Climate 2050

– Literature review

Climate 2050 – Literature review

TemaNord 2008:539

© Nordic Council of Ministers, Copenhagen 2008

ISBN 978-92-893-1690-3

Print: Ekspresen Tryk & Kopicenter

Copies: 0

Printed on environmentally friendly paper

This publication can be ordered on www.norden.org/order. Other Nordic publications are available at www.norden.org/publications

Printed in Denmark

Nordic Council of Ministers

Store Strandstræde 18
DK-1255 Copenhagen K
Phone (+45) 3396 0200
Fax (+45) 3396 0202

Nordic Council

Store Strandstræde 18
DK-1255 Copenhagen K
Phone (+45) 3396 0400
Fax (+45) 3311 1870

www.norden.org

Nordic co-operation

Nordic cooperation is one of the world's most extensive forms of regional collaboration, involving Denmark, Finland, Iceland, Norway, Sweden, and three autonomous areas: the Faroe Islands, Greenland, and Åland.

Nordic cooperation has firm traditions in politics, the economy, and culture. It plays an important role in European and international collaboration, and aims at creating a strong Nordic community in a strong Europe.

Nordic cooperation seeks to safeguard Nordic and regional interests and principles in the global community. Common Nordic values help the region solidify its position as one of the world's most innovative and competitive.

Content

Preface	9
Summary	11
Introduction	17
Methodological considerations	19
Baseline emission scenario	19
Emission reduction scenario(s)	20
Modelling methodologies and outputs	20
Types of models	20
Modelling outputs	21
Technology development and abatement costs	22
Induced Technological Change (ITC)	22
From R&D to market	23
Two externalities: The rationale for policy action to promote technology development	23
Policies and measures that induce technological change	24
Induced technological change and the timing of emission reductions	25
Technological change in climate modelling	25
The international climate regime and abatement costs	26
Selection of studies for review	27
Selection of studies	27
Key studies	27
Overview studies	27
Nordic studies	27
Criteria for selection of studies	28
Studies selected for review	28
Key studies	28
Overview studies	29
Nordic studies	30
Key Study findings	31
Cost estimates	31
Findings and explanations	32
Modelling techniques	32
Energy supply (with Carbon Capture and Sequestration)	32
Energy demand and efficiency	33
Transport	33
Other sources and sinks	33
Key Study #1: Climate change and a European low-carbon energy system	35
General/crosscutting	35
Baseline assumptions and emissions	35
Reduction scenario parameters and assumptions	36
Reduction scenario outputs	37
Modelling methodologies applied	38
Energy supply (with Carbon Capture and Sequestration)	39
Baseline assumptions and emissions	39
Reduction scenario parameters and assumptions	40
Reduction scenario outputs	40
Energy demand and efficiency	41
Baseline assumptions and emissions	41

Reduction scenario parameters and assumptions	41
Reduction scenario outputs	41
Transport:	42
Baseline assumptions and emissions	42
Reduction scenario parameters and assumptions	42
Reduction scenario outputs	43
Other sources and sinks:	45
Baseline assumptions and emissions	45
Reduction scenario parameters and assumptions	50
Reduction scenario outputs	54
Key Study #2: Our energy future - creating a low carbon economy + background	
study: Options for a low-carbon future	57
General/crosscutting	57
Baseline assumptions and emissions	57
Reduction scenario parameters and assumptions	59
Reduction scenario outputs	59
Modelling methodologies applied	61
Energy supply (with CCS)	61
Baseline assumptions and emissions	61
Reduction scenario parameters and assumptions	61
Reduction scenario outputs	62
Energy demand and efficiency	62
Baseline assumptions and emissions	62
Reduction scenario parameters and assumptions	62
Reduction scenario outputs	63
Transport:	63
Baseline and Reduction scenario parameters and assumptions	63
Reduction scenario outputs	63
Key Study #3: Energy Technology Perspectives	67
General/crosscutting	67
Baseline assumptions and emissions	67
Reduction scenario parameters and assumptions	68
Reduction scenario outputs	68
Policies and measures to achieve targets	70
Modelling methodologies applied	70
Energy supply (with CCS)	71
Baseline assumptions and emissions	71
Reduction scenario parameters and assumptions	71
Reduction scenario outputs	72
Energy demand and efficiency	74
Baseline assumptions and emissions	74
Reduction scenario parameters and assumptions	74
Reduction scenario outputs	74
Transport:	75
Baseline assumptions and emissions	75
Reduction scenario parameters and assumptions	75
Reduction scenario outputs	76
Brief review of overview studies	79
Overview study #1: Options for a Low Carbon Future:	
Review of Modelling Activities and an Update	79
Stabilization wedges: Solving the Climate Problem for the Next 50	
Years with Current Technologies	79
EMF 19	80
Response from a MARKAL technology model to the EMF scenario	
assumptions	81
Overview study #2: Endogenous Technological Change and the Economics of	
Atmospheric Stabilisation (Energy Journal Special Issue)	82

General/crosscutting remarks	82
Baseline assumptions and emissions	83
Reduction scenario parameters and assumptions	84
Reduction scenario outputs	85
Overview study #3: The costs of greenhouse gas abatement: a meta-analysis	
of post-SRES mitigation scenarios	85
Costs	86
Explanations	86
Brief review of selected Nordic Studies	89
Analysis and Evaluation of the Triptych 6 - case Finland	89
General/crosscutting remarks	89
Baseline assumptions and emissions	89
Reduction scenario parameters and assumptions	89
Reduction scenario outputs	90
The NORDLEDEN project – Final report from phase II, 2003 (PROFU)	90
Information of relevance to the study phase	95
Crosscutting	95
Baseline assumptions	95
Modelling methodology	95
Resulting cost indication	95
Energy supply (with CCS)	96
Energy demand and efficiency	98
Transport	99
Baseline parameters and assumptions	99
Reduction scenario parameters and assumptions	100
Other sources and sinks	100
Modelling methodology	100
Baseline parameters and assumptions	100
Reduction scenario parameters and assumptions	101
References	102
Sammendrag	105
Appendix A: Energy Sector Analysis Report	109
Summary and Conclusions	110
Introduction	115
Methodology and assumptions	115
The MARKAL-NORDIC model	115
Today's power generation in the Nordic electricity market	116
Approach	117
Baseline scenario assumptions	117
Results of analyses	119
Energy sector MAC curves	119
Electricity generation and investments in new technologies	120
Electricity and heat prices	124
References	125
Appendix B: Projections of transport demand and CO ₂ emissions from	
transport 2010–2050	127
Appendix C: Other Greenhouse gasses	131
C2 Data for baseline projections	140
C3 Assumptions in baseline scenario	141
C4 Marginal abatement cost curves	141

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 literature review is a part of this study.

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

Oslo, September 2008

Jon Dahl Engebretsen

Chairman of the Climate Change Working Group

Summary

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 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.

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).

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 S1.

Table S1. 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 \$/bbl 2050: 35\$/bbl	App. 25\$/bbl	2030: 39\$/bbl 2050: 60\$/bbl

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 S2:

Table S2. Overview of literature cost estimates

Study	Model	Cost indication	Emission reduction target	Geogr. scope
EEA	Bottom-up	MAC: 65€/t CO2 GDP: 1%	CO2 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 CO2 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 %	CO2 content 550PPM	EU 15 plus Norway, Switzerland and Iceland
Overview Study # 2 Energy Journal special edition	Diff. models	MAC: 30-70 \$/t CO2 GDP: ~0.5 % but up to 6 %	CO2 content: 450-500-550 PPM	World

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 re-*

ductions in CO₂ 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.

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.

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, CO₂ reductions in the transport sector is obtained through increased use of bio-fuels 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

Other sources than energy and transport

Non-CO₂ 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

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.*”

Introduction

This literature review report is part of the reporting under the study “Climate 2050 - the road to 60-80 percent reductions in the emissions of greenhouse gases”. The study is commissioned by the Climate Group under the Nordic Council of Ministers.

The purpose of the study is to analyse the consequences of ambitious long term reductions in the emissions of greenhouse gases (GHG) by Nordic countries. The outputs will serve as inputs to the strategy considerations regarding future action and commitments by the Nordic countries under the UNFCCC. The reductions under consideration are 15 to 30 percent relative to 1990 emissions in 2020 and 60 to 80 per cent in 2050. It is a central output of the project to address whether the ambitious long term reductions can be met without significant adverse socio-economic consequences.

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 present report includes the following elements:

- Identification of a limited number of relevant studies
- An overview of key assumptions in the studies
- An overview of modelling methodology applied in the studies.
- An overview of key outputs of past studies
- Recommendations as to how the experience from other studies could be used in the Nordic study in terms of assumptions and methodology.
- A section on the role of technology development in long-term emission abatement

The report is divided into two parts:

Part 1 provides the reader with an overview of the methodologies used for long term scenario analysis, the studies selected for review and the key findings from the reviews.

Part 2 presents the in depth reviews of the selected studies, including technical descriptions on assumptions, methodologies and emission sources.

Methodological considerations

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

- 1 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.
- 2 The reduction scenario in which policy action is undertaken to reduce emissions.

For both baseline and 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.

In the following, some of these issues are briefly introduced as a background to the presentation of the results of the literature review.

Baseline emission scenario

The concept of a *baseline scenario* is central to the assessment of emission reduction costs, both in the studies reviewed and in the analyses carried out under this project. The costs of achieving emission reductions of 60-80% depend on the counterfactual baseline (or *reference*, or *business-as-usual*) scenario against which the reduction scenario is compared.

Important drivers and the underlying key parameters determining the emission scenarios in the baseline include:

- Economic growth
- Population development
- Developments in energy prices
- Technological developments in energy production (in particular both conventional and low or zero emission technologies)
- Improvements in energy efficiency in production/conversion, transmission/distribution and end-use
- Developments in the transport sector, e.g. the use of biofuels and energy efficiency improvements

- Emission trends not related to energy and transport (LULUCF, industry gases and process emissions)
- Effects of structural changes in the economy, including trends in exports and imports of energy commodities and manufactured goods.
- Significant policies and measures - mainly at national and EU level - that is included in the baseline, e.g. carbon taxes and support schemes for renewable electricity.
- The international climate regime. Key issues here are whether any emission reduction commitments are included in the baseline after 2012 and the extent of international trade in emissions allowances.

Emission reduction scenario(s)

Similarly to the baseline scenario, one or more abatement scenarios are defined by the associated assumptions concerning a range of key factors determining the costs of reducing GHG emission:

- Emission targets and pathways (which in turn will depend on the global climate regime)
- The global climate regime (including i.a. commitments of other countries such as US and developing countries; inclusion of international bunkers; the framework and scope of international emissions trading)
- Policies and measures applied in the reduction scenario to promote low-carbon technologies. P&M may be categorized in several ways such as “market pull” vs. “technology push”; economy-wide vs. sectoral; or economic instruments vs. non-economic ones.
- Assumptions regarding technology development and deployment with regard to energy supply and energy efficiency (potential and costs)
- Assumptions regarding technology development and deployment within transport
- Assumptions regarding emissions not related to energy and transport.
- The role of carbon capture and sequestration (CCS)

Modelling methodologies and outputs

Types of models

Models utilized to analyze long-term emission reduction targets come in a large variety of shapes and forms. Generally, a distinction is made between top-down and bottom-up models.

The *top-down models*, which include general equilibrium models, are characterised by including limited detail in the specification of technologies. Their particular strength is that they account for secondary knock-on effects on production and prices in other sectors and the economy in general. Because they model equilibria, they are not very good at capturing transitional costs and innovation processes. Top-down models assume that markets operate efficiently at the outset, and therefore any mitigation policy will incur costs.

Bottom-up models - or engineering-based models - are characterized by a high degree of detail in the specification of technologies, e.g. including resource availability, costs, and related emissions. They are either simulation or optimization models (such as MARKAL). These models tend to arrive at the lowest estimates of the costs of mitigation.

