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Climate 2050

The road to 60–80 percent reductions in the emissions of greenhouse gases in the Nordic countries

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Content

Preface

In May 2006 COWI was commissioned by the Climate Change Working Group of the Nordic Council of Ministers to undertake the study "Climate 2050 – the road to 60–80 percent reductions in the emissions of greenhouse gases" in cooperation with PROFU, Sweden.

The objective of the study is to analyse the measures and costs of reaching ambitious emission reduction targets in the Nordic countries by 2050. This work has been ongoing in parallel with a similar study for the Danish Environmental Protection Agency. Findings from that study with regards to emission reduction options within the transport sector and within non-CO_2 has been used in this study.

The Climate Change Policy Working Group does not necessarily share the views and conclusions of the report, but looks at it as a contribution to our knowledge about the likely scenarios for a carbon-constrained future for the Nordic countries.

Oslo, March 2007
Jon Dahl Engebretsen
Chairman of the Climate Change Working Group

Summary

This study has analysed ways to reduce the emissions of GHG in the Nordic countries by 2050 with 60–80% compared to the baseline emissions.

The methodology applied to this study has been to investigate three key sectors, namely the Nordic energy sector (electricity and heating), the transport sector and others GHG than CO_2. The analysis of each sector is made on a partial basis. The Nordic energy sector is analysed by simulations on a Nordic energy sector model, the MARKAL Nordic. A large number of scenarios has been analysed, and the marginal abatement costs for reaching different GHG emission reductions estimated. The transport sector and the non-CO_2 GHG sector has be analysed by combining the baseline emission projections with a number of possible emission reduction options, and associated costs have been identified.

The Nordic countries are analyzed as a whole, which has the benefit of ensuring that a systems perspective is taken which takes into account the integrated nature of the Nordic energy systems. At the same time, the integrated Nordic approach means that the results cannot directly be transferred to the national circumstances of the individual Nordic countries. As an example, Norway's electricity production is almost CO_2-free, while the oil and gas sector is responsible for about a quarter of the country's GHG emissions.

Marginal abatement costs have been estimated for 2020 and 2050 to estimate total costs of emission reductions and to provide information about the increasing costs as response to more ambitious targets.

The key findings are that:

- with the assumptions used in the analysis an emission reduction of 57% of 1990 emission, was obtained in 2050, i.e. leaving a Nordic GHG emission at 43% of the 1990 level
- the energy sector is expected to reduce the GHG emissions by approximately 80% by 2050. The main drivers for these reductions are the phasing out of fossil fuels in power and heating sectors, and the increasing utilisation of wind and to some extend wave and photo voltage. There is induced a limit to the availability of biofuels
- based on the assumptions the transport sector only reduces 40% of baseline emissions in 2050, because limitations are assumed on the availability of biomass and on the market share of electric cars. These assumptions can be discussed and are quite important to the overall emission reduction obtained.

- Non-CO_2 emissions are reduced only by 33%, mainly due to difficulties in reducing N2O and methane from agriculture. This may be a conservative estimate as it is based on existing technologies, and as new technologies and management systems may improve the GHG emission performance in agriculture in the long term
- these reductions are barely enough to meet a 60% emission reduction target. Higher emission reduction in the energy sector therefore seems to be needed to approach 80% reductions.
- some part of non-CO_2 emissions are likely not to be removed. This puts larger pressure on transport and energy sectors to reach 80 % reduction in the Nordic countries, as
- costs of reductions are at around 60% of baseline emission amounts to around 11 billion EUR/year, or 0.5 to 1 % of GDP per year, in 2050
- if the restrictions on biomass are abandoned and unlimited access to an international biomass market is assumed the reduction potential for the transport sector is increased and a total emission reduction of 68% at only limited additional costs, still amounting to 0.5–1% of GDP, in 2050
- additional energy sector reductions could also increase overall emission reduction to almost 70%, but would increase costs to around 1% of GDP by 2050

The study is based on a large number of assumptions, many of which are based on weak foundations. Therefore some important reservations must be underlined:

- as submodels for transport and energy were used, synergies and externalities between reductions in these two sectors are not explicitly accounted for.
- obviously there are very large uncertainties about technological development for the period until 2050 as well as fuel and raw material prices
- the analysis is based on the assumption of a general development of the available technologies. It does not consider the opportunity that some technologies develop more rapidly and therefore may result in lower costs. Therefore the analysis could be regarded as a rather conservative with regards to the technological potential in such a long term
- external effects of R&D not accounted for, neither on the benefit side (increased innovation in related sectors) nor on the cost side (R&D resources displaced from other R&D fields).

Among the issues that will require further analysis in the future are the dynamics of policies, research and technology development in order to establish a better understanding of the right timing and right policies and measures to achieve ambitious emission targets at the lowest cost to society.

1. Methodology

This study will present an assessment of the consequences of ambitious reductions in the Nordic emissions of greenhouse gasses (GHGs) in the medium and long term. The reductions under consideration are 15 to 30% in 2020 and 60 to 80% in 2050, both relative to 1990 emissions.

At the present stage the knowledge of such ambitious reductions, especially on the long term, is rather sparse, and thus present several challenges to this type of study:

- Integrated models are yet to be developed fully, such that a wider range of emission sources, the potential interaction between different reduction measures, as well as the measures' direct and indirect costs can be described in a consistent framework;
- Long term technological progress – a key driver of the reductions of costs and enlargement of potentials of abatement measures – is inherently difficult to model and predict;
- The general uncertainty of long term developments of energy use, emissions and further indicators of abatement costs are rather large.

The above limitations implies that this study's assessment rather than being a forecast in fact is *a consequence analysis given some simplified assumptions* on e.g. costs, technological developments and interactions. Thus the results are thus tentative indicators for possible future developments of reduction costs and other consequences rather than a specific forecast of the future. Because of these limitations this study has been divided into two parts:

- a *literature review*, serving the purpose of indicating reasonable technology options and cost ranges from international studies of long term abatement costs, and
- a *reduction analysis*, where the findings from the literature review as well as specific data on Nordic emissions and reduction potentials and costs are pieced together to form the assessment of the consequences of ambitious Nordic reductions.

The methodologies of these two parts are described below.

1.1 The literature review

The literature review intends to screen a rather large number of studies in order to find the most relevant information available for the present study. The focus of the literature review is three-fold:

- Baseline scenario assumptions, i.e. the magnitude of emissions and available technologies in 2020 and 2050 absent strong climate policy action
- Reduction scenarios, i.e. information about reduction potentials and costs in case strong climate action is taken
- Cost results, i.e. the cost of the climate policy, either in terms of % of GDP, or marginal or average cost of reductions
- Other insights and methodological caveats of importance

Of the screened studies only a smaller number is reviewed in detail. Three *Key Studies*, which documents thorough model analyses of various baseline and reduction scenarios, are reviewed rather thoroughly. Then two overview studies are also reviewed in order to gain knowledge of two topics: a meta-analysis, comparing a large number of cost estimates for ambitious reductions, and a study concerning the potential impact of climate policy on technological change.

The key findings of the literature review include the emission reduction targets and the indicators of estimated costs of achieving the emission reductions.

1.2 The reduction analysis

There is no complete model covering all the emissions and sectors in the Nordic countries available for the analysis. Therefore the analysis of the consequences of ambitious emission reductions is based on a combination of partial analyses of three sectors, namely analyses of

- the emissions from the Nordic energy sector,
- the emissions from the Nordic transport sector, and
- the non-CO_2 GHG emissions in the Nordic countries.

This approach has the advantage of providing insight in the individual sectors, but the downside of not including the interactions between these sectors.

Because the interactions and detailed side effects are not subjected to modelling, the scope of the costs investigated is limited to the so-called “system costs”. The system costs also take into account wider effects outside the specific reduction. This concerns e.g. costs of intermittency of wind power in the electricity system, emission from production of biofuels etc.[1]

The analysis aims to present a picture of the emission reduction costs for the whole Nordic area, both at different levels of reduction of the emission of GHG and including in all of the three sectors. For this reason the system costs are expressed in terms of marginal abatement costs for a host of different reductions sources. With these terms, each type of reduction has a potential measures in megatonnes CO_2e (Mt) and a cost measured in Euro per tonne CO_2e.

The different measures and emission reduction potentials are order according to the costs, so that the least cost measures are utilised first, and then gradually more costly measures are utilised as emission reduction requirements are increased, ranked across the three sectors according to costs. This methodology presents a very transparent image of the incremental costs associated to increasing emissions reductions, and the method allow policy makers to identify which emission reduction initiatives seems to be more attractive, and in which sectors emission reductions should be given priority.

The marginal abatement costs differ between 2020 and 2050, and curves therefore are prepared for both years. The scope of the analysis is abatement options and costs available in the Nordic context, and therefore purchase of international emission allowances and credits are not taken into consideration.

The choice of abatement technologies also differ somewhat, depending on how ambitious the emission reduction targets are. Some technologies sufficient for achieving 60% reduction may need to be replaced by more costly measures with a larger reduction potential to enable higher emission reductions. Choice of an emission reduction technology with large reduction potential therefore may in some case be on the expense of a less costly, but also less potential, emission reduction technology. For this reason the marginal abatement cost curves therefore will not have completely smooth courses.

The information gathered to prepare the MACs for the three sectors is based on the following:

The energy sector MACs are generated by modelling exercises on the MARKAL-Nordic model. A number of different scenario runs have been undertaken for different years, and these scenario runs have provided results in terms of costs and emission reduction for the Nordic energy system which have been gathered in MAC.

[1] While taking into account other system costs is an improvement compared to accounting only for the specific technical cost of a particular reduction, the accounting of system costs does not concern itself with wider macro economic effects, such as reduced international competitiveness, effects on savings and investments or consumption. Also social costs, such as distortions of consumer and firm choices, value of time, distributional effects etc. are not accounted for. See chapter 7 on limitations

The transport sector MACs are based on EU Primes forecast for 2030, extended to 2050, and a range of different emission reduction technologies available on medium and long term. These measures mainly concerns alternative fuels (based on biomass) with lower CO_2 emissions.

The non-CO_2 *GHG emission* MACs are based on forecasts from the National Communications of the Nordic Countries in combination with data from an EU study by Bates et al. A number of measures and the associated costs and potentials are gathered from existing studies, including measures on methane and N2O in farming, manure handling, solid waste management, and measures on F-gases.

The methodologies, assumptions and sources for the MACs for the three sectors are presented in the technical annexes for each sector.

2. Nordic emission reductions and costs

This section presents the estimated emission reductions obtained in the Nordic countries in the study and the associated costs in 2020 and 2050. First the projected GHG emissions and the projected reductions are presented, then the methodology to estimate the costs is described and the marginal abatement cost (MAC) curves – derived through this study – are presented. Finally, the MAC curves are used for assessment of the total costs of the GHG emission reductions.

2.1 Overview of GHG emissions projections and emission reductions

The GHG emission in the Nordic countries in 1990 and 2004/05 is presented in the table below. The Nordic emissions are calculated on basis of the most recent UNFCCC reporting in the CRF for each of the Nordic countries.

