.

6. REFERENCES

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APPENDIX 1: MATERIAL REQUIREMENTS FOR PRODUCT ALTERNATIVES

products	materials
<input type="checkbox"/>	Reference family house
<input type="checkbox"/>	Wooden family house
<input type="checkbox"/>	Reference apartment
<input type="checkbox"/>	Max. met. apartment
<input type="checkbox"/>	Asphalt roads
<input type="checkbox"/>	Brick roads
<input type="checkbox"/>	Concrete roads
<input type="checkbox"/>	Tropic wood waterworks
<input type="checkbox"/>	Steel waterworks
<input type="checkbox"/>	Concrete waterworks
<input type="checkbox"/>	Plastic waterworks
<input type="checkbox"/>	Other build./infrastr.
<input type="checkbox"/>	Steel cars
<input type="checkbox"/>	Aluminum cars
<input type="checkbox"/>	Plastic cars
<input type="checkbox"/>	Steel trucks
<input type="checkbox"/>	Aluminum trucks
<input type="checkbox"/>	Plastic trucks
<input type="checkbox"/>	Reference machinery
<input type="checkbox"/>	Max. plastic machinery
<input type="checkbox"/>	Reference appliances
<input type="checkbox"/>	Max. plastic appliances
<input type="checkbox"/>	Other objects at home
<input type="checkbox"/>	Steel furniture
<input type="checkbox"/>	Wooden furniture
<input type="checkbox"/>	Other int. decoration
<input type="checkbox"/>	Steel cans
<input type="checkbox"/>	Aluminum cans
<input type="checkbox"/>	Glass multiple use bottle
<input type="checkbox"/>	Paper/board packaging
<input type="checkbox"/>	Plastic disp. packaging
<input type="checkbox"/>	PET multiple use pack.
<input type="checkbox"/>	One-way glass bottle
<input type="checkbox"/>	Degradable plastic pack.
<input type="checkbox"/>	Papers
<input type="checkbox"/>	Sanitary paper
<input type="checkbox"/>	Wooden pallets
<input type="checkbox"/>	Plastic pallets
<input type="checkbox"/>	Other ind. packaging
<input type="checkbox"/>	Plastic clothing
<input type="checkbox"/>	Nat. org. clothing
<input type="checkbox"/>	Agents
<input type="checkbox"/>	Compost
<input type="checkbox"/>	N-fertilizer
<input type="checkbox"/>	Paint
<input type="checkbox"/>	Lubricating oil
<input type="checkbox"/>	Detergentia
<input type="checkbox"/>	Chlorine
<input type="checkbox"/>	Na(OH)