A third category is *(macro)econometric models*, which represent better than the bottom-up models the wider impacts on the economy of climate policies. They are fitted to historic time-series data on the economy and usually have simplified assumptions on technologies and technology innovation.

The MARKAL model which is used in the scenario analyses of “Climate 2050” is an example of a bottom-up model which includes a large amount of country- and time specific technology data. It covers the energy system, and in some applications also the transport sector.

The distinction between bottom-up and top-down models is becoming less clear as the models are developed to encompass elements from each other.

Integrated Assessment Models (IAM) assess the costs of climate protection by considering both the economic and biophysical systems as well as the interactions between them. IAMs combine elements of biophysical and economic systems into one integrated system. The models are able to determine the economic costs of different constraints on CO₂ emissions. IAMs have been used in the analyses carried out by the IPCC.

Modelling outputs

The outputs provided by different models differ substantially and the modelling approach therefore has to be clearly stated whenever results of model runs are presented and comparisons made across different models.

Key outputs of climate-economy models include:

- Emission reductions compared to the baseline scenario and base year
- The relative contribution to emission reductions from different sectors and gases.
- The relative contribution to emission reduction by increased energy efficiency, changes in energy supply, and demand reduction/product substitution

- The relative contribution to emission reductions from international trade in emission allowances.
- Other outputs regarding e.g.: leakage and spillovers; ancillary benefits of emission reductions; capital movements; distributional effects, etc.
- Economic and/or financial costs of emission reductions compared to the baseline scenario

The economic consequences of emission reductions may again be expressed in different ways, including e.g.:

- The additional costs in one single year (e.g. 2050) compared to the baseline scenario, possibly expressed in % of GDP.
- The total additional costs throughout the period analyzed, possibly discounted to a present value and compared to discounted GDP.
- Marginal abatements costs, i.e. the cost of the last and most expensive abatement option.
- Rebound effects, e.g. on fuel prices due to reduced fuel demand
- Effects on competitiveness and resulting changes in capital movements and trends in exports and imports of energy commodities and manufactured goods. The resulting “leakage” of emissions.
- Possible first-mover advantages of ambitious climate targets.
- Distributional effects, both intra-national and international
- Ancillary, non-GHG benefits of emission reductions

Technology development and abatement costs

The extent of long-term emission reductions - and the costs of achieving them - will depend heavily on the expected pace of technology development in the years to come. This fact poses challenges for estimation of modelled future costs of emission reductions.

This section provides a brief introduction to the theoretical underpinnings regarding policies and measures in relation to technology development.

Induced Technological Change (ITC)

Induced technological change refers to the *additional* technological change that takes place as a result of climate policy implementation, i.e. beyond the technological change in a baseline scenario without these policies.

From R&D to market

The below figure is provided for illustrative purposes (adapted from Foxon). It provides an integrated perspective of the process of bringing new technologies to the market. Policy measures can be applied throughout the process with the emphasis being on “technology push” measures in the early stages of the innovation chain.

Induced technological change is usually described as taking place through two different avenues:

One is incentives for additions *Research and Development (R&D)*, and the other is stimulating market development and deployment of the technologies, thereby reducing costs through “*learning-by-doing*”.

Two externalities: The rationale for policy action to promote technology development

A significant level of uncertainty is associated with ITC. The results of both R&D and technology learning are uncertain (as are also many of the relationships between emissions and the climate). It is thus not possible to calculate accurately the economic costs and benefits of ITC policies.

However, there are two major justifications for policies to support ITC which are based on economic theory, namely two market failures:

1. The knowledge externality or spillover benefits to society from R&D investments by individual firms.
2. The existence of negative externalities that are not taken into account in the market prices for products and activities leading to GHG emissions.

The knowledge externality means that innovation and invention by one firm spills over to other firms without the investing firm being able to reap the benefits from this spillover. Part of the benefit from technology development will spill over to others who are able to imitate or further elaborate upon the innovation (also termed the “standing on shoulders” effect). As with any positive externality, this means that without government intervention, the private investment in R&D is likely to be *less* than socially optimal.

An additional cause of underinvestment in climate-friendly technology R&D is uncertainty about future policies and regulation. Uncertainty adds to the risk of investments in climate-friendly technology development and can have significant impact on the costs of achieving reductions. Conversely, announcing policy measures in advance can thus contribute to reducing costs. The unpredictability of the future international climate regime and national policies thus strengthens the case for government intervention to support R&D in climate-friendly technologies.

It should be noted that other factors will counteract the undersupply of R&D. Firstly, competition may encourage firms to duplicate R&D efforts (termed “stepping on toes”), thus wasting resources. Secondly, the R&D may be aimed at “rent seeking” by creating competitive advantage through a marginal improvement in existing products, thus reducing competition.

There is general agreement that the combined effect of the above factors with regard to R&D is that there is a net undersupply of R&D in the absence of government intervention. Studies have found the social return to R&D to be two to four times as high as the private return.

Policies and measures that induce technological change

It is a considerable challenge for governments to design and implement policies that simultaneously address emission reduction policies and technology development.

The existence of dual market failures calls for two types of policies to achieve least-cost emission reductions.

- Firstly, direct emission reduction policies such as an emissions trading scheme or a CO₂ tax provides an incentive to internalize external costs of GHG emissions.
- Secondly, support for R&D addresses the inability of firms to capture all the returns of investments in technology development.

One of the approaches to correcting the R&D market failure is to grant patents to innovators, thus granting them exclusive rights to the innovation (but at the expense of competition).

Another policy measure is to subsidise research, thereby decreasing the cost of innovation¹. The *design* of support measures for R&D is a difficult challenge which will have to consider possible fraud and mismanagement

Finally, some of the R&D would have been undertaken even in the absence of the support. Subsidised R&D may to some extent crowd out other research, thus representing a smaller net addition to R&D activities than suggested by the amount of support.

Induced technological change and the timing of emission reductions

The presence of induced technological change may influence the optimum emission pathway in two directions. If the ITC effects are mainly a result of R&D, some benefits may derive from postponing emission reductions and thus gain from technological advances made in the meantime. If learning through market deployment is the main cause of cost reductions, early abatement will tend to reduce the costs through technology learning.

Technological change in climate modelling

The extent to which technological change is incorporated in modelling of future emission reductions and the way this is done have a very significant impact on the expected costs of achieving reductions. As seen in the section on the review of the Overview Study #2: “Endogenous Technological Change and the Economics of Atmospheric Stabilisation”, the combined effect of choice of model and inclusion of technological development has a huge impact on the modelling results.

Models that ignore the potential for cost reductions from technological development will tend to overstate abatement costs. A recent EU study “Ex-post estimates of costs to business of EU environmental legislation” (IVM 2006) concludes that predicted costs of EU environmental legislation are often overestimated compared to the actual costs incurred, and a main reason for this is a failure to include factors contributing to cost reductions:

- Unanticipated substitution options
- Technological innovation
- Learning curve effects.

¹ For a national government, the benefits of doing this is somewhat reduced by the existence of international spillovers - the fact that part of the benefits from innovation will accrue to firms in other countries. This effect is less for larger countries and regions such as EU.

Other factors that explain differences in ex-ante and ex-post cost estimates include differences in the concepts of costs and the construction of the counterfactual baseline scenario.

The international climate regime and abatement costs

Another key driver in determining not only the level of emissions in the future but also the costs of achieving emission reductions is the international framework, or “climate regime”.

The consequences and costs of achieving 60-80% reductions in the Nordic countries depend on the international regime in several ways:

- A comprehensive regime with strong global efforts among many other countries and regions will increase the positive spillovers from technology development and will thus tend to reduce reduction costs for the Nordic countries compared to a scenario with more limited participation.
- A comprehensive regime with strong global efforts will also reduce the negative effects of competitive distortions vis-à-vis countries without similar obligations.
- Conversely, a lax regime with opportunities to trade cheap project emission reductions may reduce the need for expensive domestic reductions.

The international climate regime will also influence the emission pathway, which in turn has an effect on when reduction measures are undertaken and the costs of doing so. For example, strong early commitments will mean that higher costs are incurred in the short term, but will also increase the pace of technology development and dissemination.

Selection of studies for review

Selection of studies

A large number of publications have been screened for the purpose of identifying the most relevant studies for further review.

The screening process has resulted in the selection of studies within three categories:

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:

- The selection of assumptions and parameters
- The modelling approach
- Comparison of outputs of scenario runs.

Overview studies

As a very large number of individual studies have by now been carried out in different contexts, providing an overview of the results of these is in itself a time-consuming endeavour beyond the scope of this review.

Fortunately, 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 this 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.

Criteria for selection of studies

The selection of studies - in particular the key studies - has been based on a number of criteria:

- They should be comprehensive in scope and preferably cover a range of technologies and sectors.
- They should be based on recent data and projections
- Their geographical coverage should be relevant, i.e. preferably EU and the Nordic Countries
- They should provide information on assumptions and parameters regarding baseline and scenarios
- They should include output with regard to both energy, emissions and economics
- They should cover a relevant timeframe, i.e. include long-term mitigation.

Studies selected for review

On the basis on the above criteria, the following studies have been selected for the review:

Key studies

Key Study #1: Climate change and a European low-carbon energy system
In 2005, the European Environment Agency released the report “Climate Change and a European low-carbon energy system” describing model simulations of especially the European energy use in presence of significant reduction requirements from 2000 to 2030. This study has been singled out as a Key Study because it is the most recent comprehensive analysis of long-term emission reductions in the European context.

It builds upon a number of previously undertaken analyses carried out for the European Commission and the EEA, some of which have been reviewed as well in order to assess more detailed background data. Among these studies are:

- Bates et al (2004): SoEOR2005: Greenhouse gas emission projections and costs 1990-2030. EEA-ETC/ACC. 2004/1 (non-CO2 GHGs).
- Criqui et al (2003): Greenhouse gases reduction pathways in the UNFCCC process up to 2025;
- Mantzos et al (2003): European energy and transport: trends to 2030. European Commission.
- Commission of the European Communities (2005): Winning the Battle against Global Climate Change

Key Study #2: Our energy future - creating a low carbon economy + Options for a low carbon future

As part of the preparation of the UK government's Energy White Paper "Our energy future - creating a low carbon economy" in 2003, a comprehensive modelling effort was undertaken using the MARKAL energy model. These modelling results are reported in "Options for a low carbon future", which was published in 2003. The UK studies are relevant as they address issues similar to the present study: The possibility of achieving emission reductions by 2050 and the costs associated with such emissions. The two studies are closely linked to the Overview Study #1: "Options for a Low Carbon Future: Review of Modelling Activities and an Update" (see below).

Key Study #3: Energy Technology Perspectives

The IEA publication (2006) demonstrates how energy technologies can make a difference in a series of global energy and emission scenarios to 2050. As such, it provides important input for the parameters to be used in the MARKAL modelling for the Nordic countries.

The report reviews in detail the status and prospects of key energy technologies in electricity generation, buildings, industry and transport. It also assesses ways the world can enhance energy security and contain growth in CO₂ emissions by using a portfolio of current and emerging technologies.

Overview studies

Overview Study #1: Options for a Low Carbon Future: Review of Modelling Activities and an Update

The study was published in 2005 as a follow-up to the analyses carried out in connection with the 2003 UK Energy White Paper (Key Study #1). The main part of the study provides a summary of findings from other global and national CO₂ mitigation cost modelling studies. The report also summarises the the modelling work undertaken for the 2003 Energy White Paper (see Key Study #2).

Overview Study #2: Endogenous Technological Change and the Economics of Atmospheric Stabilisation (Energy Journal Special Issue)

The Special Issue of the Energy Journal is the primary output of the "Innovation Modelling Comparison Project". The project focuses on the incorporation of innovation and technology development in modelling of long-term emission reductions. It aims to "open the black box" of endogenous innovation to scrutiny by comparing the results from different applied modelling approaches.