The projected baseline emissions for 2020 and 2050 are based on different sources for each of the three sectors:

- *The energy sector* emission projection for 2020 and 2050 is based on the Markal Nordic Baseline scenario, as defined in the Energy Sector Technical Annex.
- *The transport sector* emission projection is based on the 2005 update to the 2003 *European energy and transport – trends to 2030*. For the period 2030–50 COWI has assumed the same profile as for 2020–30.
- *The Non*-CO_2 *GHG* emissions projection is based on an EU 1990–2030 study[2]. For the period 2030–50 COWI has assumed unchanged emissions. Subdivision of GHG emissions between sectors and sources is based on the NC4 reports for the respective Nordic countries.

The emission reductions identified is based on different options within each sector, based on current best estimates of technology development and potential reductions. The specific assumptions and technologies are described in more details in Section 4 to 6 of this report and in the technical annexes.

[2] *GHG emission projection and costs 1990–-2030* , Bates et al. 2004

Table 2.1: Overview of GHG emissions in baseline (CO_2 equivalents in Million ton) and estimated emission reductions by 2050

	Energy sector	Transport sector	Non CO_2	Total GHG
1. Baseline GHG emissions				
1990	136	67	73	276
2004	149	81	65	295
2020	124	94	71	289
2050	107	81	71	259
2. GHG emission reduction in 2020 compared to Baseline	61	6	16	83
3. GHG emissions in 2020	63	88	55	206
4. GHG emission reduction in 2050 compared to Baseline	76	47	20	143
5. GHG emissions in 2050	31	34	51	**116**
6. Emission chg. relative to 1990 emissions (relative to 2050 baseline)	**-82 %** (-71%)	**-49 %** (-58%)	**-30 %** (-28%)	**-58 %** (-55%)

2.2 Methodology to estimate costs

Obtaining the emission reductions on a least cost principle is done by including potential emission reductions, ordered according to their unit reduction costs (i.e. EUR/ton CO_2 equivalent). Each potential emission reduction measure has a cost in EUR/ton and a reduction potential in terms of the amount of emission reductions that may be obtained by implementing the measure. When plotting these potential emission reductions on charts showing total reductions (e.g. in Mt, or in per cent of total emissions) this will lead to a staircase formed graph. This graph is known as a Marginal Abatement Cost (MAC) curve.

In this project MAC curves has been created for Energy, Transport and Other emissions. These curves are combined[3] into a total MAC curve covering all potential reductions in these three sectors.

This total MAC curve can be used in two ways: A reduction target can be set, and the marginal and most expensive reduction measure needed is revealed by the MAC curve. Alternatively, a maximum acceptable cost can be decided, and the reductions available at this marginal cost (or less) are shown by in the MAC curve.

Finally, the total costs of the reductions obtained can be calculated as the area below the MAC curve for those reductions that are performed. It should be noted that this is only one of many total cost measures that can be used.

The advantage of the MAC curve is that the estimates of total costs and the magnitude of the cost efficient reduction efforts are very transparent. Further, it is quite easy to compare a wide range of reductions in terms of differences of sources, technologies and potentials.

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[3] This process is called “horizontal addition”, and consists of a reordering of all potential reductions from the three sectors, and a redrawing of the MAC curve.

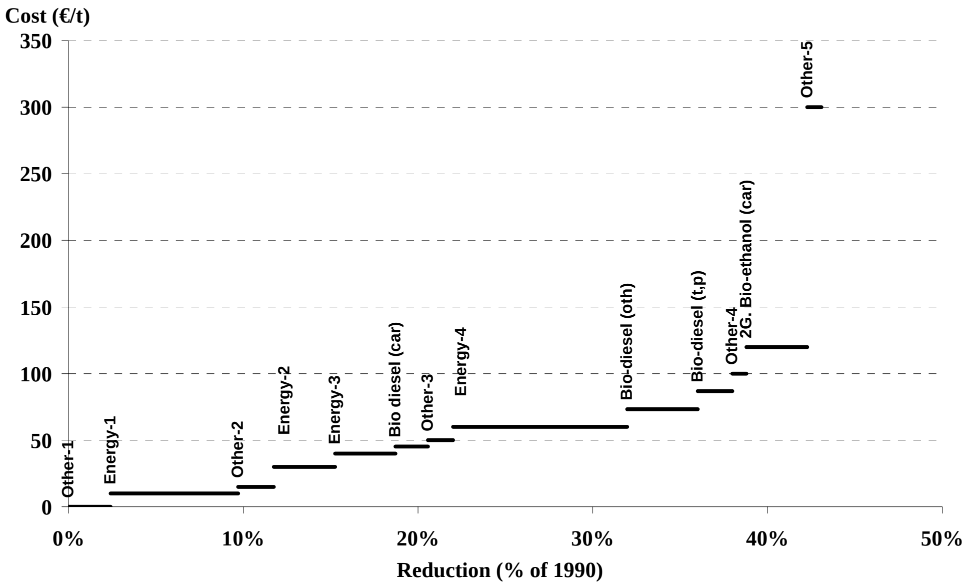
Some more elaborate cost measures include also socio-economic costs of distortions of consumer choice and location and allocation of productive activities outside the emission intensive sectors. This is not handled in the analyses of costs, but is treated in more qualitative details in the literature review.[4]

One disadvantage of MAC curves is that interdependencies between different reduction potentials are difficult to illustrate. In this study, this is overcome for the energy sector by using an energy model to construct a MAC curve for the entire energy sector.

2.3 MAC curves

Two set of MAC curves are prepared, one for 2020 and one for 2050. The one for 2020 can be seen in figure 2.1 below.

Figure 2.1: MAC curve 2020 (Euro/tCO_2e)



Source: Own calculations. Note: The energy MAC curve point estimates (see chapter 4) have been converted to intervals using interpolated mid-points.

The MAC curve indicates the increasing marginal costs involved in increasing the emission reduction targets.

For 2020 the measures ranked according to costs starts with low cost energy measures and low cost measures within non-CO_2. Also limited options within transport sector seem possible. Emission reductions up to 32 % can be undertaken at a marginal abatement cost below 60 EUR/t. If larger reductions are needed the marginal abatement costs increases rapidly as more costly measures in the transport sector is needed to reach target.

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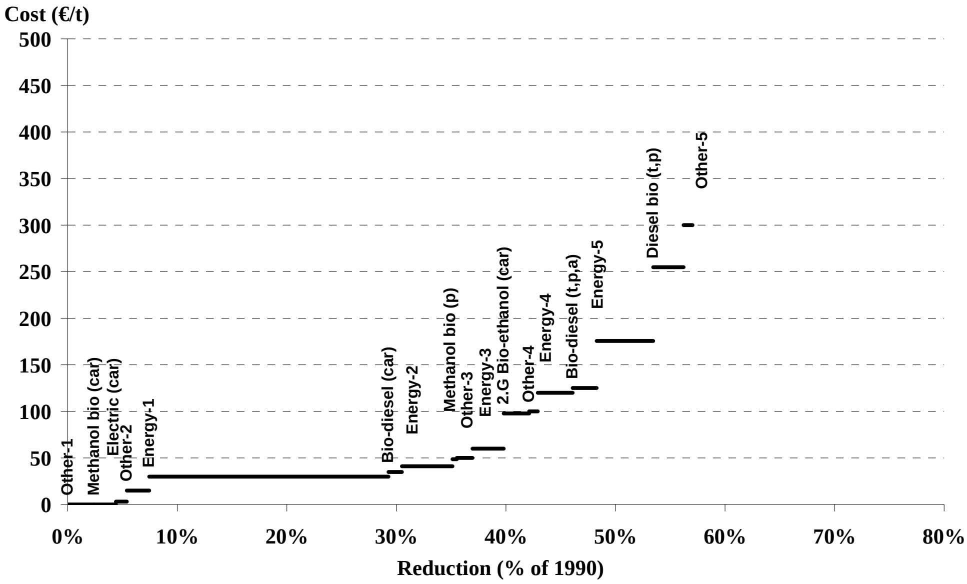
[4] See chapter 3 and the separate technical appendix A

The 2050 situation

The 2050 emission reductions are assessed, assuming certain limitations as to the reduction potential for some of the measures. This is particularly important with regards to the transport sector, where limits on the supply of biomass have been assumed. Further it is assumed that CCS technology only removes 90% of the carbon. Only well known options for emission reductions within non-CO_2 from agriculture are taken into account. Finally carbon sequestration in terms of LULUCF and afforestation/reforestation is not included. These assumptions limit the total emission reduction obtainable in the calculations, as can be seen in Figure 2.2 below.

Figure 2.2: MAC curve 2050 (Euro/tCO_2e)



Source: Own calculations. Note: The energy MAC curve point estimates (see chapter 4) have been converted to intervals using interpolated mid-points.

The curve indicates that it will be difficult to reach a total emission reduction of 60% by 2050 with the measures and limitations on potentials included in this analysis, as only 57% emission reduction is obtained. This reflects that the energy sector may have to take larger emission cut than 70–80% in order to reach the objectives of 60–80% of GHG emission in total, as emission reductions in the transport sector and in the non-CO_2, particularly within agriculture, currently seems to be relatively costly.

To assess the importance of the restrictions put on the transport sector and the energy sector a set of sensitivity analysis has been made to illustrate the reduction potentials and the costs. The results of sensitivity analysis are presented in section 2.5 below.

2.4 Total costs

The total costs to the Nordic countries reflect the level of ambition of the reduction targets. The total emission reduction costs are calculated as the sum of the costs of all measures, i.e. reduction quantity of the measure multiplied with the measure's marginal abatement cost. In visual terms this corresponds to "the area below the MAC curve" .[5]

It is most practical to relate the size of the total costs to the size of GDP. Table 2.2 below provides a simple forecast of the Nordic GDP for 2020 and 2050, assuming a 1.7% average annual GDP growth during the period.

Table 2.2: GDP forecast (billion Euros)

	2005	2020	2050
Finland	147.4	189,8	314.7
Sweden	278.5	358,6	594.7
Norway	197.5	254,3	421.7
Denmark	194.7	250.7	415.7
Total	818.1	1053.4	1746.8

Source for 2005 GDP: https://www.cia.gov/cia/publications/factbook/geos/xx.html

As mentioned above both a 15% and a 30% reduction was possible in 2020. However, in 2050, the analysis showed that only a 60% Nordic reduction was feasible with the reduction potentials identified by the analysis. The total reduction costs for these three cases are described in table 2.3 below.

Table 2.3: Reductions and costs in 2020 and 2050 with 15, 30 and 57% reduction

	2020	2020	2050
Reduction (Mt)	41	83	158
Reduction (%) of '90	15%	30%	57%
Cost (% of GDP)	0.05%	0.26%	0.63%
Average cost (€/t)	13	33	70
Marginal cost (€/t)	30	60	300

Source: Own calculations.

From the table it can be seen that the reduction costs for the 2020 reduction of 15 to 30% is between 0.05% and 0.26% of GDP. The average cost of the reduction is between 13 and 33 Euro/tonne CO_2e, while the marginal cost of the 15% and 30% reduction is 30 and 60 Euro/tonne, respectively.

For 2050 the 60% reduction target is almost met as the reduction is 57% (i.e. the emissions are 43% of the 1990 emission). The average cost of the reductions is 70 Euro/tonne CO_2e, while the marginal cost is 300 Euro/tonne CO_2e.

In the analysis of energy and transport emissions are, however, subject to certain technical restrictions which limit the reduction potentials.