Overview Study #3: The costs of greenhouse gas abatement: a meta-analysis of post-SRES mitigation scenarios

Economic analyses have produced widely differing estimates of the economic implications of policies for greenhouse gas (GHG) mitigation ranging from high costs to modest benefits.

In assessments of the costs of GHG emissions, both the characteristics of the models applied and the assumptions adopted play an important role in the modelling results. The paper is relevant because it not only presents a range of results from international modelling efforts, but also analyses the extent to which the model results for the global costs of GHG mitigation can be explained by the model characteristics and the assumptions.

*Nordic studies*²

Nordic study #1: Analysis and Evaluation of the Triptych 6 - case Finland
The study provides an operationalization of one of the proposed designs of a future international climate regime - the "Triptych". The corresponding long-term emission reduction pathways are analysed for Finland based on a number of assumptions and parameters. The study is particularly interesting to review because of its explicit consideration of the international climate regime.

Nordic study #2: The NORDLEDEN project – Final report from phase II, 2003 (PROFU)

The project was an extensive Nordic research project focusing on climate- and energy-policy issues. The project dealt with several strategic and political questions that affect the short- and long-term development of the energy system and its impact on the environment. The project used 3 energy models, including the MARKAL-NORDIC, to analyse the energy sector development until 2050. The project was carried out in two phases, namely 1996-2000 and 2000-2003.

² An major Norwegian study was published on October 4, 2006. The study was conducted by the Commission on Low Emissions "Lavutslippsutvalget" (NOU 2006: 18). Due to the timing of the publication, the study has not been considered for inclusion in this literature review.

Key Study findings

The studies have been reviewed taking into consideration a number of different aspects, including sector aspects (energy, transport and non-CO₂) and estimated costs. The main findings are briefly presented below.

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 indications of costs and the associated emission reductions.

Table 4.1 Cost indication in selected studies

Study	Model	Cost indication	Emission reduction target	Coverage of cost indication
Key Study #1 EEA	PRIMES, POLES and others	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
Key Study #2 DTI	MARKAL	MAC: 80-400 EUR/t CO ₂ GDP: <1%	45-70% of 2000 emission	UK
Key Study #3 IEA	ETP-MARKAL	CO ₂ Price: 25 - 40 \$/t 0.1% of world GDP	Stabilisation of global emissions in 2050 at 1990 level (30% OECD reduction)	World
Overview Study # 1 Stanford EMF ECN	Different plus MARKAL	Costs: 0.19-0.8% reduced annual consumer and producer surplus (MARKAL 2100)	CO ₂ content 550PPM	EU 15 plus Norway, Switzerland and Iceland
Overview Study # 2 Energy Journal special edition	Different models	MAC: 30-70 \$/t CO ₂ Costs: 0.5% of Global GDP, but extremes scenarios up to 6%	CO ₂ content: 450-500-550 PPM	World

Findings and explanations

Modelling techniques

Interpretation of the above listed results must be made with care. One meta analysis of studies shows that 70% of the variation can be explained by a few model attributes and assumptions made. In addition to the CO₂ reduction target compared to the baseline (the more ambitious the more expensive) and the number of years to reach the target (the shorter the more expensive) the explanatory factors are the following, ordered by the degree to which their inclusion contributes to explaining differences:

1. The choice of model. CGE models consistently tend to give lower costs than time-series macroeconomic models.
2. The assumed use of carbon tax revenues
3. The inclusion of non-climate related environmental benefits
4. The inclusion of international emissions trading
5. The availability of a constant-cost backstop-technology in the model
6. The inclusion of avoided climate-change damages in the model
7. Whether the model allows for product substitution

In summary, the worst case results come from using a macroeconomic model with lump-sum recycling of revenues, no emission permit trading, no environmental benefits in the model and no backstop technology.

Energy supply (with Carbon Capture and Sequestration)

A key assumption of any study of abatement options and the associated costs is the relative price of coal compared to oil and in particular compared to natural gas, as fuel switch from coal to natural gas play an important role.

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 could be limited, provided that adequate substitutes exist (such as e.g. sufficiently cheap CCS technology).

All three key studies conclude that especially wind power is an important source for reductions in CO₂ emissions. However, the baseline wind power deployment is low in the three studies³.

In several studies, CCS is expected to become an important source of emission reductions. It is also noteworthy that some studies point out that

³ In a Nordic context where large deployment of wind power is already present, the further expansion of wind power will raise issues about the intermittency of wind power in the Nordic electricity system.

the absence of both CCS and nuclear expansion may lead to much larger costs or smaller reductions.

Energy demand and efficiency

Energy efficiency measures are considered a cheap reduction option in all three key 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.

Transport

The key results for the definition of the baseline scenario are that 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 is expected to remain as the main source of motive power in 2050, predominantly still running on petrol and diesel. Furthermore the use of hybrids will increase. Oil products account for the largest share of the energy demand from the transport sector, and synthetic fuel from coal and gas is also expected to take an important share. There are varying views on the time scale in which hydrogen could be introduced. The results show that hydrogen fuel cell vehicles most like will show (virtually) no market penetration in the baseline scenario as it remains too costly.

Important findings relevant for the definition of the emission reduction scenario(s) are that the demand for transport services is regarded as being rather insensitive to increased costs of transports and that modal shift effects are very small. In most scenarios, CO₂ reductions in the transport sector are obtained through increased use of biofuels and improved energy efficiency. However, technological improvements in terms of energy efficiency improvements also accelerate when there is a strong international emission reduction effort. Fuel efficiency could improve by around 40%. In most scenarios hydrogen fuel cells show virtually no market penetration

Other sources and sinks

Other sources and sinks present opportunities to reduce GHG emissions across sectors and over time that could be cost-effective. In Key Study #1, which is the main source of information for Other Sources and Sinks,

the definition of the baseline scenario is based on a bottom up technology approach. Separate figures for the Nordic countries are reported, and may be used for this study in order to estimate baseline emissions until 2030 and beyond. However, baseline emissions are reported only for broad categories of non-energy CO₂ and non-CO₂ GHGs. This makes it difficult to extend the time horizon to 2050 on the basis of changes in underlying activities. This also complicates the estimation of costs and emissions reductions in a consistent way, without recurring to a careful (and time consuming) inspection of a large number of primary data sources.

With respect to the GHG emissions reductions and their costs, we note that Non-CO₂ GHGs entail low cost options for reducing emissions, F-gases appear to have a particularly large potential for GHG reductions. For sinks, a considerable potential exists, but the estimates are highly uncertain. Assessing the reduction costs is complicated due to the fact that the emission sources are very dispersed, and the assessment of emissions reductions and costs depend on source by source estimates.

Key Study #1: Climate change and a European low-carbon energy system

General/crosscutting

The report by European Environment Agency “Climate Change and a European low-carbon energy system” (ELCES) describes model simulations of especially the European energy use in presence of significant reduction requirements from 2000 to 2030. The report builds upon a number of previously undertaken analyses carried out for the European Commission and the EEA.

The report presents an assessment of possible greenhouse gas emission reduction pathways made feasible by global action and a transition to a low-carbon energy system in Europe by 2030. It analyses trends and projections for emissions of greenhouse gases and the development of underlying trends in the energy sector. It also describes the actions that could bring about the transition to a low-carbon energy system in the most cost-effective way.

Baseline assumptions and emissions

The baseline assumptions for the EU are based on the assumption that current EU policies are implemented. Examples of policies that are included are initiatives to improve air quality in New Member States.

Since the point of departure is the PRIMES baseline from 2003, policies to comply with the Kyoto Protocol such as the EU ETS are *not* included in the baseline. This means that the total emissions in 2010 are 2.3% lower than in 1990, but that CO₂ emissions from energy rise by 19% in EU 15 and 14% in EU 25. In the baseline scenario, total they are projected to rise steadily and be 8% above 1990 levels by 2030.

Population is expected to be stable and decline in the later stages. EUROSTAT historical data and projections are used for the population. UN projections are used for household size

The baseline scenario is a “modestly optimistic” economic growth scenario. According to (Mantzios et al., 2003), GDP growth in EU-15 reaches 2.3% pa on average in 2000-2030. In EU-10, GDP growth is 3.5% in 2000-2030.

This means that gradual convergence of the EU economies is assumed to continue, although by 2030, per capita GDP in EU-10 remains more than 30% lower compared to the EU-15.

Structural changes of the economies continue throughout the projection period, involving:

- Restructuring away of primary and secondary sectors and towards services
- Dematerialisation of industrial production as a result of increasing importance of new industrial activities with high value added and a lower material base (e.g. pharmaceuticals; computer equipment etc.)

Weather conditions in 2000 are maintained throughout the projection horizon.

Total EU GHG emissions and sinks under baseline assumptions

	1990	2000	2020	2030	1990–2020	1990–2030
EU-25						
CO ₂ (Energy)	3 769	3 665	4 041	4 304	7.2 %	14 %
CO ₂ (Non-energy)	133	131	145	147	9.1 %	10 %
CH ₄	535	419	410	376	– 23 %	– 30 %
N ₂ O	459	403	397	382	– 14 %	– 17 %
F-gases	48	61	144	150	200 %	210 %
Sinks	0	0	0	0		
Total	4 945	4 680	5 140	5 360	3.9 %	8.4 %
EU-15						
CO ₂ (Energy)	3 082	3 118	3 444	3 669	12 %	19 %
CO ₂ (Non-energy)	110	112	122	122	10 %	11 %
CH ₄	414	335	325	300	– 22 %	– 28 %
N ₂ O	409	350	339	327	– 17 %	– 20 %
F-gases	46	58	131	137	180 %	190 %
Sinks	0	0	0	0		
Total	4 062	3 970	4 360	4 550	7.3 %	12 %

Reduction scenario parameters and assumptions

The global context for the reduction scenarios is a global emissions pathway to achieve a GHG concentration of 550 ppm CO₂-equivalent. This reflects the EU long-term target for global temperature increases of no more than 2° Celcius above pre-industrial levels.

The EU Environment Council has signalled that to achieve stabilisation in an equitable manner, developed countries should reduce emissions to about 15–30 % below the 1990 level by 2020 and to 60–80 % below by 2050.

In the light of this, the report analyses a number of *Low Carbon Energy Pathway* (LCEP) scenarios, which assume EU emission reduction targets of:

- 20 % below the 1990 level by 2020
- 40 % below by 2030, and
- 65 % below by 2050.

A “Climate Action” core scenario with a number of variants was developed for the study, with 2030 as the time horizon. Global energy scenarios were developed reaching to 2050.

Scenarios include policies and measures to reduce all six Kyoto Protocol gases. Achieving a low-carbon energy system requires further measures in addition to a carbon price, including the removal of potentially environmentally harmful subsidies; setting targets for renewables and energy efficiency; and increases in R&D and awareness-raising

In the core reduction scenario, cost-effectiveness of measures alone determine development. In other scenarios, a high share of RE is ensured through a RE premium on top of the permit price. Another noteworthy aspect of the assumptions is that CCS has not been part of the detailed European model analysis.

Reduction scenario outputs

The climate action scenario shows that by domestic actions alone, based on a carbon permit price of EUR 65/t CO₂, the EU could reduce its greenhouse gas emissions to 16–25 % below the 1990 level by 2030. Thus a substantial share of the reductions needed to achieve the assumed target of 40 % by 2030 could be achieved by actions inside the EU, with international emissions trading providing the remaining reductions.

The relative share in emission reductions from different sources

Reductions in the *energy intensity* of the economy are expected to account for almost half of the emission reduction in 2010. Towards 2030, their contribution will decrease, requiring a shift of effort to further long-term changes in fuel mix, mostly in the power generation sector.

Substantial low-cost emission reductions are projected in the climate action scenario for nitrous oxide and methane emissions from industry, waste management and agriculture. However these options will have been almost fully exploited by 2030 (see section 5.6).

Substantial changes in the EU energy system are projected, leading to energy-related emissions of CO₂ (the most important greenhouse gas) in 2030 that are 11 % below the 1990 level, compared with 14 % above in the baseline scenario. A reduction to 21 % below 1990 levels would require the permit price to more than double by 2030.

Towards 2030, more than 70 % of the CO₂ emission reductions (in the climate action scenario compared with the baseline) are expected to be realised in the power generation sector, mostly as a result of a shift to low or non-carbon fuels.

Considerable reductions in CO₂ emissions are projected for the industry, services and household sectors, mainly from fuel switch in industry and efficiency improvements in heating, electrical appliances and lighting.

CO₂ emissions from *transport* are projected to continue to grow in all climate action scenario variants (to 25–58 % above the 1990 level by 2030), because of the steady increase in passenger and freight demand (see section 5.5).

Abatement costs

The additional annual costs of the climate action scenario compared with the baseline scenario are projected to be about EUR 100 billion by 2030. This would represent about 0.6 % of EU GDP, which is projected to double between 2000 and 2030.

For the *industrial sector*, the additional costs by 2030 represent on average about 1.6 % of the value added by the sector, with different costs for subsectors. For the *services sector*, the additional costs by 2030 represent about 0.2 % of the value added by the sector. For *households*, the additional costs by 2030 would be relatively small, about EUR 110–120 per household, compared with an increase in energy costs, under baseline assumptions, of EUR 1,900/household in the EU-15 and EUR 3,400 in the EU-10 by 2030.

A low-carbon energy system is expected to result in additional benefits, including ancillary environmental benefits, enhanced security of supply, and potential beneficial effects for employment. The EEA has published a separate report on ancillary benefits for air quality “Air quality and ancillary benefits of climate change policies”. For details, see table 4.3, p.35.

Modelling methodologies applied

A number of different modelling methodologies are behind the results of the study.

The European baseline is based on the PRIMES model and the study “European energy and transport Trends to 2030” (Mantzou et al., 2003). PRIMES is a partial equilibrium model for the EU energy system covering EU Member States, EU accession countries and neighbouring countries.

The global baseline is based on:

- a. the POLES model and the calculations made for the EU report “Greenhouse gases reduction pathways in the UNFCCC process up to 2025. (Criqui 2003) and
- b. Regional costs and benefits of alternative post Kyoto climate regimes (van Vuuren et.al, 2003).

Emissions of non-CO₂ GHGs, sinks and process emissions are based on the study “SoEOR2005: Greenhouse gas emission projections and costs 1990–2030” (Bates et al, 2004), which applies the IMAGE and TIMER models

Energy supply (with Carbon Capture and Sequestration)

Baseline assumptions and emissions

The baseline emissions of CO₂ from the energy sector are stated in fact box A.

Fact box A: Baseline emissions

CO ₂ emissions from energy production (mt CO ₂ /year)				
	1990	2000	2020	2030
EU15	3,082	3,118	3,444	3,699
EU10	687	547	597	635
EU25	3,769	3,665	4,041	4,304

Source: ELCES, table 4.1, pp. 30

The most relevant information about the energy system characteristics assumptions is presented in fact box B.

Fact box B: Energy system characteristics

* The baseline EU25 use of CHP is 16.3% in 2030, up from 12.6 % in 2000. (p. 46)

* The baseline EU25 efficiency of thermal electricity production is 48.7% in 2030 (p.46)

* The baseline EU25 electricity generation increases with 52% between 2000 and 2030 (p.47)

* The baseline EU25 share of renewable electricity is 14.6% in 2000 and 18.2% in 2030 (p. 49); the increase is mainly driven by wind power

* The EU25 nuclear capacity falls from 140.3GW to 108GW in the baseline scenario; sensitivity analyses are between 71GW and 209 GW (p. 51)

* EU25 Nuclear electricity share falls from 31.8% to 17.4% (p. 51)

* The crude oil price is 30 and 35 Euro/barrel in 2020 and 2030 respectively. The EU25 natural gas price is 10.8 Eurocent/m³ in 2000, 14.5 in 2020 and 16.0 in 2030. (p. 62)

Further, the available relevant information about CCS is presented in fact box.C. CCS is however not a part of the ELCES simulations.

Fact box C: Carbon Capture and Sequestration assumptions

* The efficiency loss from carbon capture of coal based electricity generation is 12 percentage points for existing plants, and 4 percentage points from future fuel cells.

* The potential for storage is 500 Mt in Danish depleted oil and gas fields, and 10,200 Mt in depleted Norwegian fields. Further 10,800 Mt is available in Norwegian closed deep saline aquifers. In less leak-safe open deep saline aquifers 476 Gt is available in Norway.

Reduction scenario parameters and assumptions

There are no changes in the assumptions about the energy technology developments between the baseline and the reduction scenarios.

Reduction scenario outputs

One very important source of emission reductions in the ELCES study is *improvements in energy efficiency*, especially before 2030. In the baseline scenario, gross inland consumption of energy increases with 19% while it increases with only 10% in the reduction scenario.

A major part of the energy efficiency improvement is found in *the energy supply sector*, in particular electricity generation through fossil fuels. The overall efficiency of thermal production increases from 48.7% to 50.6% in the reduction scenario. This is caused by shifts to more efficient generation technologies. An increase in the share of CHP generated electricity from 12.6% to 16.3% also helps increasing energy efficiency.

However, the most important source of emission reductions is the *fuel mix*, as electricity production shifts away from coal and to other sources. More than 70% of the CO₂ emission reductions in 2030 occur in the power generation sector, despite the fact that the reduction scenario's electricity consumption is only slightly below that of the baseline scenario.

Regarding *nuclear power*, three different scenarios are presented. The core reduction scenario is based on the EU25 countries' present policies of continuation, expansion or decommissioning of nuclear power. In the phase-out scenario, CO₂ emissions are 3 pct. higher, while a scenario with accelerated nuclear investments has 3.5% lower emissions of CO₂.

Fact box D: Reduction scenario outputs

A comprehensive overview of the reactions of the EU25 energy system to the reduction requirements are given in table 5.1 in the ELCES report. The table describes 2030 emissions by sector, energy use, fuel mix, final energy consumption, electricity generation, shares of nuclear and renewable electricity, CHP penetration, efficiency, carbon intensity and import dependency. Table 5.2 in the ELCES report describes improvements in final energy intensity, and table 5.3 describes the use of CHP.

Energy demand and efficiency

Baseline assumptions and emissions

Final energy consumption is projected to increase by 30% between 2000 and 2030 in the baseline scenario, equivalent to 0.87% p.a. This is substantially less than the growth in GDP and consumption and thus leads to a decline in the energy intensity of final energy consumption. This decline is expected to come from the implementation of several EU energy conservation policies.

The baseline improvement in final energy intensity is stated in fact box D.

Fact box D: Baseline emissions

Change in final energy intensity 1990-2030	
	Change 1990-2030
Industry	-49 %
Households	-48 %
Services	-42 %
Transport	-33 %

Source: Climate Change and a European low-carbon energy system, table 5.2, p. 45

Reduction scenario parameters and assumptions

There are no changes in the assumptions about the energy demand and efficiency between the baseline and the reduction scenarios.

Reduction scenario outputs

A modest part of the reduction in gross inland consumption in the reduction scenario is caused by improvements in *final energy consumption*: households and services reduce their energy demand by 8-10% due to more efficient lighting, heating and cooling and better appliances. Industrial production efficiency improvements are more modest.

Transport:

Baseline assumptions and emissions

From 1990 to 2000, transport related CO₂-emissions in the EU-25 increased by 21.8% equivalent to an annual growth rate of 1.99%.

In the *baseline scenario*, CO₂-emissions from transport is projected to increase by 30% between 2000 and 2030 or 0.88% p.a.

This implies that transport will account for an increasing share of CO₂-emissions in EU-25, as total emissions are projected to increase more slowly, namely by 14% from 2000 to 2030 under the baseline assumptions.

Reduction scenario parameters and assumptions

Reductions in emissions from the transport sector can be obtained through (a combination of):

1. Improvement of the energy intensity of the sector⁴, e.g. by increasing the energy efficiency on the demand and supply side or by lower demand.
2. Switching from fossil fuels to fuels with a lower carbon content.
3. Increasing the share of non-fossil fuels (e.g. biofuels) and technologies.

The more specific factors which could contribute to lower CO₂-emissions from road transport (which account for 80% of transport final energy consumption in 2030) are presented and shortly discussed in the table below.

⁴ Final energy consumption per unit of GDP, value added or private consumption.

Table 5.1 Factors which specifically could contribute to lower CO₂-emissions from road transport

Category	Element	Comment
Engines	Improvements to internal combustion engines, including advanced fuel injection systems, and downsizing. <i>Hybrid vehicles</i> , which have an internal combustion engine used in combination with an electric motor. <i>Fuel cell vehicles</i> , which have a dedicated electric motor.	See p. 55 for overview on e.g. cost of motoring, time scale, vehicle emissions and refuelling of infrastructure. <i>Time scale: Short, 2005-</i> See p. 55 for overview on e.g. cost of motoring, time scale, vehicle emissions and refuelling of infrastructure. <i>Time scale: Short and medium, 2005-2003</i> See p. 55 for overview on e.g. cost of motoring, time scale, vehicle emissions and refuelling of infrastructure. <i>Time scale: Long, Post 2030</i>
Fuels	<i>Hydrogen for fuel cells</i> from one of a wide range of possible sources. <i>Biofuels</i> , including alcohols made out of starch crops and diesel made from oilseeds as well as advanced fuels based on the gasification of biomass.	It is assumed that the use of liquefied hydrogen in transport reaches a share of 0.15% both in the baseline and the LCEP scenarios. (see p. 55 for overview) <i>Time scale: Short and medium, 2005-2030</i> The market share of renewables on the demand side reaches 10.3 % in the renewables expanded variant and 5–5.5 % in the other LCEP variants compared with 4.5 % in the baseline scenario. Most of the growth occurs in rising quantities of biofuels mixed in petrol and diesel fuel. However, while expanding the growth of biomass for energy purposes in agricultural and forestry areas, attention should be given to conflicting land use, in particular to nature conservation requirements (see pp. 50 and 55 for overview) <i>Time scale: Long, Post 2030</i>
Modal shift		The effect is low in all scenarios (see pp. 56).

Additional information on the transport sector is presented in the fact box below.

Fact box 5.1 Additional key data on the transport sector

Average fuel consumption of private cars/trucks in the baseline scenario decreases by 35% / 20% in 2030 compared to 1990.

Average fuel consumption of private cars/trucks is 37% / 24% below 1990 levels in the LCEP scenario

Aviation shows a drastic decrease of 19 % in final energy consumption between the baseline and LCEP scenarios in 2030, due both to lower transport activity (a reduction of 4.4 %) and a substantial improvement in efficiency.

Reduction scenario outputs

The CO₂-emissions from transport in EU-25 in relevant scenarios and the costs of passenger and freight transport are summarised in the table below.

Table 5.2 CO₂-emissions from transport and cost of transport in EU-25 in relevant scenarios

Year/Scenario		CO ₂ emissions (mt CO ₂ /year)	Cost of passenger transport (€/per pkm)	Cost of freight transport (€/per tkm)
Historical /Baseline	1990	795	-	-
	2000	968	0.21	0.27
	Baseline 2020		0.22	0.3
	Baseline 2030	1258	0.24	0.32
Scenarios (2030)	LCEP	1164	0.25	0.32
	Renewables expanded	990	0.25	0.32
	Nuclear accelerated	1167	0.25	0.32
	Nuclear phase-out	1167	0.25	0.32

Source: Table 5.1 and Table 6.3

Under the Low Carbon Energy Pathway scenario, CO₂-emissions from transport will only be marginally lower compared to the baseline scenario, reflecting a low 'elasticity' of the transport sector (how much it is flexible and can shift to low or zero-carbon fuels and more efficient technologies or reduce energy demand).