[5] There are several methods for estimating total costs, reflecting different definitions and scopes of the costs. The costs described here can be described as "System costs". For a discussion of different cost concepts, see chapter 7.5

While these restrictions are *a priori* reasonable as central estimates, the uncertainty connected with long term analyses like this are considerable. Hence, it is appropriate to relax these restrictions in sensitivity analyses. These are presented in chapter 2.5.

2.5 Sensitivity analysis

The target of 60–80% reduction requires that the restrictions imposed on the MAC curves are relaxed. Three analyses have been carried out, namely:

- The *limitations on the supply of biofuels* for the transport sector are assumed to be removed by an international biofuels or biomass market. This allows a larger emission reduction to be achieved. This topic is discussed in further details in chapter 4.
- Additional emission reductions in the energy sector. The Markal-Nordic model encompasses restrictions on the energy consumption which limits the models ability to illustrate larger emission reductions than 70–80%, particularly fossil fuel consumption in industry. This may be a realistic assumption for the 2020 case, but in a 2050 perspective there are likely also to be ways to reduce or substitute the remaining fossil fuel consumption in industry. Options include substitution of oil, gas and coal consumption with biofuels, hydrogen and fuel cells and other measures. It is assumed that the remaining emissions can be removed at a cost of 200 Euro/tonne CO_2e.
- Access to emission allowances on an *international allowance market:* An international or even global GHG allowance market may exists in 2050, and leave the Nordic countries with the opportunity to buy GHG allowances this market. The literature review undertaken in the course of this project has revealed marginal GHG abatement cost estimates ranging from 25 to 400 EUR/ton. A reasonable central estimate for an international allowance price with ambitious climate policies was found to be around 100 Euro/tonne CO_2e.

Each of the relaxations of these restrictions is sufficient to attain a 60% reduction. The costs of the reductions are shown in table 2.4.

Table 2.4. Sensitivity analysis results for 60% reduction

	Unlimited access to bio-mass for transport	Additional reduction in energy sector	International allowance market
Reduction (Mt)	166	166	166
Reduction (%) of '90	60%	60%	60%
Cost (% of GDP)	0.44%	0.69%	0.40%
Average cost (€/t)	47	73	42
Marginal cost (€/t)	125	200	100

Source: Own calculations.

However, neither unlimited access to biomass nor additional reductions in the energy sector are sufficient to reach an 80% reduction. In table 2.5 the costs for the maximum reduction (at or below 80%) for the three relaxations are shown.

Table 2.5. Sensitivity analysis results for a max. 80% reduction

	Unlimited access to biomass for transport	Additional reduction in energy sector	International allowance market
Reduction (Mt)	187	190	221
Reduction (%) of '90	68%	69%	80%
Cost (% of GDP)	0.66%	1.00%	0.71%
Average cost (€/t)	62	92	56
Marginal cost (€/t)	300	300	100

Source: Own calculations.

Combining the relaxations of access to biomass and additional reductions in the energy sector is almost sufficient to meet the 80% target. The reduction in this case is 79%, at a cost of 1.03% of GDP. The marginal cost of reduction is 300 Euro/tonne CO_2e, while the average cost is 82 Euro/-tonne CO_2e.

3. Literature review

The literature review aims at providing a relatively brief overview of the studies undertaken regarding large-scale emission reductions in the long term. The purpose of the review is to provide an indication the consequences of ambitious emission reduction targets as suggested by other studies and to help identify relevant assumptions, parameters etc. needed for scenarios analyses of this study. The literature review is found in it full length in appendix A.

The approach to the literature review has been to focus attention on a number of issues with regard to:

- The baseline emission scenario, i.e. the likely course of events in the absence of ambitious emission reduction targets and the corresponding policies and measures necessary to achieve the targets.
- The reduction scenario in which policy action is undertaken to reduce emissions.

For both the baseline and the reduction scenarios, a number of drivers determine the level of future emissions and the cost of reducing emissions. Different studies apply widely differing approaches to modelling the baseline, the reduction scenarios and the resulting abatement costs. Differences exist between models both with regard to the drivers that are included in the models and the modelling approach.

3.1 Selection of studies to review

Three types of studies were reviewed:

- *Key studies:* These are comprehensive studies that provide significant information about emissions and abatement costs in several sectors and therefore both have the potential to provide input for the scenario analysis in this project in terms of one or more of the following:
- *Overview studies:* A number of studies reviewing and comparing different studies have been made. These are sometimes carried out using a structured approach and labelled meta-studies. For the purpose of gaining quick access to a large number of scenario results, a selection of these overview studies have been included in the review.
- *Nordic studies:* A few studies have been carried out in the Nordic countries with a focus on long-term climate mitigation, providing a useful opportunity to consider assumptions specific to the Nordic

countries and in some cases more detailed country-specific information. Therefore two such studies have been reviewed.

The review focused its attention on three Key Studies, although some relevant insights were also recovered from the overview and Nordic studies. The three selected key studies were made by EEA (2005), DTI (2003) and IEA (2006).

3.2 Baseline assumptions

The literature review paid special attention to the assumptions of the reviewed key studies' baseline scenarios. These assumptions are very important for the resulting cost estimates, which must always be seen in close relation to the assumptions behind. In particular, the development in energy use (which in turn depends on GDP, population etc.), fossil energy prices and the ambitiousness of the required reductions are of great importance to the estimated costs.

As the key studies cover different geographical areas, the assumptions behind the studies varied somewhat, especially concerning reduction requirements, and fossil fuel prices. Also energy and other growth assumptions vary, but these are attributed to the geographical scopes of the studies. An overview of some of these assumptions can be seen in table 3.1.

Table 3.1: Baseline assumptions from the review key studies

	EEA	DTI	IEA
Geogr. scope	EU25	U.K	World
GDP growth	EU15:2.3% p.a., EU10 3.5% p.a.	2.25% p.a.	2.9% p.a.
Population	Stable	65 mn in 2050	
Global energy consumption	2½ times 2000 consumption in 2030	N.a.	More than 2 times 2005 level
Fuel price	2020: 30 $/brl 2050: 35$/brl	App. 25$/brl	2030: 39$/brl 2050: 60$/brl

3.3 Cost estimates

The different studies are based on different assumptions and models, and have different reduction targets and different measures of the costs. This means that it is difficult to compare directly the findings on the costs across the studies.

Nevertheless, a comparison provides an indication of the magnitude of the estimated costs for ambitious emission reductions, and therefore a table is presented showing an indication of the costs and the associated emission reduction. An overview of the cost estimates can be seen in table 3.2:

Table 3.2: Overview of literature cost estimates

Study	Model	Cost indication	Emission reduction target	Geogr. scope
EEA	Bottom-up	MAC: 65€/t CO_2 GDP: 1%	CO_2 content: 550 ppm 65% reduction by 2050 compared to 1990. Some reductions through use of flexible mechanisms.	EU 25
DTI	Bottom-up	MAC: 80–400 €/t CO_2 GDP: <1%	45–70% of 2000 emission	UK
IEA	Bottom-up	MAC: 25–40 $/t GDP: ~0.1%	Stabilisation of global emissions in 2050 at 1990 level (30% OECD reduction)	World
Overview Study # 1 Stanford, EMF, ECN	Diff. models	Welfare loss: 0.2–0.8%	CO_2 content 550PPM	EU 15 plus Norway, Switzerland and Iceland
Overview Study # 2 Energy Journal special edition	Diff. models	MAC: 30–70 $/t CO_2 GDP: ~0.5% but up to 6%	CO_2 content: 450–500–550 PPM	World

3.4 Energy supply

The reviewed studies had some general findings about energy supply, which are presented in bullet form below:

- *Fuel mix and CHP:* The studies showed quite a bit variation concerning the relative prices of natural gas and coal. This influenced the results concerning the fuel mix quite a lot, e.g. a lot of substitution from coal towards gas in either the baseline or the reduction scenario. A *key assumption of any study of abatement options and costs is thus the relative price of coal compared to oil and in particular natural gas.*
- *Nuclear power:* Because of the uncertainty of future use of nuclear power, additional analyses of the significance of nuclear power in emission abatement are presented in all three key studies. The reviewed studies tend to illustrate that nuclear power may make a rather big difference concerning the costs of emission abatement. The studies reviewed show that the future use of nuclear power may make important differences to future emissions and costs. However, *the impact of the use of nuclear power on reduction costs and emissions may be limited, provided that adequate substitutes exist* (such as e.g. sufficiently cheap CCS technologies, i.e. nuclear power serves as a potentially quite important back-stop technology).

- *Renewable Energy Sources:* For all three key studies wind power is the most dominant renewable energy technology, while biomass for heating and some extent CHP is also important. Other technologies do not appear in significant quantities in the studies. All three studies conclude that especially *wind power is an important source for reductions in* CO_2 *emissions*. However, the baseline wind power deployment is low in the three studies. This raises questions about *the intermittency of wind power in a Nordic electricity system*, where large deployments of wind power are already present.
- *CCS:* It can be concluded that CCS may become an important source of emission reductions. It is also noteworthy that some studies point out that *the absence of both CCS and nuclear expansion may lead to much larger costs or smaller reductions*. In other words, CSS and nuclear serves as supplementing back-stop technologies.

3.5 Energy demand and energy efficiency

It can be concluded that energy efficiency measures are considered a cheap reduction option in all three studies, at least for low and intermediate levels of reductions. But *at very ambitious reduction targets the potentials for efficiency improvements are exhausted and reductions on the supply side become important*. It should be taken into consideration here that this conclusion might be partly explained by characteristics of the energy models (and researchers), which tend to emphasize energy supply and put less emphasis on long-term demand side efficiency improvements.

3.6 Transport sector emissions

The review found that even without climate action the transport sector's technology improvements in terms of improved fuel efficiency can be quite substantial (-10% to -20%) even in the absence of additional reduction targets. The internal combustion engine remains the main source of motive power in 2050, predominantly still running on petrol and diesel. Furthermore the use of hybrids will increase.

Climate policy in general will have little demand on the demand for transport services, as it is insensitive to increased costs of transports, and modal shift effects are very small. In most reduction scenarios, CO_2 reductions in the transport sector is obtained through increased use of biofuels and improved energy efficiency.

- Technological improvements in terms of energy efficiency accelerate within an international context of strong emission reduction efforts.

Fuel efficiency could improve by around 40%.In most scenarios hydrogen fuel cells show virtually no market penetration

3.7 Other sources than energy and transport

Non-CO_2 GHGs entail a large variety of low cost options for reducing emissions, which could play a significant role in reaching ambitious reduction targets at the lowest possible cost, and especially F-gases appear to have a particularly large potential for GHG reductions.

For sinks, a considerable potential exists, but the estimates are highly uncertain. However, the task is complicated by the fact that the emission sources are very dispersed, while the assessment of emissions reductions and costs depend on source by source estimates

An assessment of the uncertainties associated with these estimates, and of the possibility that technological improvements and learning might improve the potential for emission reductions, while lowering their cost, would be recommendable, but is beyond the scope of the present study

3.8 Endogenous Technical Change and climate policy

Endogenous technical change (ETC) implies that a relation exists between future costs and historic use of certain GHG mitigating technologies. The most important effect of ETC is that the modelled costs of climate change mitigation will be lower, as the utilised technologies will become less expensive.

However, it may also be the case that the direction of causality is that the costs drive market penetration, which would mean that some of the economic arguments for early action are diminished.