The main reason for this is the rapid increase in passenger and freight demand and the difficulty in replacing fossil fuels on which the transport sector is almost totally dependent (except for biofuels in the renewables expanded variant).

The *renewables expanded scenario* only results in a marginal increase in emissions from the transport sector from 2000 to 2030. This is achieved by tax regulation in the transport sector.

Emissions from transport under the '*nuclear*' scenarios are only slightly lower compared to the baseline scenario.

Despite the fact that all scenarios result in higher CO₂-emissions from the transport sector in 2030, it is projected that the final energy intensity⁵ will decrease by 5 percentage points as a response to the introduction of a carbon permit price (see table below). The reduction is mainly the consequence of reductions in road transport fuel use.

Table 5.3 Improvements in final energy intensity in the transport sector in EU-25

Year/Scenario		Final energy intensity (index 1990=100)
Historical emissions/Baseline	1990	100
	Baseline 2030	67
Scenarios (2030)	Core LCEP	62
	Renewables expanded	62
	Nuclear accelerated	62
	Nuclear phase-out	62

Source: Table 5.1, p. 41

⁵ See page 55 for a discussion.

Other sources and sinks:

The treatment of other sources and sinks in Key Study #1 is based on the detailed report by Bates et al. (2004). In the report, other sources include:

- non-energy CO₂ emissions (i.e., CO₂ emissions not related to the consumption of fossil fuels for energy production),
- non-CO₂ greenhouse gases (i.e., methane, nitrous oxide, and fluorinated gases).

Carbon sinks include land use change and forestry activities. There are two types of activities:

- afforestation, reforestation and deforestation (ARD),
- forest management, management of crop and grazing lands, and revegetation.

ARD activities can be used for CO₂ emissions reductions under the Kyoto Protocol (Article 3.3). Member states of the EU are therefore obliged to report sinks related to ARD activities under the first commitment period (2008-2012). Other activities (Article 3.4) can be included on a voluntary basis during the first commitment period, but their inclusion would subsequently be mandatory.

Baseline assumptions and emissions

Non-energy CO₂ emissions

The non-energy CO₂ emissions stem from sources not related directly to the combustion of fossil fuels. In the case of cement production, limestone is converted by a chemical process, where carbon dioxide is released. This chemical reaction accounts for about 0,5 ton of CO₂ per ton of cement produced, and 0,85 ton of CO₂ per ton of lime produced, following the IPCC (1997) guidelines. Other process related emissions of CO₂ stem from the production of iron, steel and aluminium. However, since these emissions originate from the fuel supplied as raw material, they are included in the energy balance of the PRIMES model. To avoid double counting, they are not included among the non-energy CO₂ emissions in the ELCES study.

Cement and lime production

The CO₂ emissions from cement and lime production in the baseline scenario are shown in the table below. Production figures were obtained from the RAINS WEB (2003) model, on the basis of input data from PRIMES.

Table 5.4 Non-energy CO2 emissions (Mt/year) from cement and lime production.

	1990	2000	2010	2020	2030	1990-2030
EU-15	110	112	120	122	122	11%
EU-10	23	19	22	23	25	9%
EU-25	133	131	142	145	147	11%
Europe-30	160	159	179	194	210	31%
Nordic countries	5	4	5	5	5	0%

Source: Bates et al. (2004), Tables 38-41.

CO2 emissions from cement and lime production are expected to increase by 31% from 1990 to 2030 in Europe-30 in the baseline scenario. A large part of this increase is due to an expected growth in the cement production in Turkey. No increase is expected in the Nordic countries.

Non-CO2 GHGs in the baseline scenario

The non-CO2 GHG emissions (methane, nitrous oxide, and fluorinated gases) are estimated from a bottom up technology assessment of gases from major industrial sectors, agriculture, transport and waste. Emissions are calculated by means of the recommended methodology (IPCC, 1997, 2000), where activities are multiplied with an emission factor to obtain total emissions in a given year. The projections are based on expected changes in these activities (and/or the emission factors) until 2030. Table 5.5 and Table 5.6 below illustrate the parameters and assumptions used in the study by Bates et al. (2004) for methane (CH4) and for nitrous oxide (N2O), respectively.

Table 5.5 Baseline parameters and assumptions for methane (CH4).

Source	Methane baseline parameters and assumptions	
	Activity	Emissions factor
Agriculture: • Enteric fermentation • Manure management	Livestock numbers (dairy cattle, non-dairy cattle, poultry, sheep, goats, horses)	Emissions per dairy cow allowed an increase of 1,5% p.a. due to changes in yield
	Projections based on CAFÉ RAINS baseline version 2 (RAINS WEB, 2003)	IPCC guidelines (IPCC, 1997, 2000) and UNFCCC national reports
Waste: • Landfill	Quantity of municipal solid waste (MSW) accumulated (2% p.a. 1920-1990) Growth in quantity of MSW generated according to PRIMES Degradable fractions from EEA-European Topic Centre on Waste (fractions include compliance with EU Landfill Directive)	First order decay model for accumulated emissions (Bates and Haworth, 2001) Weighted average emission factor per tonne MSW (IPCC, 2000) Landfill gas recovery (flaring or energy production) is subtracted from emissions
Industry (fugitive emissions): • Coal • Oil and gas	Coal, oil and gas production, and gas distribution Projections based on LREM-E (PRIMES) scenario for sector study (Hendriks and de Jager, 2001)	Source distribution based on IEA (1997) Relative emission factors unchanged over time (Hendriks and de Jager, 2001, App. 2)
Energy and transport	Energy use from transport based on an aggregate fuel/ sector split (IPCC, 1997) Projections of energy use based on LREM-E and SEP (PRIMES) scenarios	Emission factors from IPCC (1997), updated for LPG and natural gas vehicles

Table 5.6 Baseline parameters and assumptions for nitrous oxide (N₂O).

Source	Nitrous oxide baseline parameters and assumptions	
	Activity	Emissions factor
Agriculture: • Nitrogen fertilizers (soil)	Livestock numbers (dairy cattle, non-dairy cattle, poultry, sheep, goats, horses) Projections based on CAFÉ RAINS baseline version 2 (RAINS WEB, 2003)	Emissions determined from data on crops of cereals and pulses (EU-ROSTAT) Projections based on future changes in the production of cereals (Bruinsma, 2003) and pulses (FAPRI, 2003) IPCC guidelines (IPCC, 1997, 2000) and UNFCCC national reports
Industry: • Adipic acid production • Nitric acid production	Data from GHG inventories in national communications to UNFCCC Nitric acid production assumed to grow with fertilizer consumption in agriculture	Adipic acid emissions assumed to grow 1,75% p.a. (IEA, 2003)
Energy and transport	Energy use from transport based on an aggregate fuel/ sector split (IPCC, 1997) Projections of energy use based on LREM-E and SEP (PRIMES) scenarios Assessment of cars with catalytic converters (EEA TERM Indicator Fact Sheet)	Emission factors from IPCC (1997), updated for LPG and natural gas vehicles Emission factors for cars with catalytic converters assumed to be reduced in the future (Bates et al., 2001)

F-gases

The fluorinated gases (so-called F-gases) comprise hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF₆). Estimates of these gases were obtained for the following sectors (Bates et al., 2004):

- HFCs from use in refrigeration and air conditioning, mobile air conditioning, metered dose inhalers, aerosols, solvents, foams, and fire fighting applications;
- PFCs from use in fire fighting applications, aluminium production, and semiconductor manufacture;
- SF₆ from use in magnesium production, electrical transmission and distribution, manufacture and use of gas insulated switchgear.

Estimates for 1990 and 2000 are based on national communications to the UNFCCC. These totals were subsequently disaggregated to derive sectoral estimates based on the data given for the country grouping in IEA (2003). The projected sectoral emissions from IEA (2003) were used to calculate emissions for 2010 and 2020. For 2030 no projections were available, and so for this year emissions were scaled from the 2020 figures, based on projected GDP changes for each country. Generally, estimates of the F-gases are scarce in many countries. A pragmatic approach was therefore applied with respect to these gases.

Global warming potentials (GWPs)

The non-CO₂ GHGs are converted to CO₂ equivalents by means of global warming potentials (GWPs) defined by IPCC (1995). These GWPs are used for emissions up to 2010 to allow for a comparison with the targets of the Kyoto Protocol. Revised estimates of GWPs by IPCC (2001) are used to calculate emissions for 2020 and 2030, in order to give a more accurate picture of future emission levels (Bates et al., 2004, Table 1.1). The adjustment of the GWPs leads to an increase by 9 percent in the emissions of CO₂ equivalents from methane, and a decrease by 5 percent in the CO₂ equivalent emissions of nitrous oxide. In the case of the F-gases, the CO₂ equivalent emissions are adjusted upward with 19 percent for PFCs, and downward with 7 percent for SF₆.

Projections of non-CO₂ GHG emissions

The projections of methane and nitrous oxide emissions to 2030 are based, for the most part, on an update of the study by Blok et al. (2001), which is extended beyond the EU-15. Following the baseline parameters and assumptions identified above, the emissions of methane and nitrous oxide are disaggregated by source for EU-15 in Table 5.7.

Table 5.7 CH₄ and N₂O emissions (Mt CO₂ equivalent/year) in EU-15 by source

	1990	2000	2010	2020	2030	1990-2030
Methane (CH₄)						
Enteric fermentation	144	132	135	138	127	-12%
Manure management	45	45	47	50	49	9%
Landfill	111	82	70	58	47	-58%
Fugitive emissions: coal	49	19	11	9	8	-83%
Fugitive emissions: oil & gas	33	28	36	39	39	19%
Energy and transport	32	29	28	30	29	-9%
Total	414	335	327	325	300	-28%
Nitrous oxide (N₂O)						
Agriculture	215	203	206	193	180	-16%
Chemical industry	106	50	53	53	51	-52%
Energy and transport	88	97	99	93	95	8%
Total	409	350	358	339	327	-20%

Source: Bates et al. (2004), Tables 4.8, 4.10, 4.12, 4.13, and 4.14 for methane, and Tables 4.16 and 4.18 for nitrous monoxide.

Projections of methane

For methane a steady decline in baseline emissions is expected from 1990 to 2030 in the EU-15. This is mainly due to an expected reduction in the number of animals in agriculture, and to the effects of the EU Landfill Directive that makes the recovery of methane at new landfill sites mandatory. Fugitive emissions from coal are also expected to decline, as the production from deep coal mines continue to fall in the UK and Germany. By contrast, oil and gas production is expected to rise until 2020, and then level off. For the Nordic countries (Norway in particular), the ten-

dency for total emissions of methane is reversed, as shown in Table 5.8, and the total emissions of methane are expected to rise until 2030.

Projections of nitrous oxide

The emissions of nitrous oxide are expected to fall in the baseline scenario for the EU-15 in 2030, compared with the 1990 level. This is partly due to a decline in the consumption of nitrogen fertilizers in agriculture, partly due to reductions of emissions in the chemical industry (adipic acid manufacturers). However, up to 2010, emissions slowly rise due to an increase in the use of nitrogen fertilizers, and an increasing number of catalytic converters in cars. From 2010 onwards, the emissions tend to fall. This pattern is also found in the baseline scenario of the Nordic countries, reported below in Table 5.8.

Table 5.8 Non-CO₂ GHG emissions (Mt CO₂ equivalent/year) in the baseline scenario by region.

	1990	2000	2010	2020	2030	1990-2030
Methane (CH₄)						
EU-15	414	335	327	325	300	-28%
EU-10	121	84	87	85	76	-37%
EU-25	535	419	414	410	376	-30%
Nordic countries	25	24	29	30	30	20%
Nitrous oxide (N₂O)						
EU-15	409	350	358	339	327	-20%
EU-10	51	53	58	58	56	10%
EU-25	460	403	416	397	383	-17%
Nordic countries	33	31	32	28	28	-15%
F-gases (HFCs, PFCs, SF₆)						
EU-15	46	58	96	131	137	198%
EU-10	51	53	58	58	56	10%
EU-25	97	111	154	189	193	99%
Nordic countries	6	5	7	11	11	83%

Source: Bates et al. (2004), Tables 38-41.