In addition to the question of causality direction, another question of ETC is whether the R&D in energy technology “crowds out” R&D in other areas. “Crowding out” means that scarce R&D resources are directed towards energy technology from other fields. The implication is that the economic savings coming from cheaper GHG mitigation technologies to some extent are counterbalanced by technological developments not realised in other sectors.

In contrast to the “Crowding out” view is the “Learning curve” view, in which more efficient and cheaper technology emerges as a result of developing and using the technologies. This happens without interfering with R&D in other fields. The contrast of these two views has diminished in the recent years due to further developments in the understanding of R&D and technological development. Most likely both views have some merits.

A final lesson from ETC is that the signals about the demand for R&D in energy technology need to be credible. Investments in R&D are uncertain and the profits arise only in the long term, so

> " … future rounds of the Kyoto protocol which duplicate the structure of sequential 5-year limits without any clear and credible signals about the longer term evolution of the system, are unlikely to deliver the depth of innovation and adjustment to infrastructural investments required to minimize long-term costs."

4. The energy sector

When aiming at achieving ambitions green house gas reduction targets, the energy sector plays an important role. Within this project, a number of quantitative analyses have been carried out focussing on the effects in the energy sector of different reduction targets.

The implementation of reduction measures will lead to a shift in electricity generation towards technologies with lower CO_2-emissions. These technologies include for instance biomass, wind, solar PV, wave and fuel cell technologies. The shift in technologies will have a positive influence on the CO_2-emission, which is also the aim of the measures. Furthermore, it may influence on electricity prices, transmission patterns, system costs and the emissions of other pollutants.

The quantitative long term analyses have in particular focused on year 2020 and 2050, and have been carried out for a number of different scenarios. The scenarios differ from each other with respect to assumptions on technological development, the EU emission trading system, reduction target, other policy measures, fuel prices and discount rates. Further reporting of the energy sector analysis is found in appendix B.

4.1 Baseline emissions

The main characteristics of the *Business as Usual* (BaU) scenario is that an allowance price of 20 EUR/ton is assumed for the whole period until 2050 and that other default policy measures also are implemented. Further, the prices of oil and natural gas are expected to increase markedly, roughly doubling to 92 USD/barrel of oil and 72 USD/boe[6] for natural gas. The price of coal is expected to increase from 13 to 20 USD/boe over the period. The price development for oil, gas and coal up to 2030 is similar to updated modelling carried out for the EU using the global POLES model (World Energy Technology Outlook). In WETO, the prices are expected to rise further by 60% from 2030 to 2050. This price increase has been applied for this study for oil and gas, whereas the coal price increase has been estimated at 34% during the period. The assumption of continuously rising fossil fuel prices together with assumed constant prices for biomass obviously tends to favour the use of biomass as compared to e.g. fossil fuels with CCS.

These price signals implies that the electricity generation is shifted from a mix of mainly hydro, nuclear and coal in the beginning of the

[6] Barrel of oil equivalents

period to a mix of mainly hydro, bio and wind by the end of the period covering 87% of the electricity generation. The remaining 13% is covered by nuclear and coal. Natural gas is covering only around 5% of electricity generation in 2025 and 0% in 2050. However, a number of fossil fuel industrial installations and other commercial and residential use of fossil fuels remain in the model simulations, as some of these uses have no easy substitution possibilities.

The shift from fossil fuels towards other sources of energy means that the BaU scenario shows a marked decline in the CO_2 emissions from energy production. The Nordic countries' energy sectors emitted 149 Mt of GHGs in 2004. The BaU emissions are 125 Mt in 2020 and 108 Mt in 2050. Compared to the 1990 energy sector emissions of 136 Mt, these are reductions of 8% and 21% respectively.

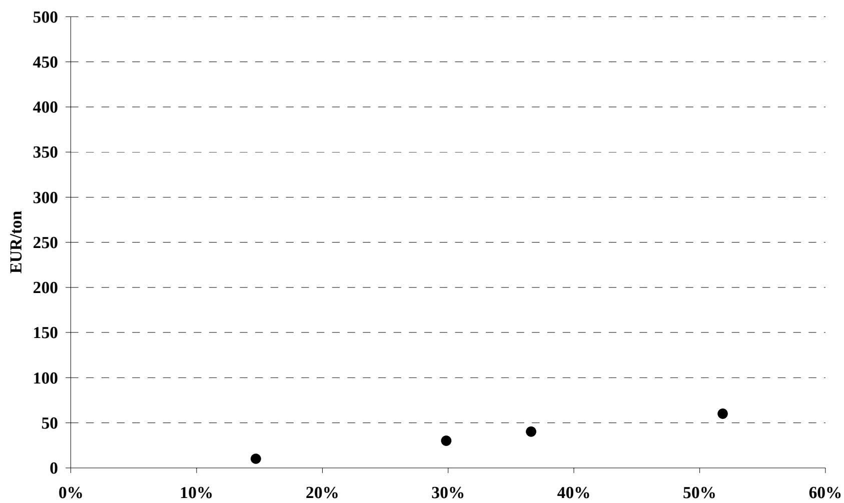
The reduction of emissions should be seen in relation to an increase in the electricity demand of 0.3% p.a. from now and to 2050.

4.2 Abatement costs

In the *Reduction scenarios*, more ambitious reduction schemes are implemented compared to the BaU scenario. The primary purpose of the reduction scenarios is to attain the marginal abatement cost of CO_2 in 2020 and 2050 for a number of various reduction requirements in order to create marginal abatement cost curves. Further, some of the reduction scenarios investigate the consequences of changing some of the most important assumptions, such as energy prices or technological progress.

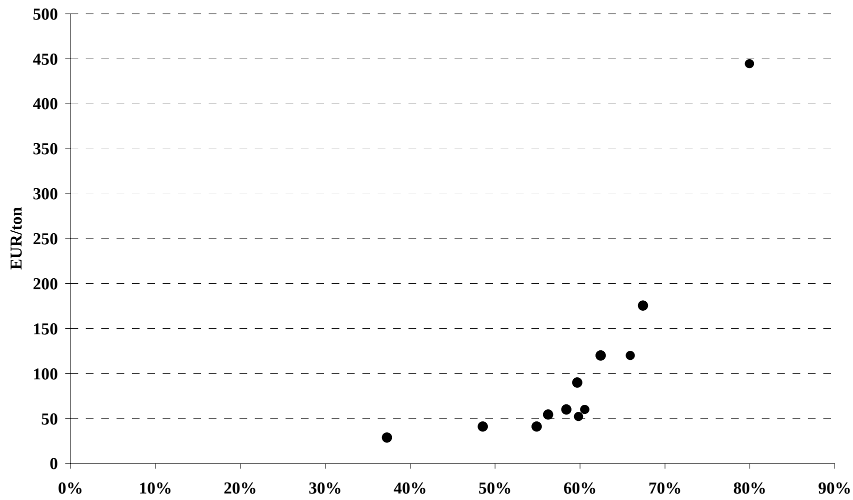
Based on the scenario simulations marginal abatement cost curves (MACs) have been generated for short term (2020) and for the long term, presented as 2050. These are shown in the figure 4.1 and 4.2 below.

Figure 4.1: 2020 MAC curve, energy sector



Note: The energy MAC curve point estimates is been converted to intervals using interpolated mid-points in the vertical addition with transport and other reduction potentials.

Figure 4.2: 2050 MAC curve, energy sector



Note: The energy MAC curve point estimates is been converted to intervals using interpolated mid-points in the vertical addition with transport and other reduction potentials.

A deeper analysis of these numbers shows that the reduction costs in general are lower by the end of the period than by the beginning of the period. The reason for this is the increase in fossil fuel prices that makes renewable technologies with low CO_2-emissions relatively more competitive. Another reason is an assumed technological development decreasing costs of renewable energy technologies.

4.3 Technology and fuel choice

Investment costs decrease over time due to technological development and learning as experience with the production of technologies accumulate. This effect applies to both the baseline and the reduction scenarios. The effect is more pronounced in the reduction scenario which assumes that there is significant international R&D and deployment in new energy technologies, contributing to a more rapid cost decline. Table III below shows the relative reduction over time in the investment costs of key technologies.

The cost estimates for CCS are based on IEA (2004) "Prospects for CO_2 capture and storage" . According to IEA, the estimated costs are 20–25 USD/tCO_2 for coal-based generation and 25–30 USD/tCO_2 for gas-based generation. These cost estimates include efficiency losses at the generation plant and therefore reflect assumptions about fuel costs. The cost of CCS in the MARKAL modelling becomes an output of the model reflecting assumptions about rising fuel prices. The costs of CCS will therefore tend to be higher than the figures quoted by IEA, in particular in the later years.

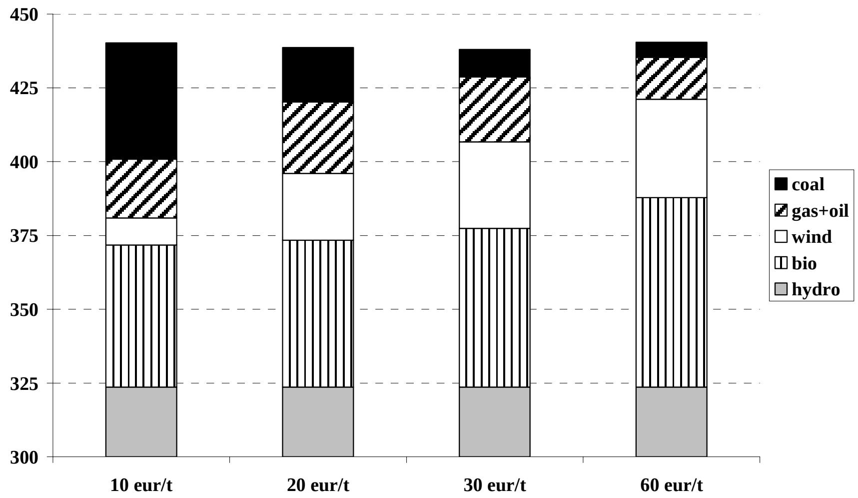
Table III: Development in investment costs for key energy technologies

	2005	2010	2020	2030	2050
Baseline scenario					
PV	100%	92%	76%	59%	27%
Wind onshore	100%	98%	94%	90%	82%
Wind offshore	100%	98%	94%	90%	82%
Wave	100%	98%	95%	91%	85%
Fuel cells	100%	94%	83%	71%	48%
Reduction scenario					
PV	100%	90%	71%	52%	14%
Wind onshore	100%	96%	87%	78%	60%
Wind offshore	100%	96%	87%	78%	60%
Wave	100%	95%	84%	73%	52%
Fuel cells	100%	92%	77%	61%	30%

In scenarios with ambitious reductions, investments come up in wave and solar PV. In particular solar PV accounts for a noticeable part of the electricity with a share of up to 10%. Also in these scenarios, the main electricity generation contributors by the end of the period are hydro, bio and wind technologies, while all fossil fuel electricity generation is phased out. Still, some industrial, commercial and residential use of fossil fuels remains.

In 2020 the phasing out of fossil fuels from the electricity system by increasing the allowance price and reduction requirements can be clearly seen. Especially coal is being replaced by wind power but gas and oil is also gradually phased out when CO_2 emissions become more expensive. See figure 4.3 below.