Projections of F-gases

For the F-gases in the EU-15, a significant increase in CO₂ equivalent emissions is expected. Since the early 1990s, the emissions of HFCs have increased rapidly, as they have replaced the use of ozone depleting substances in a variety of applications. PFC emissions are expected to increase throughout the period from 2000 to 2030. This is mainly due to an increased use in fire fighting systems and in aluminium production. The amount of PFCs used in semi-conductor manufacture is also expected to increase. Emissions of SF₆ is expected to increase as well, as cover gas for magnesium production, but only some time between 2010 and 2020. The overall pattern of emissions of F-gases in the EU-15 is reproduced in the Nordic countries, although the increase in total emissions is less significant, as shown in Table 5.8.

Carbon sinks and projections

Carbon sinks are reported in the study by Bates et al. (2004) for both article 3.3 and 3.4 under the Kyoto Protocol. However, since these sinks and their changes are assumed to be a function of human activities, they are all related to the reduction scenarios. Sinks in the baseline scenario are therefore by definition set at zero over the entire period.

Total baseline emissions

The total emissions from all sources in the baseline scenario are shown in the below table for the Nordic countries. Total emissions, including CO₂, are expected to increase by 25 percent from 1990 to 2030. The largest contribution to this increase comes from the emissions of F-gases, CO₂ and methane. Over the entire period, emissions from other sources and sinks are about 25 percent of total emissions in the baseline scenario, although this share is expected to decline a little. Among the Nordic countries, the most significant contribution to the increase in the baseline emissions come from Sweden and Norway, while the total emissions from Denmark are even expected to decline.

Table 5.9 Total baseline emissions (Mt CO₂ equivalent/year) for the Nordic countries.

	1990	2000	2010	2020	2030	1990-2030
Nordic countries						
Denmark	71	70	64	62	63	-11%
Finland	68	68	66	71	73	7%
Norway	46	48	62	63	62	35%
Sweden	70	65	72	86	120	71%
Greenhouse gases						
CO ₂	186	187	191	208	245	32%
Non-energy CO ₂	5	4	5	5	5	0%
CH ₄	25	24	29	30	29	16%
N ₂ O	33	31	32	28	28	-15%
F-gases	6	5	7	11	11	83%
Sinks	0	0	0	0	0	0%
Total	255	251	264	282	318	25%
Other sources in % of total	27%	25%	28%	26%	23%	

Source: Bates et al. (2004), Tables 38-41.

Reduction scenario parameters and assumptions

CO₂ equivalent reductions and prices

Mitigation options were identified for non-energy CO₂ emissions (cement and lime), non-CO₂ GHGs, and sinks. No reductions were estimated for energy and transport. Similarly, the reductions of non-energy CO₂ and non-CO₂ GHG emissions that would follow from CO₂ emission reductions in the energy and transport sectors were not included. The costs were estimated using a discount rate of 4%. The lower cost options are assumed to be implemented first. Given the estimated costs, emis-

sions reductions were obtained by selecting the options with a cost below the following thresholds (Bates et al., 2004; EEA, 2005):

- 12 EUR/tCO₂ equivalent in 2010
- 30 EUR/tCO₂ equivalent in 2020
- 65 EUR/tCO₂ equivalent in 2030

Ambitious reduction scenario

The thresholds were obtained by an iterative process, where CO₂ permit prices were adjusted to the assumptions that (i) the Kyoto Protocol will be successfully implemented, and (ii) permit prices in the global FAIR model would be chosen such that a Sustainable Emission Pathway (SEP) scenario emerges. This scenario is referred to as a Climate Action scenario in the main report (EEA, 2005). The scenario includes the objective of limiting global GHG emission concentrations to 550 ppm CO₂ equivalent.

Observations about emission reductions and costs

An important point should be emphasized. First, the ambitious (SEP) reduction scenario is assumed to involve compliance with the Kyoto Protocol in the near term future. Compliance with the Protocol is not part of the baseline scenario. Emissions in the baseline scenario are therefore larger than they otherwise would have been, if full compliance with the Protocol had been assumed. This leads to the observation that, in order to reach a given CO₂ stabilization target, larger emissions reductions are needed in the study by Bates et al. (2004). The total costs of reaching the target are therefore also larger in this study. The observation is important, because the baseline scenario for the Nordic countries will be assumed to comply with the Kyoto Protocol. Total emissions reductions and costs will therefore not be directly comparable between the two studies. However, depending on the approach used for estimating the cost of GHG reductions in the Nordic countries (e.g., bottom up technologies and costs), the costs of specific options and reductions would still be comparable.

CH₄ and N₂O emission reductions and costs

For methane a number of low cost options are available to reduce the emissions. The reductions stem primarily from sources in agriculture and industry. Options applied in these sectors contribute to a moderate reduction of GHGs, compared with the baseline scenario. Similarly, for nitrous oxide low abatement costs, mainly in agriculture and the chemical industry (adipic and nitric acid production), contribute to reductions of GHGs. The reduction parameters and assumptions are described in more detail in Table 5.10 and Table 5.11 below. Note that the parameters for estimating emission reductions correspond to the activities reported in the baseline

scenario. Following this approach, emission reductions and their costs are calculated on the basis of changes in underlying activities (e.g., number of cattle, tonne of manure, tonne of waste). References to more detailed studies are included following Bates et al. (2004).

Table 5.10 Reduction parameters and assumptions for methane (CH₄).

Source	Methane reductions	
	Emission reductions	Reduction cost
Agriculture: • Enteric fermentation • Manure management	Dairy and other cattle (food digestion, food intake and genetics, more lactations, increased level of malate): Δ emissions/animal 2-10% Sheep (vaccination): Δ emissions/animal 10% Stable adaptation (manure): Δ emissions/tonne n.a. Heat and power production (manure): Δ emissions/tonne n.a.	All options also improve the productivity of the animals and are assumed to have no net cost (Bates, 2001 and ECCP, 2002) Cost based on other sheep vaccinations (12 EUR/tCO ₂) No cost assumed from reductions of ammonia Cost from heat and power prod. (-7 to 187 EUR/tCO ₂)
Waste: • Landfill	Reduction of waste to landfill (beyond EU Directive): Δ emissions/tonne n.a. Recovery of LFG: Δ emissions/tonne n.a. Reduced methane venting through capping: Δ emissions/tonne n.a. Total reductions beyond the EU Landfill Directive only from 2020 to 2030	Cost of waste mitigation options (Bates and Haworth, 2001): Paper recycling (-150 EUR/tCO ₂) Incineration (60 EUR/tCO ₂) Composting (61 EUR/tCO ₂) Improved capping (25 EUR/tCO ₂)
Industry (fugitive emissions): • Coal • Oil and gas	Emission reductions derived from EMF-21 study, applied separately to each sector by region	Cost curves from EMF-21 study (Weyant and Chesnaye, 2006)

Low cost reductions of methane

Among the activities that contribute to reducing emissions of methane, the following measures appear to be most cost-effective (including negative cost):

- recovery and use of methane in mines
- reduction of fugitive emissions in oil production
- reduction of emissions from cattle through more lactations
- reduction of emissions from manure through heat and power production

In the waste sector there are also several cost-effective measures, including some with net savings. However, these measures are assumed to be implemented with the EU Landfill Directive in the baseline scenario.

Table 5.11 Reduction parameters and assumptions for nitrous oxide (N₂O).

Source	Nitrous oxide reductions	
	Emission reductions	Reduction cost
Agriculture: • Nitrogen fertilizers • Manure management	Improvement in fertilizer use (Δ nitrogen consumption 10%):	Net savings (negative cost) estimated by Bates (2001)
	Enhanced spreader maintenance	Higher cost estimated by ECCP (2002)
	Fertilizer free zones	Cost of package assumed to be 0.
	Precision farming	
	Nitrogen optimization	
	Retention from EU set-aside (Δ nitrogen/ha 50kg):	
Industry: • Adipic acid production • Nitric acid production	Set-aside area in EU-15 unchanged from 2001	
	End of pipe technologies applied in chemical industry:	Cost at adipic acid plants (0,19 EUR/tCO ₂)
	Adipic acid production: Δ emissions 95%	Cost at nitric acid plants (0,54 EUR/tCO ₂)
	Nitric acid production: Δ emissions 80%	

Low cost reductions of nitrous oxide

For nitrous oxide there are no net savings associated with the emission reductions, but low cost measures are available for the following activities:

- Adipic and nitric acid production
- Improved fertilizer use in agriculture
- Continuation of EU set-aside of Common Agricultural Policy

F-gas emission reductions and costs

The options for reductions of F-gases are based on a study by Ecofys (2000), reported in Bates et al. 2004 (Table 4.20). The options include those with proven technologies and relatively robust cost estimates. It is assumed that reduction costs are the same across all countries. The options and their costs are described in Table 5.12.

Table 5.12 Reduction parameters and assumptions for F-gases (HFCs, PFCs, SF₆)

Source	F-gas reductions	
	Emission reduction fraction	Reduction cost
HFCs	Thermal oxidation: Δ emissions 95%	0,264 EUR/tCO ₂
	PU alternatives: Δ emissions 95%	17,82 EUR/tCO ₂
	XPS carbon dioxide: Δ emissions 100%	6,468 EUR/tCO ₂
	MAC leak reduction: Δ emissions 37%	7,788 EUR/tCO ₂
	Aerosol alternatives: Δ emissions 30%	12,804 EUR/tCO ₂
PFCs	AL SWPB conversion: Δ emissions 97%	-0,66 EUR/tCO ₂
	Semiconductor alternative chemistry: Δ emissions 8%	0 EUR/tCO ₂
SF ₆	SF ₆ Mg: Δ emissions 100%	0,396 EUR/tCO ₂
	SF ₆ GIS: Δ emissions 25%	4,752 EUR/tCO ₂

For the F-gases, a number of measures are available that could lead to significant emission reductions if widely implemented. An important part

of this observation is related to the fact that the F-gases have high global warming potentials. This makes emission reductions for these gases particularly interesting. The costs of the measures differ, although they are assumed to be constant across countries. For PFCs costs are assumed to be negative or zero.

Carbon sink potentials

Emission reductions from carbon sinks are estimated in relation to their potential for carbon sequestration. Sinks include land use change and forestry activities under the Kyoto Protocol (Article 3.3 and Article 3.4). To assess the potential for carbon sequestration, projections are made for each country of the future changes in land use activities under the two articles. The changes are based on data for long term growth rates in forest coverage (ECCP, 2003), and information found in national communications to the UNFCCC.

Cost of carbon sinks

Estimates of costs vary greatly, and so a range of high, low and middle values is presented. Estimates of the IPCC (Kauppi et al, 2001) are considered as a minimum, estimates of Graveland et al. (2002) a maximum, with estimates by McCarl and Schneider (2002) in between. Depending on the level of costs used in the analysis, the variation in the CO₂ permit price of the reduction scenario determines the amount of carbon sequestration that will be undertaken.

Reduction scenario outputs

Total GHG emissions in the reduction scenario

On the basis of the parameters and assumptions described above, the emission reductions of other sources and sinks are estimated by Bates et al. (2004). However, note that the information presented here by itself is insufficient for completing the calculations. This would require a more careful study of the underlying emission sources, following the references cited.

The total GHG emissions in the reduction scenario are shown in Table 5.13 for the Nordic countries. For the purpose of comparison, the CO₂ emissions are also included, together with the emissions from other sources and sinks.

Table 5.13 Total GHG emissions in the Nordic countries (Mt CO₂ equivalent/year) for the reduction scenario.