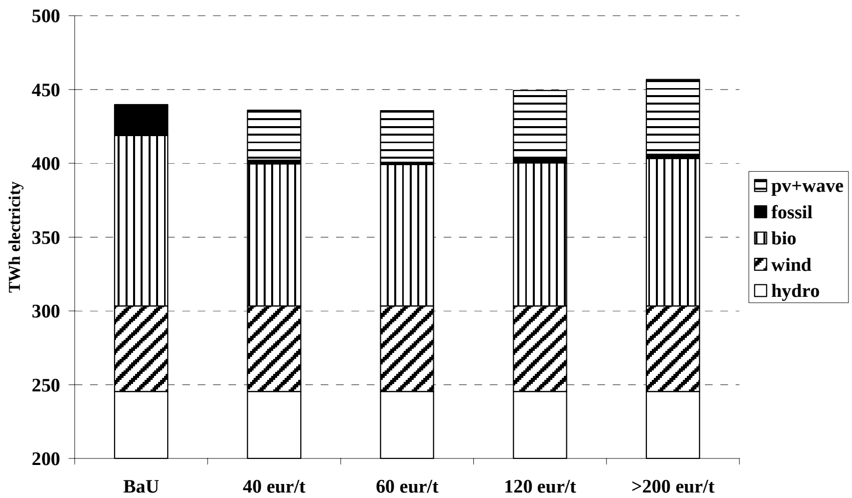
Figure 4.3: Electricity generation technology composition and allowance price (2020)



Note: The composition of electricity generation capacity is shown for different marginal abatement. In order to magnify some of the smaller technologies, the second axis has been cut away between 0 and 200 TWh. This baseload consist of nuclear and hydro power.

In the BaU as well as the reduction scenarios, all potential for wind and hydro power is used fully in 2050. The technological improvements in solar PV and wave in the reduction scenarios mean that these two technologies become viable for electricity generation, and to some extent replace biomass fired plants. As the allowance price increases in the reduction scenarios, the demand for electricity and heat increases, mainly as a result of industry switching away from internal energy production to the use of electricity. This demand is met by increasing solar PV and wave capacity. See the figure below.

Figure 4.4: Electricity generation technology composition and allowance price (2050)



Note: The composition of electricity generation capacity is shown for different marginal abatement. Note: In order to magnify some of the smaller technologies, the second axis has been cut away between 0 and 200 TWh. This baseload consist of nuclear and hydro power.

Investments in fuel cells do not come up in any of the analysed scenarios. Furthermore, investments in new fossil fuel plants with carbon capture are also almost absent in all scenarios. The reason for this is that fossil fuel plants with carbon capture still emit some amount of CO_2, and that fossil fuel prices are high. Therefore, fossil fuel plants – even with carbon capture – can not compete with renewable energy sources such as for instance wind and biomass when ambitious reduction targets are implemented.

In general it can be said, that by use of the assumptions set up for this project as described in the note “Approach to scenarios for Climate 2050” , renewable technologies such as wind and biomass become very competitive by the end of the period whereas fossil fuels are almost phased out, in particular gas. In the Base1 scenario, fossil fuels only cover 5% of the electricity generation by the end of the analysed period, and this share comes from coal. The main reasons for this significant shift in technologies are of course the reduction targets, but also the assumed fuel prices. During the period, a gas price increase of more than 100% has been assumed whereas the price for biomass remains constant in all years.

Not only fossil fuels, but also nuclear power, are phased out. The reason for this is that existing nuclear power plants are continuously decommissioned due to age, and that new nuclear power plants has not been assumed as an investment option/reduction technology.

4.4 Electricity and heat prices

Electricity prices in general increases, due to the shift in generation towards cleaner but more expensive technologies. In 2020, the average electricity price is quite stable around 40 EUR/MWh, both in the BaU and in the reduction scenarios. In 2050 the corresponding number is 50 EUR/MWh. The reason that the increased reduction requirements do not cause the electricity prices to increase is that most fossil fuels in electricity and heat production has already been almost phased out of the BaU. Adding further costs to fossil technologies thus has little effect on the electricity price.

With respect to heat prices, these can go both up and down for increased reduction targets. If heat is produced at heat boilers, the heat price may go up. But, if heat is produced at a combined cycle plant with a high power to heat ratio and/or based on clean fuels with respect to CO_2, the plant may benefit so much from increased electricity prices that heat prices go down.

In 2020, the average heat price is around 20 EUR/MWh both in the BaU and the reduction scenarios. In 2050, the average heat price is around 18 EUR/MWh, both in the BaU and reduction scenarios.

5. The transport sector

5.1 Projection of baseline emissions

This section presents a forecast of CO_2 emissions and energy use in the transport sector for Sweden, Denmark, Norway and Finland until 2050.

The projections until 2030 is based upon the 2005 update to the 2003 European Commission report “European energy and transport – trends to 2030” .

It is assumed that demand for transport will increase towards 2030 especially for trucks, aviation and private cars. The associated energy demand does not increase to the same extent as the energy efficiency is expected to improve considerably – especially for private cars and aviation.

For the 2030–50 development COWI has assumed the same profile as for 2020–30. Figure 5.2 shows that the CO_2 emissions projected to be higher in 2020 than in 2005, but hereafter decreases so that the CO_2 emissions in 2050 are lower than in 2005. More details are provided in the appendix C on the transport sector.

In the update to the 2003 European Commission report “European energy and transport – trends to 2030” it has been assumed that biomass penetrates the market and reaches a share of 8.3 percent in 2030. However, in this analysis (and in table 5.1) no biomass is included in the baseline. This is in order to focus on alternative transport fuels compared to a simple baseline with conventional fuels only – reflecting the situation as of today.

As Figure 5.1 illustrates, significant energy efficiency improvements are expected in the baseline scenario, and no further measures to improve efficiency are included in the reduction scenarios.

Figure 5.1: Development in transport vehicle efficiency

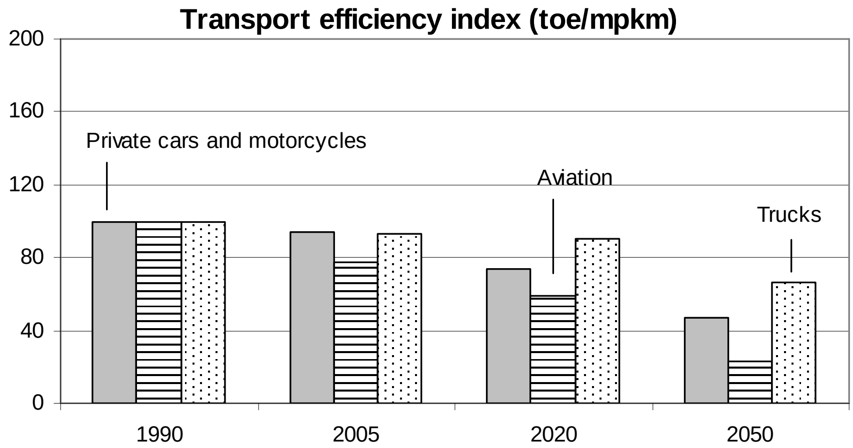
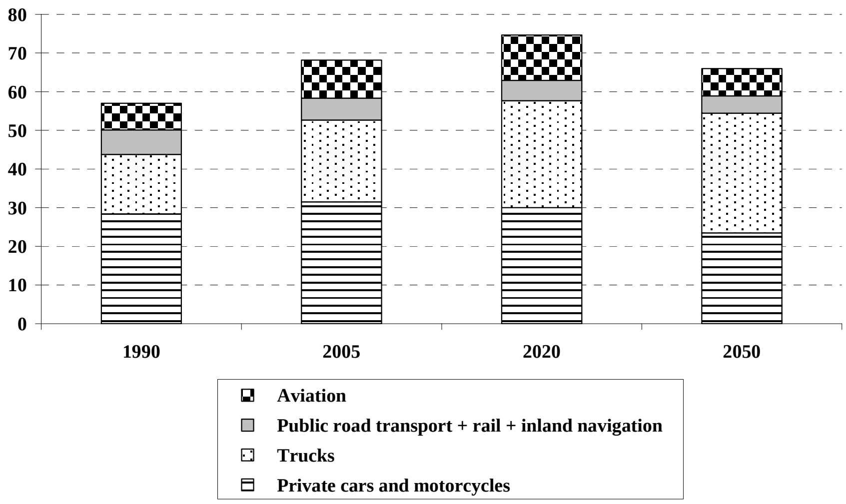


Figure 5.2: CO_2 Emissions (Mt of CO_2)



The baseline for private cars is assumed to be 30% diesel and 70% gasoline during the period until 2050.

5.2 Main technological developments

The power systems of the different transport modes in this analysis are briefly presented in this section. The base technologies are conventional petrol and diesel engines for road transport, shipping and to a limited extent also for rail transport. Aviation is based on conventional technologies utilising jet kerosene.

Ten alternatives have been investigated in the analysis, cf. table 5.1. Some of these are shortly presented below:

- *Cars, trucks and buses utilising bio-diesel (RME).* The traditional diesel engine can utilise bio-diesel, produced on rapeseed and other oil crops, without modification of the engine.
- *Cars, trucks and buses utilising rapeseed oil or other vegetable oils.* The traditional diesel engine is slightly modified to make up for the different characteristics of vegetable oil compared to diesel oil., i.e. replacement of nozzles and some tubes, installation of heat sensors and heaters. The estimated costs associated with the modification are 12,000 DKK.
- *Cars, trucks and buses utilising DME.* The traditional diesel engine is modified and a pressurized tank installed as the DME must be kept under pressure. The DEM is assumed to be produced on biomass, e.g. wood. The estimated additional costs associated with these modifications of the vehicle are 25% of the costs of a traditional diesel engine.
- *Cars utilising 2. generation bio ethanol mixed with gasoline.* The traditional petrol engine is slightly modified is able to operate on a variety of mixes between ethanol and gasoline. The ethanol is assumed to be produced on different types of crop and biomass. No additional cost for the engine is included.
- *Cars utilising compressed natural gas.* The traditional petrol engine and the fuel system are modified as the CNG is pressurized. Modifications include pressure tank and engine modification. Additional costs compared to tradition petrol car are assumed to around 25%. These costs are assumed to decline over the next decades.
- *Cars using methanol in fuel cells.* On the longer term the fuel cell technology is expected to be commercially available in cars. The methanol is produced on synthesis gas, which is generated from wood or other biomass. The methanol is utilised in a fuel cell which has a high energy efficiency compared to a combustion engine.

The GHG emissions for different technologies, measured in CO_2e, are presented in the table below. The emissions are split between emissions from use in the engine and non-engine emissions. Non engine emissions comprise emissions up stream, e.g. from use of fertilizer, use of energy in the fuel production process, etc.

Table 5.1: Technologies, fuels, engines and CO_2-emissions

Technology	Fuel	Type of engine	Fuel costs, as share of total social costs, 2020	CO_2e emission, engine *Kg CO_2/GJ*	CO_2e emission, non-engine *Kg CO_2/GJ*	Potential CO_2-reduction, from engine
Conventional diesel	Diesel	Standard diesel	13%	440	56	-
Conventional petrol	Petrol	Standard petrol	19%	477	104	-
1. Generation Bio-ethanol	Wheat etc.	Slightly modified petrol	28%	104	241	-78%
2. Generation Bio-ethanol	Straw	Slightly modified petrol	25%	104	187	-78%
Bio-diesel (RME)	Rapeseed etc.	Standard diesel	17%	144	238	-69%
Rapeseed oil	Rapeseed	Slightly modified diesel	15%	144	225	-69%
Compress. natural gas	Natural gas	Modified petrol (Otto)	17%	379	38	-19%
Methanol in fuel cells (biomass)	Wood	Fuel cells used in an electric engine	12%	0	21	-100%
Hydrogen (fuel cells)	Electricity	Fuel cells used in an electric engine	13%	0	70	-100%
Electric car	Electricity	Electric engine	6%	0	27	-100%
Diesel from coal	Coal	Standard diesel	15%	440	84	-5%
DME, diesel from biomass	Wood	Modified diesel	21%	144	39	-69%

Note: Not all technologies are assumed available in 2020

5.3 Biomass resources

Biomass can be utilised both for stationary energy sources as heat and power plants, and for mobile sources, e.g. in the form of biofuels for transport.