	1990	2000	2010	2020	2030	1990-2030
Nordic countries						
Denmark	71	70	61	55	54	-24%
Finland	68	68	59	59	51	-25%
Norway	46	48	56	58	52	13%
Sweden	70	65	68	74	68	-3%
Greenhouse gases						
CO ₂	186	187	183	190	177	-5%
Non-energy CO ₂	5	4	5	5	5	0%
CH ₄	25	24	27	27	25	0%
N ₂ O	33	31	28	26	26	-21%
F-gases	6	5	5	5	6	0%
Sinks	0	0	-4	-7	-14	n.a.
Total	255	251	244	246	225	-12%

Total GHG emission reductions

The total emission reductions are obtained as the difference between the baseline and the reduction scenarios. The reductions are shown in Table 5.14.

Table 5.14 Total emission reductions from other sources and sinks (Mt CO₂ equivalent/year) in the Nordic countries.

	1990	2000	2010	2020	2030
Nordic countries					
Denmark	-	-	3	7	9
Finland	-	-	7	12	22
Norway	-	-	6	5	10
Sweden	-	-	4	12	52
Greenhouse gases					
CO ₂	-	-	8	18	68
Non-energy CO ₂	-	-	0	0	0
CH ₄	-	-	2	3	4
N ₂ O	-	-	4	2	2
F-gases	-	-	2	6	5
Sinks	-	-	4	7	14
Total	-	-	20	36	93

Average emission reduction costs

On the basis of the information reported in Bates et al. (2004), it is not possible to estimate the costs of the individual reduction measures applied in the analysis. This would require more detailed information on changes in the level of activities and their associated costs. Below we use an alternative approach, where average reduction costs are derived from the costs of reducing emissions at the source level. The costs of reducing emissions at this level are shown in Table 5.15 for the EU-15 derived from the data reported by Bates et al. (2004).

Table 5.15 Costs of emission reductions (EUR/tonne CO₂) for the EU-15.

	2010	2020	2030
Methane (CH₄)			
Enteric fermentation	0,00	1,67	1,31
Manure management	-17,36	-8,48	12,86
Landfill	-	-	2,23
Fugitive emissions: coal	1,98	1,82	1,85
Fugitive emissions: oil & gas	-3,28	3,52	8,16
Nitrous oxide (N₂O)			
Agriculture	0,00	0,00	0,00
Chemical industry	0,48	0,49	0,48
HFC	5,32	12,29	12,26
PFC	-0,65	-0,63	-0,63
SF ₆	1,02	0,65	0,65

Key Study #2: Our energy future - creating a low carbon economy + background study: Options for a low-carbon future

General/crosscutting

As part of the preparation of the UK government's Energy White Paper "Our energy future - creating a low carbon economy" in 2003, a comprehensive modelling effort was undertaken using the MARKAL energy model. These modelling results are reported in "Options for a low carbon future" (OLCF), which was published in 2003. The White Paper and the background study are closely linked to the Overview Study #1: "Options for a Low Carbon Future: Review of Modelling Activities and an Update" (see below).

Since the modelling is done with the bottom-up, technology-based MARKAL model, a number of assumptions have been made as input to the modelling exercise regarding costs, resources and emissions from a number of technologies have been made, including changes over time in these parameters.

Only CO₂ emissions from energy and transport are covered. It should be noted that the study was made before the recent oil/gas price rises.

Baseline assumptions and emissions

Three scenarios have been developed, which are in fact one core baseline scenario with two variants:

- The *Baseline Scenario* assumes the continuation of current trends in economic development and environmental policies. GDP growth is assumed to be 2.25% p.a.
- The *World Market* scenario assumes stronger globalization, limited environmental action and economic growth at 3% p.a.
- The *Global Sustainability* scenario assumes stronger international environmental action and an economic growth at 2.25% p.a.

The baseline scenarios have been derived from other analyses carried out by the British government. The scenarios reflect different assumptions about key drivers including:

- economic growth
- population and household growth
- service and manufacturing structure, and
- transport growth.

The scenarios reflect different assumptions about the balance of business activities between sectors (e.g. energy intensive industry and services), partly reflecting different assumptions about social preferences and life-style changes. For these reasons, the two variants *World Market* and *Global Sustainability* have the same GDP growth rates, but the latter has a slower growth in demand for energy services.

The baseline scenarios are essentially global, in that the world follows similar development paths as the UK. This i.a. implies that technology development and innovation is assumed to take place globally and to benefit from advances in design, engineering and production.

A characteristic feature of the baseline scenarios is that in all of them, CO₂-emissions are expected to *decline*, even in the absence of further emission constraints. This is the result of a combination of “autonomous” energy efficiency improvements on both demand and supply sides, as well as other factors such as fuel switching away from coal.

The below table from the study provides an overview of the energy service demand projections in the three variants of BaU scenarios:

Scenario Parameter	Baseline	World Markets	Global Sustainability	Source
Basis	Business as usual	Materialist social values	Social and ecological priorities	
Economic growth	2.25% (historic average)	3%	2.25%	Scenario concept
Population levels (2050)	65m	66m	63m	Scenario concept
Household numbers (2050: total, new)	30m, 8m	33m, 11.6m	28.6m, 6m	Scenario concept
Residential demand drivers: • Occupancy level (2050) • Max. Mean Internal Temp • Light/appliance ownership • Air con. ownership (2050)	2.17 21deg.C Increasing 10.5m	2.0 22deg.C Increasing faster 14.8m	2.2 21deg.C Increasing slower 7.1m	Calculated DEFRA MTP BSRIA/BRE
Service demand drivers: • Floor area (space heat & light), based on: – Sector output growth – Employees (2050 indexed to 2000, water heat & cooking) • Air con. use (2040 indexed to 2000) • Appliance use	 2.49% 1.27 4.02 1.90	 3.25% 1.33 4.93 2.20	 2.36% 1.19 3.02 1.64	 IEA & BRE BRE Avg end-use growth
Industrial demand drivers ¹⁾ : • Sub-sector growth • Relative plant efficiency	Refer to Annex A, Economic Working Paper No.4 for detail			DEFRA & ETSU/GAD
Transport demand drivers: Demand by mode:				
• Road (all modes ex bus)	Central case	Baseline x 1.2	Baseline x 0.9	NRTF
• Bus	Central case	As baseline	Car to bus shift (20% by 2050)	
• Rail: Passenger	4.2% to 2010, 2010-50 decline to 0%	As baseline	4.2% to 2010, then +30% per decade	DfT 10yr plan
• Rail: Freight	1% to 2010, 2010-50 decline to 0%	As baseline	1% to 2010, then +10% per decade	

Note: (1) Expected process efficiency improvements are included within Industrial energy service projections, as 'low carbon' substitution possibilities for most sub-sectors are limited

Reduction scenario parameters and assumptions

Reduction scenarios are calculated for each of the three baseline variants. The reduction scenarios modelled include emission constraints for 2030 and 2050.

For 2050, emission reductions compared to 1990 are calculated for three reduction levels: 45%, 60% and 70%.

Reduction scenario outputs

The cost of implementing the abatement scenarios (the additional annual energy system cost) is in the range of 0.3 - 2 % of GDP in 2050 with most estimates around 0.5 %. This figure is This equates to a reduction of between 0.01 and 0.02 percentage points in the average GDP growth rate over the period 2000-2050 (meaning that growth will be 2.23 or 2.24 compared to the baseline figure of 2.25).

The corresponding annual cost for 2030 ranges from zero to about 0.4% of GDP.

The marginal abatement costs per tonne CO₂ are in the range GBP 2-11 in 2030 and less than GBP 67 in 2050.

The cost calculations do not cover ancillary benefits from the actions undertaken to reduce emissions, such as improved security of supply, other environmental benefits and health benefits.

The MARKAL model only covers around 85% of energy-related emissions in 2000 as some areas of energy conversion and consumption are not covered, such as refinery operations, construction, and water transport. The costs of reducing emissions from these other sources are not included in the calculations. If abatement costs are similar for these other sources, the calculated costs would represent 85% of total abatement costs *for the energy sector*. Still, abatement costs related to other sectors and non-CO₂ gases are not included in this figure.

A key finding of the study is that early action reduces overall costs. Results of the modelling also show that assumptions about innovation rates are very important to the outcome. More successful innovation implies an increased diversity as more technologies are deployed. In scenario runs with limited innovation and cost reductions in new and existing low carbon technologies, costs are significantly higher than in baseline runs.

Given the cost assumptions made, a range of different technology options become economical and available to reduce emissions. The costs of many of the lower carbon technologies are fairly close. This means that modest changes in the expected costs for a given technology can imply significant changes in the future technology mix. The implication of this is that policies should avoid picking winners and that technological changes and costs of options should be reviewed regularly.

Sensitivity analyses

Core assumptions reflect significant cost reductions as a result of international technological advances, learning-by-doing and economies of scale. This together with the absence on supply limitations on natural gas contribute to keeping the abatement costs down.

Among the sensitivity analyses carried out were the effects of a number of upside risks that may increase the abatement costs.:

- Lower level on innovation in low-carbon technologies
- Limitations in the availability of natural gas
- Variations in the discount rates applied.
- Smaller than expected improvements in energy efficiency
- Exclusion of carbon sequestration and nuclear power

Modelling methodologies applied

The modelling has been carried out using the bottom-up, technology-based MARKAL model comprising both the energy and transport sectors.

The report “Options for a low-carbon future” presents the following schematic representation of the key features of the MARKAL model.

Energy supply (with CCS)

Baseline assumptions and emissions

The most notable feature of the baseline is a strong substitution from coal to gas in electricity generation. In 2000 app. one third of UK's electricity is generated from coal. This falls to app. 3% in 2050. Instead, highly efficient gas turbines generate app. 90% of U.K.'s electricity. The remaining 10% of the electricity supply is generated by hydro, wind, waste and biomass. It is assumed that nuclear generation is phased out.

A key feature driving the baseline's substitution away from coal is that the prices of gas and oil in the long term are expected to remain at the low levels present in the start of this decade (e.g. around 25 USD per barrel of oil).

Reduction scenario parameters and assumptions

A comparison of electricity generation costs is presented in the OLCF phase 1 report (table 8). It shows that electricity generation using natural gas is cheaper than using coal based technologies. Obviously this depends to a large extent on the relative price of coal and gas. A sensitivity test shows that an increase in the gas price of 35% by 2040 will make coal technologies competitive with gas.

Reduction scenario outputs

In the reduction scenarios, the very dominant gas technologies in the baseline are substituted with nuclear electricity generation, albeit with a smaller share of gas turbines (with 60 or 70% reduction, the gas installations are equipped with CCS). Also offshore wind and biomass plays a significant role in the electricity generation.

Energy demand and efficiency

Baseline assumptions and emissions

The final energy demand (which also includes transportation) falls slightly from app. 6,500 PJ in 2000 to just below 6,000 PJ in 2050. This 9% fall is driven by significant improvements in energy efficiency, almost counterbalanced by an increased demand for energy services (called useful energy demand).

In the domestic sector a new type of condensing boilers replaces traditional boilers (heating and hot water) leading to improvements around 30%. Further, new dwellings are more energy efficient, which will also lead to reductions in final energy demand, as will more efficient lighting and electrical appliances. The increase in useful energy demand is 54% from 2000 to 2050.

The industrial sectors show improved efficiency by using electronics and better process energy efficiency. Also a shift away from heavy industry brings down the energy intensity. The increase in useful energy demand is 17% from 2000 to 2050.

In the service sectors, better controls of heating and lighting as well as more efficient equipment improves efficiency. The increase in useful energy demand is 49% from 2000 to 2050.

It is assumed that the demand for useful energy in transport will increase with 65%. This increase in demand is met by improvements in transport energy efficiency.

Reduction scenario parameters and assumptions

The demand side efficiency measures are not explicitly described, but the report notes that the measures described in most research are potential short-term improvements, while longer term improvements are not researched very often.

Reduction scenario outputs

Further measures are socially and privately beneficial when constraints on GHG emissions are applied. Requiring a 60% cut in emissions (compared to the baseline) the final energy demand falls with 14%, while a 70% cut in total emissions leads to a final energy demand 20% smaller than the baseline final energy demand.