The Nordic countries utilise large amounts of biomass for energy purpose. In 2005 biomass, including organic waste, amounted to 15% of total gross inland energy consumption in the Nordic countries[7]. As the Nordic countries, particularly Sweden and Finland, has access to relatively large amounts of biomass there is still room for increased use of biomass based on domestic Nordic resources.

In this analysis the use of biomass use in the energy sector has been restricted to a maximum increase of 50% during the period. This increase takes place in the baseline as well as in all alternatives, resulting in a biomass consumption of 29 mtoe (1340 PJ) in 2050.

[7] *European energy and transport trends to 2030*, 2005 update. EC DG Tren

Also the transport sector is expected to utilise biomass for energy purpose, the amount differ depending on the reduction targets and the restrictions on the access to biomass that has been assumed.

The future supply of biomass for energy purpose is not clear, and several international research projects aim to establish a forecast of the biomass resources in EU[8].

The European Environment Agency, EEA, in 2006 published a study[9] on potential for bioenergy that can be produced in Europe without harming the environment. According to the EEA study the environmentally sustainable bioenergy production in the Nordic countries amounts to 32 Mtoe in 2030, a number that does no change significantly over the 20 year period presented in the report.

Even though the future biomass supply is not clear, the EEA study indicates that there are limits to the domestic production of biomass in the Nordic countries, and that a large share of the available biomass resources may be used in the energy sector. This indicates a limited domestic supply of biomass for transport fuels, and that import of biomass or biofuels may be required to enable large scale use of biofuels for transport.

To illustrate this aspect restrictions have been put on the transport sectors access to biomass access in this analysis. The specific restrictions are presented the section below. Further more the effects of no restrictions on the supply of biomass has been analysed, to illustrate the importance of an international market offering biomass or biofuels.

5.4 Costs and potentials of different alternatives

For each of the ten alternatives to conventional petrol and diesel the *additional costs* to society have been identified, cf. table 5.2 (which only concerns private cars). The costs include fuels and for some of the technologies also additional costs of modified (or completely different) engines. The costs also include side effects for reduced air pollution – apart from CO_2 linked to the direct combustion. From the table it is for example seen that bio-diesel (RME) costs an additional 35 € per tonne of $CO_{2.}$ in 2050[10]

The listed costs are associated with considerable uncertainty as they depend on the prices of oil and raw materials and on assumptions regarding future technological development. Especially for the alternatives that are still not mature (like methanol (biomass) and hydrogen for fuel cells) or are expected to become much cheaper than today (e.g. electric cars), the uncertainty is considerable.

[8] For instance the IEE research programme REFUEL

[9] How much bioenergy can Europe produce without harming the environment? EEA Report No. 7/2006

[10] The costs are in factor prices.

For each alternative the *potential CO_2-reduction* from combustion has been identified. E.g. a substitution from baseline (combination of conventional petrol and gas) to bio-diesel (RME) contributes to a reduction in CO_2 from combustion by 69%. Hence, if the full transport demand (private cars) – hypothetically – could be covered by bio-diesel (full market share) the CO_2 reduction would be of this size.[11]

Table 5.2: 2020 and 2050: Costs and potentials compared to baseline (for private cars only)

	Additional social costs, 2020 (€/t)	Additional social costs, 2050 (€/t)	Potential CO_2 reduction	Cap on market share, 2020	Cap on market share, 2050
1. generat. Bio ethanol	161	191	-78%	25%	30%
2. generat. Bio ethanol	119	98	-78%	25%	30%
Bio-diesel (RME)	45	35	-69%	15%	18%
Rapeseed oil	108	92	-69%	15%	18%
Compress. natural gas	42	-209	-19%	40%	80%
Methanol in fuel cells (biomass)	86	-9	-100%	(na.)	20%
Hydrogen (fuel cells)	116	41	-100%	(na.)	20%
Electric car	103	3	-100%	15%	30%
Diesel from coal	86	-1399	-5%	40%	50%
DME, biomass diesel	278	154	-69%	(na.)	30%

Note: Trucks and buses are assumed to be able to use RME, rapeseed oil and DME. Aviation is assumed to be able to use RME in 2050, and buses, ferries and rail to use methanol and hydro in fuel cells in 2050.

However, for practical reasons none of the alternatives has the potential to cover the total energy demand in the transport sector. The **restrictions** rely on several issues. The overall restriction is shortage in providing enough “raw material” to cover the whole transport demand (biomass, crop, wood etc). This restriction will be less binding over time as more land could be included in the production of biomass etc. – also in a global context.

For those alternatives which need a modified engine, the potential can not be fully exploited in 2020 as it takes 10–15 years after the technology is introduced until a relatively large share of the vehicles has been changed. However, concerning 2050 this issue is not problematic.

Also, the transport demand is not homogenous. Hence, it can be expected that the use of electric cars for instance are restricted to urban areas and that diesel engines are restricted for those with a high transport demand.

In table 5.3 these considerations about binding restrictions on the exploitation of the alternatives are quantified for 2020 and 2050 respectively. However, these numbers are associated with considerable uncertainty and should be interpreted with caution.[12]

[11] There is not substantial uncertainty to these figures.

[12] It should be noted that the potentials of the alternatives are interdependent. If e.g. biomass can cover maybe 30 percent of the transport demand in 2050 then this potential make an upper limit of

Table 5.3: Assumed prices for fuel and raw materials (2005-price-level)

	2020 €/GJ	2050 €/GJ	2020–2050 Percentage
Wheat	10.1	13.7	37%
Straw	3.6	4.9	37%
Rapeseed	9.8	13.4	37%
Wood	4.4	5.3	18%
Crude oil	6.6	12.6	92%
Natural gas	5.8	9.9	71%
Coal	1.9	2.7	42%
Electricity	11.1	13.9	25%
CO_2-costs (global) EUR/tCO_2e	20	100	400%

Source: Biomass: Own estimates. Fossil fuels: MARKAL inputs.

Note: In the analysis of the transport sector, the price for woody biomass is expected to show a modest increase, whereas the MARKAL model assumes constant prices.

The cost and emission estimates are for practical reasons based on the emissions from the engine. The upstream GHG emission from the production, processing and transport of fuels and raw materials is attached a cost of 100 EUR/tCO_2e. This reflects the assumption that an international allowance market exists in 2050 with an allowance price of EUR 100/ tCO_2e.

As crude oil price is assumed to increase more than other fuels and raw materials, technologies based on these other fuels and raw materials will become increasingly competitive.

5.5 Marginal Abatement Cost curves for 2020 and 2050

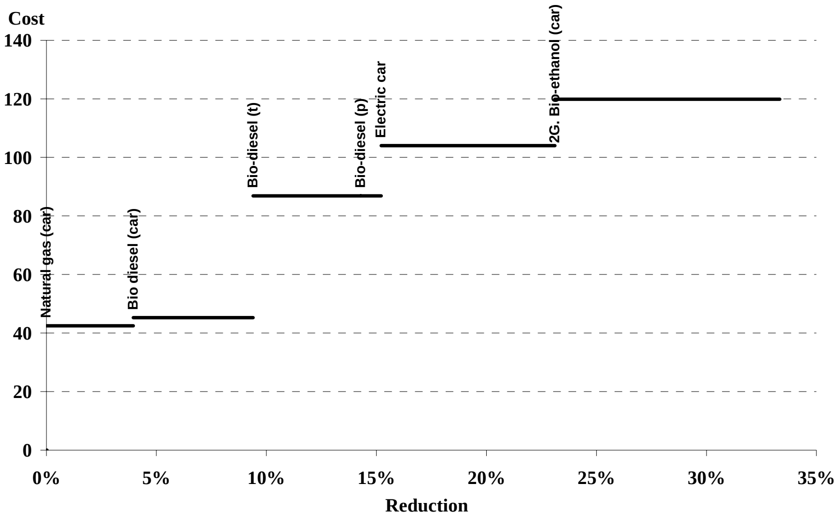
From table 5.2 it was seen that the different alternatives have different costs and scopes. The scope or potential indicates whether an alternative is effective in relation to reaching an overall reduction of CO_2. The costs indicate whether an alternative is cost efficient – which means whether or not the alternative can ensure cheap reductions.

In this section it is shown (based on the figures 5.3, 5.4 and 5.5) that there exists a trade off between alternatives that are on the hand effective and on the other hand cost efficient. Hence, it is not possible at the same time to reach a high degree of both effectiveness and cost efficiency.[13] The MAC curves presented below are based on technologies with a high emission reduction potential in order to support ambitious reduction targets.

the sum of the potentials for bio ethanol (1. generation), methanol in fuel cell (biomass) and DME, diesel from biomass. Also the potentials of bio-diesel (RME) and rapeseed oil are interdependent.

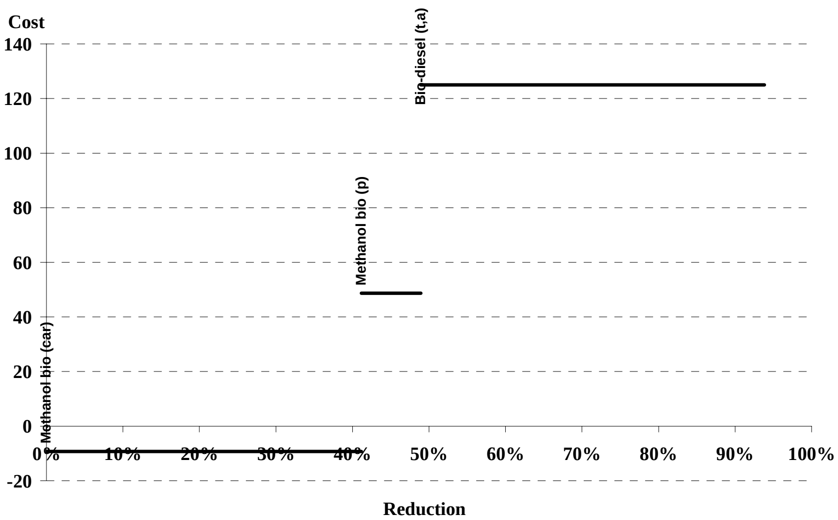
[13] Whether one should go for effective alternatives or cost efficient alternatives in the transport sector depends on emission reduction targets and the alternatives in other sectors

Figure 5.3: MAC-curve 2020



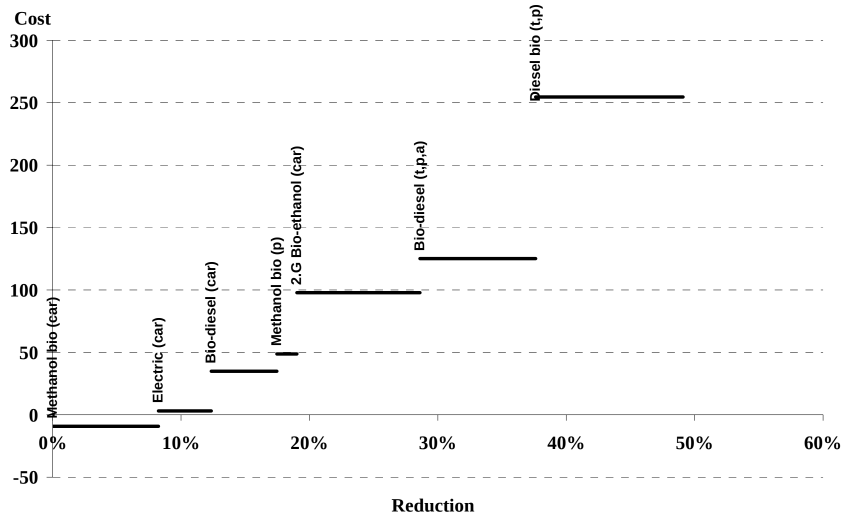
It is seen from figure 5.3 that the costs in 2020 of providing a given reduction is slightly lower than the costs in 2050, cf. figure 5.4. This can be referred to the fact that the potentials of penetrating the market for the different alternatives are larger in 2050 than in 2020 and hence enables the Nordic countries to exploit the cheaper solutions more intensively.[14]

Figure 5.4: MAC-curve 2050: No biomass restrictions



[14] However this comparison between 2020 and 2050 should be interpreted with caution as the costs are assessed for a “coming future" and are not differentiated between 2020 and 2050.

Figure 5.5: MAC curve 2050: Restrictions on biomass- ambitious



6. Other emissions

Emissions of carbon dioxide (CO_2) from the combustion of fossil fuels have long been recognized as the most important contributor to the enhanced green-house effect. If anything, the relative role of these emissions is expected to increase in the future (see sections on energy and transport). An emphasis on CO_2 in climate change mitigation policies is therefore justified.

However, the almost exclusive focus on CO_2 as a contributor to global warming has had the unintended consequence of directing attention away from other, non-CO_2 greenhouse gases (GHGs). This has been unfortunate, because opportunities for cost-effective reductions may exist among non-CO_2 GHGs, which have not previously been considered (Reilley et al., 2003).

Including non-CO_2 GHGs in climate change mitigation may have economic benefits, if the costs of reducing the non-CO_2 gases (per tonne CO_2 equivalent) are less than the costs of reducing CO_2. In that case, a larger share of the GHG reductions would occur through reductions of non-CO_2 gases, while smaller reductions of CO_2 would be required for a given stabilization target. In fact, the possibility for substitution among gases is recognized in the Kyoto Protocol, which includes not only CO_2, but also non-CO_2 GHGs in its portfolio of emissions reductions. Yet, despite the potential significance of these gases, only a few studies have analysed the costs of so-called "multigas stabilization", as compared with "CO_2 only" strategies.

One reason why there is only a limited number of "multigas studies" is related to the fact that reliable and consistent data on the costs of reducing non-CO_2 GHGs have been lacking. Moreover, while the emissions of CO_2 from fossil fuel sources can be readily estimated from market data on fuel use, the emissions of non-CO_2 GHGs are not easily measured. The analysis of abatement options for the reductions of fossil based CO_2 also benefits from decades of research on energy markets, energy efficiency, and alternative energy supply technologies.

As the capability to measure and assess the non-CO_2 GHGs is gradually improving, it is becoming clear that their control is an essential part of a cost-effective climate policy. Recent studies have shown that including non-CO_2 GHGs in the portfolio of GHG emissions reductions could lead to as much 30 to 40% savings on costs in reaching a given stabilization target, compared with a "CO_2 only" strategy (van Vuuren et al., 2006). Studies have also found that non-CO_2 gases can significantly improve the flexibility of climate policies over time, by taking advantage of the fact that non-CO_2 gases have different atmospheric lifetimes (and different “radiative forcing”) and, therefore, may contribute to both short term and long term stabilization targets in ways that are different from CO_2.

In the following is briefly described what the “other” GHGs are. Then the baseline emissions in the Nordic countries in 2020 and 2050 are presented, followed by a brief presentation of the technologies included in the assessment, and their marginal abatement costs.

6.1 “Other” greenhouse gases

The “other” GHGs include two classes of emissions:

- non-energy CO_2 (process emissions)
- non-CO_2 GHGs (CH4, N2O and F gases).

Non-energy CO_2 emissions are related to industrial processes (cement production, metal smelting, etc.), where the emissions are not produced as a result of fossil fuel combustion. These processes are also quite energy intensive and therefore typically involve significant GHG emissions.

Table 6.1: Anthropogenic Sources of Non-CO_2 Greenhouse Gases

Non-CO_2 GHGs	Major sources
Methane (CH4)	Oil and coal production, gas distribution, animal livestock, and landfill waste
Nitrous Oxide (N2O)	Agricultural soils (nitrogen fertilizers), chemical production
Hydrofluorocarbons (HFCs)	Air conditioning and foam blowing, substitutes for chlorofluorocarbons (CFCs)
Perfluorocarbons (PFCs)	Semi-conductor production, aluminium smelting
Sulphur Hexafluoride (SF6)	Insulator in electrical switchgear, magnesium smelting

Source: Reilly et al. (2003) and 4th National Communications to the UNFCCC (2006).

The non-CO_2 GHGs include methane (CH4), nitrous oxide (N2O), and a group of industrial, so-called F gases: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF6). The human contributions to these gases stem primarily from agricultural production (animal digestion, animal manure, and fertilizers), industry (fugitive emissions from energy production, chemical industry), and solid waste (landfills). The major sources of non-CO_2 GHGs are shown in Table 6.1.

At a global scale, non-CO_2 gases currently account for about 25% of GHG emissions in terms of 100 year global warming potentials. In the Nordic countries, non-CO_2 gases accounted for a little less of the total gases in 2004 according to the national communications to the UNFCCC (United Nations Framework Convention on Climate Change).

Notice that this study does not include land use, land use change and forestry (LULUCF) measures, even though these may contribute significantly to carbon sequestration. The analysis of other GHG emissions relies extensively on a study of the same topic by Bates et al. (2004), as well as on studies by the US Environmental Protection Agency (USEPA, 2006) and the Energy Modelling Forum-21, which recently con-ducted a global analysis on multigas mitigation.

Data on marginal abatement cost are derived from the USEPA and the EMF-21 studies for the EU-15. Thus, it is assumed that these estimates apply to all the Nordic countries.

In the two studies, the host of different reduction potentials from the varying sources are assembled to tranches of reduction potentials which in turn can form the MAC curves.

6.2 Projection of baseline emissions

The baseline emissions are based on data reported to the UNFCCC for the year 2004. These data are disaggregated on a 3-digit level in order to ensure compatibility with the energy and transport sectors, and in order to ensure that the sources of emissions are sufficiently detailed to allow the application of the abatement technologies, and their costs, described by the USEPA (2006).

The emissions of other gases reported to the UNFCCC are shown in Table 6.2 below and compared with the emissions included in this study. Notice that for the energy and transport sectors, non-CO_2 gases are included separately, and so they are not included here.

Table 6.2: Non-CO_2 GHGs in the Nordic countries in 2004 (Gg CO_2 eq.)

Nordic Countries	CO_2	CH_4	N_2O	HFCs	PFCs	SF_6
	CO_2 eq. (Gg)					
Total GHG emissions (w/o. LULUCF)	222.397	23.040	26.914	2.588	1.177	415
International Bunkers	18.919	10	253			
Total GHG emissions	260.322	24.209	25.090	5.334	2.877	948
Energy	145.118	2.533	2.280			
Transport (incl. International Bunkers)	79.201	239	1.735			
Other gases	18.001	21.436	21.074	2.667	1.438	474
Industry and Solvents	17.699	53	3.624	2.667	1.438	474
Agriculture	0	13.724	17.450			
Waste	303	7.659	0			

Source: UNFCCC.

The projection of the baseline emissions are made on the basis of a study by Bates et al. (2004), which analyses emissions of non-CO_2 GHG gasses in the EU-15. In the present study we project these emissions to 2030, where most of the emissions in the baseline are relatively stable. It is therefore assumed that there are no further developments in these emissions between 2030 and 2050.

One notable exception is that Bates et al. (2004) finds that non-CO_2 emissions from the energy sector increases dramatically between 2000 and 2020. This is caused by the replacement of decommissioned nuclear power with fossil energy power sources. It is assumed that this replacement is completed in 2020, and that the emissions from this source are stable after 2020. The baseline emissions in 2020 are shown in Table 6.3.

Table 6.3: Non-CO_2 GHGs in the Nordic countries in 2020 (Gg CO_2 eq.)

Nordic Countries	CO_2	CH_4	N_2O	HFCs	PFCs	SF_6
	CO_2 eq. (Gg)					
Other gases (this study)						
Industry and Solvents	18.842	53	3.624	5.227	2.819	930
Agriculture	0	13.724	17.450			
Waste	303	7.659	0			
Total	19.145	21.436	21.074	5.227	2.819	930

Source: UNFCCC.

6.3 Main technological developments

In this study we focus on known technologies, which have been analysed and assessed with respect to their costs and their applicability and effectiveness in reducing emissions (USEPA, 2006). This assessment is global in nature, and has been used as a source of a growing number of non-CO_2 modelling studies. In this study, we use only the reduction potentials and their costs, as they apply to the EU-15. The emission sources reduced and their costs are reported in the appendix D with respect to the following sectors:

- agriculture
- chemical industry
- solid waste

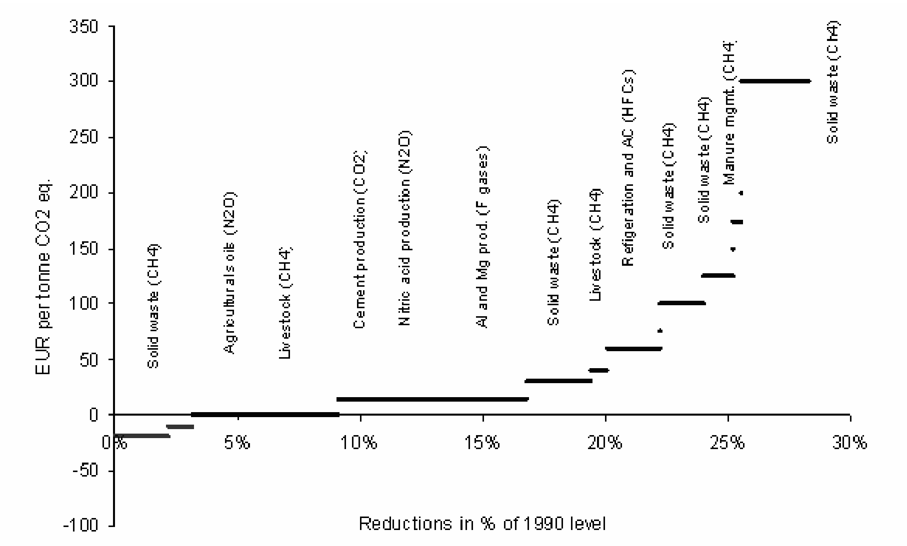
Since the majority of the non-CO_2 GHGs in the Nordic countries derive from methane (CH4), technologies related to reductions of methane in agriculture and the waste sector (animal livestock, solid waste landfills) dominate the analysis. There are also important sources of reductions of N2O and of F-gases from the chemical industry (nitric acid production, refrigeration).

6.4 Marginal abatement cost curve

Since we assume no technological development in the abatement technologies, this means that marginal abatement costs for 2020 and 2050 are identical.

The MAC curves are shown as tranches of reduction potential summarised and ordered by their costs. While the composition of the curve is described in brief terms below, the reader is also referred to the technical appendix D for a break-down of the reductions by gases, and to the USEPA (2006) for a detailed exposition of the composition of the MAC curve. The MAC curve for 2020 is shown in Figure 6.1.

Figure 6.1: MAC curve for other GHG emissions, 2020 and 2050



Source: Own calculations

As can be seen, approximately 35% of the other emissions in the Nordic countries are covered as potential reductions by the MAC curve. However, most of these reduction potentials are relatively cheap, i.e. around or below 30 EUR per tonne.

In brief terms the composition of the Nordic MAC curve for other GHG emissions is as follows:

- Managed land disposals contribute with 14% points of the reductions. One half of these reductions cost is at approximately 60 Euro/tonne, while the other half is at 30 Euro/tonne or below.
- Chemical N2O is also an important source of reductions with 4% point of the reduction.
- Animal livestock (or enteric fermentation, related to animals in agriculture) contributes with 3.2% point of the shown reductions. Its

cost is for the most par below 30 Euro/tonne, albeit a smaller part costs 60 Euro/tonne. In total, only 16% of emissions from animal livestock can be reduced.

- Agricultural soils contribute with 4.0% points of the reduction. Most of this is concentrated at costs around 15 Euro/tonne or below.

7. Perspectives and reservations

The climate change issue and issues related to GHG emissions reductions are very complex issues with great impacts on society. In practical terms it is not possible to fully address all issues and to ensure full consistency in the modelling and assessments, and it is important to state that a number of potentially important topics have been identified through the project but are not fully treated in this report.These topics are presented below.

7.1 Conservative technology development assumptions

The selection of “winner” technologies is not part of this project. Rather an average approach is used, which assumes that a range of technologies, e.g. different biofuels and electric cars within the transport sector, are available in 2050. However, in real life not all technologies will develop, but some are likely to be significantly more successful than others, and probably provide cheaper solutions on for instance battery technologies than foreseen in this study. In this respect, the study is rather conservative and tends to underestimate the potential emission reductions and over estimate the costs.

7.2 Biofuels

Biomass and biofuels are not confined to include only Nordic sources, biofuels and biomass are also assumed to be available and bought on an international market. In this sense the reductions are not necessarily “Nordic” reductions. In this analysis rather strict limitations were put on the availability of biofuels. The availability of biomass in the Nordic countries and in the EU is being analysed in EU research projects which can provide valuable insight when results are published[15]

7.3 Dynamics and timing of reductions

The abatement costs depend on the timing of the implementation of measures and on the technological development. These aspects are not

[15] E.g. the REFUEL EU research programme, is expected to present results on biomass potentials in 2007.

fully accounted for in this analysis, as focus is on the selected years and emission target, whereas the road in terms of policy measures etc. to go to meet the targets at the least costs has not been assessed.

The ambitious targets and the policy measures used to achieve the targets will affect the technology development and thereby also the costs associated with meeting targets. In this analysis the learning effects of policy decisions and research activities have not been assessed, rather simplified exogenous assumptions on the technology development has been used.

An important issue for further study therefore is analyses of the dynamics of policies, research and technology development which could help to establish a better understanding of the right timing and right policies and measures.

7.4 Partial analysis

In this analysis marginal abatement costs from three sectors are merged. This provides a challenge to the full picture for the Nordic countries, as the three sectors (energy, transport and non-CO_2) are not independent of each other. For instance increased biomass consumption for fuels for transport purpose will affect the agricultural sector and the emission of non-CO_2 GHG from agriculture. This interplay between sectors has been handled in the analysis by assuming an international market for biomass, and adding a CO_2 allowance cost to the biomass used for biofuels.

To overcome this problem of interplay between sectors a full modelling of all sectors and their interaction should be undertaken. Development of such models is on its way in several research projects and will provide important insight on effects of policies.

7.5 Different measurements for costs of reductions

The cost estimates in this study are based on *system costs*. These include the direct investment and operation costs, and include investments and costs in the system, e.g. the energy system, in terms of reserve capacity, transmission costs etc. These are typically used when bottom-up modelling techniques are used.

These costs are however not necessarily presenting the full picture. Besides system costs (and benefits) also other sectors will be affected of the system costs through higher electricity prices, higher prices for agricultural products, transport services etc. These costs may reduce the competitiveness of the economy, reduce consumption etc., leading to secondary effects. Including these costs will provide information about the *macroeconomic costs* of meeting reduction targets, and would normally be estimated by use of a General Equilibrium model.

In addition to the macroeconomic cost the *welfare-economic costs* in terms effect on equality and other welfare aspects could be included in an attempt to provide an even more comprehensive measure.

7.6 Research and development costs

The development of new and improved technologies often carries a cost for period before the benefits are harvested in the form of increased energy efficiency etc. The development costs are not included in this project. Generally it is assumed that the Nordic countries are in line with development tendencies and GHG policies globally, and that these global trends will affect the technology development in general. The Nordic countries therefore are assumed to be taking advantage of improved technologies provided globally and not requiring specific research and development costs in the Nordic countries.

In real world this will not necessarily be true, as the Nordic countries are likely also to have R&D costs. However, R&D will not only be a cost to society, also benefits and changes in the technology development are likely to take place. It is therefore quite complicated to assess the net effects in terms of macro economic costs of increased R&D, as the benefits are difficult to assess. This is further complicated by the fact that money spent on climate change related R&D may be taken from R&D in other areas, which on their side might also give rise to benefits, areas which then may forego opportunities.

7.7 Benefits not accounted for

The costs estimates include direct benefits in terms of reduced fuel costs etc. However not all benefits are included, for instance positive externalities from R&D as mentioned above and environmental benefits in terms of reduced emissions from fossil fuels,

Finally it should be underlined that LULUCF not accounted for in this project. This does not mean that this is not an important issue. On the contrary the GHG amounts covered by LULUCF are of a scale that can affect the gap.

Sammenfatning

Dette studie vurderer mulighederne for at reducere udledningerne af klimagasser fra de nordiske lande i 2050 med 60–80% sammenlignet med udledningerne i basisfremskrivningen.

Metodemæssigt har studiet analyseret tre nøglesektorer, nemlig den nordiske energisektor (el og varme), transportsektoren samt andre klimagasser end CO_2 („andre gasser“). Analysen af hver sector er sket partielt. Den nordiske energisektor er analyseret ved hjælp af simuleringer på en nordisk energisektormodel, MARKAL Nordic modellen. Et stort antal scenarier er blevet belyst, og de marginale reduktionsomkostninger forbundet med at nå forskellige reduktionsmål er blevet vurderet. Transportsektoren og „andre gasser“ er blevet analyseret ved at kombinere basisfremskrivningerne med et antal mulige reduktionsteknologier og de tilhørende omkostninger.

De nordiske lande er analyseret samlet, idet der er anlagt en systemtilgang som tager højde for det sammenhængende nordiske energisystem. Denne nordiske tilgang indebærer imidlertid, at det ikke er muligt at overføre de nordiske resultater direkte til de enkelte lande på grund af forskelle i de nationale omstændigheder. Eksempelvis er norsk elproduktion næsten CO_2-fri, mens olie-gas sektoren er ansvarlig for omkring en fjerdedel af landets udledninger af klimagasser.

De marginale reduktionsomkostninger er blevet estimeret for 2020 og 2050 for at beregne de samlede reduktionsomkostninger og give information om de stigende omkostninger ved mere ambitiøse reduktionsmål.

De centrale resultater er at:

- Med de anvendte forudsætninger i analysen opnås en emissionsreduktion på 57 % af 1990 emission i 2050, hvilke efterlader en nordisk emission på 43 % af 1990 niveauet
- I beregningerne reducerer energisektoren emissionerne med ca. 80 % i 2050. De centrale reduktioner opnås ved udfasning af fossile brændsler i el og varmeproduktionen, og gennem øget udnyttelse af vindenergi og i et vist omfang bølgeenergi og solceller. Der er forudsat begrænset adgang til bioenergi.
- Transportsektoren forventes kun at reducere med 40 % af emissionerne i basisfremskrivningen på grund af forudsætninger om begrænset udbud af biobrændstof og en begrænset markedsandel for eldrevne biler. Disse forudsætninger er væsentlige for resultatet og kan diskuteres.
- „Andre gasser“ reduceres kun med 33 %, primært på grund af vanskeligheder ved at reducere N2O and metan fra landbrug. Dette synes at

være et konservativt bud, da det baseres på eksisterende teknologier, og da nye teknologier og driftsformer kan forventes at reducere klimagasudledningerne på længere sigt.
- Disse reduktioner er ikke nok til at nå 60 % emissionsreduktion. Større emissionsreduktioner i energisektoren synes derfor nødvendige for at nå 80 % reduction samlet set.
- Nogle dele af emissionen af „andre gasser“ vil næppe kunne fjernes. Dette øger presset på at nå 80 % reduktion i energi- og transport-sektorerne.
- Omkostningerne ved at reducere ca. 60 % af basisfremskrivningens emissioner udgør ca. 11 milliarder EUR/år, eller 0,5–1 % of BNP per år, i 2050.
- Hvis begrænsningerne på biomasse løsnes og der gives ubegrænset adgang til et internationale biomasse marked kan reduktionspotentialet i transportsektoren øges og en samlet emissionsreduktion på 68% opnås med begrænsede yderligere omkostninge, stadig omkring 0.5–1 % af BNP i 2050.
- Yderligere energisektor reduktioner kan også øge den samlede emissionsreduktion til næsten 70 %, men dette ville øge omkostningerne til omkring 1 % af BNP i 2050

Analysen er baseret på et stort antal forudsætninger og antagelser, hvoraf mange er svagt funderede, især i lyset af den lange tidshorisont. De er derfor vigtigt at understrege en række reservationer:

- Da der blev benyttet delmodeller for transportsektoren og energisektoren er synergi og eksternaliteter mellem reduktioner i de to sektorer ikke taget i betragtning.
- Der er naturligvis store usikkerheder om den teknologiske udvikling frem til 2050 og om brændselspriser og priser på andre råvarer.
- Analysen baseres på generelle forventninger til udviklingen af teknologier. Muligheden for at visse teknologier udvikler sig hurtigt eller mere succesfuldt, og dermed reducerer omkostningerne, tages ikke i betragtning. Analysen kan derfor betragtes som relativt konservativ i sit udgangspunkt.
- Afledte effekter af forskning og udvikling er ikke medtage, hverken på den positive side (øget innovation i tilstødende sektorer) eller på omkostningssiden (forskning her kan dirigere midler væk fra andre potentielle forskningsområder).

Blandt de emner der vil kræve yderligere analyser i fremtiden er analyser af dynamikken mellem politik, forskning og teknologiudvikling med henblik på at få en bedre forståelse af den rigtige timing og de rigtige politikker og virkemidler for at opnå ambitiøse reduktionsmålsætninger til de laveste samfundsøkonomiske omkostninger.

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