Transport:

Baseline and Reduction scenario parameters and assumptions

The table below shows the estimated *demand for energy services/useful energy demand*. It is important to realise the useful energy demands can be met by a variety of competing fuels, e.g. fossil fuels and biofuels.

Table 6.1 Useful energy demands in the transport sector (index, 2000=100)

Year	Baseline scenario	World markets scenario	Global sustainability scenario
2000	100	100	100
2010	118	122	112
2020	135	145	122
2030	148	165	127
2040	158	183	130
2050	165	198	129

Source: Table 1, pp. 17

The scenario demands for useful energy in transport were constructed assuming annual road transport growth rates would diminish due to road capacity constraints and saturation effects in car ownership.

Reduction scenario outputs

Under all three scenarios, total carbon emissions fall over the period from 2000 to 2050. Under the *Baseline scenario*, the fall is 22% and under the WM and GS scenarios emissions decline by 11% and 33% respectively. This equates to a fall in emissions intensity (carbon emissions per unit of GDP) of between 2.7% and 3.1% per year and compares to the average reduction over the last 30 years of 2.9% per year.

On the demand-side the largest improvements in energy efficiency are seen in the domestic and transport sectors.

In the transport sector, the internal combustion engine remains the main source of motive power under all scenarios, predominantly still running on either petrol or diesel. However, there are significant improvements in the efficiency of such vehicles, not least because diesel hybrids take a significant share of the bus and Heavy good vehicle (HGVs) market after 2020. A small amount of alternative fuelled vehicles

also penetrate the market, due to the favourable tax regime applied to the first 3% deployment of these fuels.

The scenario results show that the transport sector will undergo significant changes in the fuel mix and engine technologies, as carbon constraints are applied.

In 2030, major changes only occur under the most severe 70% carbon constraint, when hydrogen takes a 30% share of the fuel mix being used in fuel cell cars in place of petrol burnt in an internal combustion engine⁶.

In 2050, the introduction of hydrogen is more widespread across all abatement scenarios. In the Baseline scenario the uptake ranging from 11% of transport energy consumption with a 45% emission constraint rising to 66% with the 70% constraint (see pp. 30 for more details on the fuel mix).

HGVs as well as cars use hydrogen under the 60% and 70% emissions constraints on the Baseline scenarios. Under the WM scenario, the faster growth of GDP and hence transport demand, necessitates more drastic action to reduce emissions. Hydrogen is also used in buses and light goods vehicles (LGVs), and with a 70% constraint, this scenario is also the only one in which hydrogen aircraft are deployed.

The preferred route for producing hydrogen is with “shift” reactors fuelled with natural gas and fitted with carbon capture facilities. When natural gas supplies are limited in the model, hydrogen is produced by gasification of biomass. Hydrogen was never produced from electricity on the basis of the cost assumptions made.

The study shows that transport carbon savings are among the higher cost options. The estimates of costs per tonne of carbon saved in 2020 and 2050 are shown in the table below. As can be seen the cost estimates are highly uncertain. See pp. 168 for comparison to options.

Table 6.2 Costs per tonne carbon saved in 2020/2050 - Road transport (£/tC)

	2020		2050	
	Low	High	Low	High
Hybrids	140	400	50	270
Biofuels	220	680	-	-
Fuel cell vehicle, H2 from renewables	310	1190	50	830
Fuel cell vehicle, H2 from natural gas	540	5450	50	3670

Note: The biofuels figures above relate to current technologies for biodiesel and bioethanol production, mainly from oilseed rape, sugar or cereal crop materials. Future production from lignocellulosic material including coppice wood, and from waste, could have lower carbon cost. Carbon saving from hydrogen fuel cell vehicles is dependent on the availability and cost of non-fossil energy sources. Source: pp. 168.

⁶ See pp. 94/126/130 for a discussion on the sensitivity of deployment of hydrogen to infrastructure costs and pp. 102 for a discussion of the influence of transport fuel taxes.

The overall emissions from the transport sector under the group of scenarios are summarised in the table below.

Table 6.3 Emissions by scenario, (CO₂ emissions, MtC)

	Baseline scenario		-45%	-60%	-70%
			reduction	reduction	reduction
Year	2000	2050	2050	2050	2050
Total	132	102	72	53	40
From transport	34	37	30	14	11
Share of emissions from the transport sector	26%	36%	42%	26%	27%

Note: Reading from graph Source: pp. 27

The results shows that the share of CO₂-emissions from the transport sector decreases the more ambitious the reduction target is. This reflects that it is relatively expensive to reduce emissions from the transport sector compared to other options. Emissions from the transport sector are only reduced when the cheaper options are exploited.

Key Study #3: Energy Technology Perspectives

General/crosscutting

The publication by IEA is a response to international requests for alternative scenarios and strategies aimed at a “clean and secure” energy future. ETP presents the status and prospects for key energy technologies and assesses their potential to make a difference by 2050.

This is done by assessing how energy technologies can make a difference in a series of global scenarios to 2050. It reviews in detail the status and prospects of key energy technologies in electricity generation, buildings, industry and transport.

Five *Accelerated Technology Scenarios* are assessed and compared to a baseline. In addition, a sixth scenario - TECH Plus - assumes more optimistic assumptions on the rate of progress for renewable and nuclear electricity as well as for biofuels and hydrogen fuel cells in the transport sector.

Apart from the assumptions and scenario outputs briefly presented in the following, the study also gives a status and outlook on a number of technologies including among other costs and potential for cost reductions. An example of such information is Table 4.13 on page 232 including key cost and investment assumptions for renewables.

Baseline assumptions and emissions

The baseline scenario was developed by extending the World Energy Outlook 2005 to 2050 from the normal 2030 time horizon. The ETP baseline includes the effects of technology developments and improvements in energy efficiency that are expected based on policies already in place.

The baseline scenario and all reduction scenarios share the same macroeconomic assumptions. World economic growth is 2.9% per year throughout the period.

Further key features of the baseline scenario include the following:

- *Oil prices* are at USD 39 per barrel in 2030 and rise to USD 60 by 2050. In the reduction scenarios, prices respond to changes in demand and supply.
- Global CO₂ emissions in the baseline scenario are set to increase by two and a half times by 2050.

- Increasing transport demand will put continued pressure on oil supply.
- The carbon intensity of the world's economy will *increase* due to greater reliance on coal for power generation and an increased use of coal in the production of liquid transport fuels.
- In the Baseline Scenario, energy use more than doubles, with most of the growth in energy demand, and hence emissions, coming from developing countries.
- Coal demand in 2050 is almost three times higher than in 2003; gas demand increases by 138% and crude oil demand increases by 65%.

Reduction scenario parameters and assumptions

The Accelerated Technology (ACT) Scenarios do not imply that growth in *demand for energy services* is constrained in developed or developing countries.

The scenarios focus on technologies which exist today or which are likely to become commercially available in the next two decades.

The policies considered are identical across all five scenarios. The differences between scenarios have to do with assumptions about how quickly the cost of major technologies can be reduced and made widely available. Although the report emphasizes the need to accelerate investment in R&D, it does not quantify the amount of investment that would be needed for this.

A common CO₂ cost of USD 25 per tonne of CO₂ is applied across all reduction scenarios. This is equivalent to the existence of an incentive mechanism being put in place either nationally or internationally (e.g. in the form of a cap-and-trade scheme or a CO₂ tax).

A 5% discount rate is applied.

Reduction scenario outputs

The main changes in the scenarios compared to the baseline are:

- Strong energy efficiency gains in transport, industry and buildings
- Decarbonisation of electricity supply due to a shift toward nuclear, renewables, natural gas and coal with CCS
- Increased use of biofuels for transport

None of the technologies are expected, *once fully commercialized*, to have incremental costs above USD 25 per tonne of CO₂ avoided emissions. However, in order to reach this stage, there are significant *transitional costs* related to RD&D and deployment programmes to commercialise the technologies and achieve the cost reductions, i.a. through the learning that takes place with increased accumulated production.

The below table shows the total CO₂ emissions in the baseline scenario compared with the core reduction scenario (named “Map”). The figures are for OECD and the world.

In the Map scenario,

CO₂ emission in baseline and core reduction scenario (“Map”)

	Baseline 1990 (Mt CO ₂)	Baseline 2050 (Mt CO ₂)	Core scenario (ACT Map) 2050 (Mt CO ₂)
OECD	12,969	21,949	8,772
World	24,532	58,022	25,968

Global CO₂ emissions in the baseline scenario increase by 136% over 1990, whereas the Map scenario emissions are 6% above 1990 levels.

For the OECD countries, baseline emission growth is 69%, whereas the Map scenario represents a reduction of 32% over 1990 emissions. As a result, the share of OECD countries in global emissions decreases from 53% in 1990 to 34% and 38% in the baseline and Map scenarios, respectively.

Further key messages from the scenario runs are that technologies do exist which can contribute significantly to emission reductions over the next 10 to 50 years. At the same time, no single technology can make a sufficient contribution on its own, meaning that pursuing a *portfolio* of technologies will be required to reduce the risk and costs of achieving the emission targets.

Effects on prices of energy sources are included in the calculations and show that the world market price of oil will be lower compared to the baseline scenario, as reduced demand will put less pressure on more expensive supply options.

Energy efficiency plays a very important role in the achievement of emission reductions. EE improvement from industry, buildings and transport contribute between 45% and 53% of emission reductions.

The net discounted costs of the electricity system in the reduction scenarios differ from those in the baseline. When comparing the Map Scenario with the baseline, it turns out that shifts in the distribution of costs occur.

- Net investment needs for electricity supply are USD 0.3 trillion *lower* in the Map scenario
- Demand-side investments are USD 1.8 trillion *higher* in the Map scenario
- Discounted fuel savings are USD 1.4 trillion.

The net additional costs of the Map scenario are thus a relatively modest USD 100 billion, illustrating that additional costs are to a large extent transitional.

Policies and measures to achieve targets

The focus of the report is not on the policies and measures required to make the scenarios materialize, but the policy implications are briefly addressed, and the major efforts are identified as:

- Overcoming barriers to commercialization, e.g. by addressing information barriers, imposing regulations and standards, and applying financial incentives.
- Increase funding resources for energy-related R&D, which have been declining over the past decade. This applies both to private and public sector R&D and is essential for technologies that need to reduce costs before they become commercial.
- Supporting the transition from R&D to deployment. This phase can be expensive, but is nevertheless essential (see the figure in Section 2.4.2). The measures include *demonstration programmes* and *deployment programmes*⁷. A number of new technologies are already in the market and more will appear. Even the ones with a large potential will need government support in order to achieve full commercialisation and benefit from the cost reductions associated with technology learning as deployment grows.
- CO₂ reduction incentives. In addition to emissions trading schemes, these may take the form of regulation, pricing, tax breaks, voluntary programmes, or subsidies.

These initiatives require government intervention that creates a supportive and stable policy environment. The means may be both fiscal and regulatory.

Modelling methodologies applied

The ETP-MARKAL is used for the calculations. It is a global model with a de-tailed coverage of the energy system, covering about 1,000 individual technologies.

The model is part of the MARKAL family and as such uses the approach of cost-optimisation to identify least-cost energy technology and fuel mixes to meet energy service demand. For the report, ETP-MARKAL has been supplemented with demand-side models for all major end-uses. The demand-side models take into account capital-stock turnover.

⁷ An example is given for CCS technology, where 10-15 demonstration plants over the next 10-15 years would have an incremental investment cost of USD 250-500 million each.

Energy supply (with CCS)

Baseline assumptions and emissions

For key baseline assumptions, refer to section 7.1.1 above.

Reduction scenario parameters and assumptions

In the ACT scenarios, the differences in assumptions are reflected in the following areas:

- The progress in cost reductions for renewable electricity generation.
- Constraints on the development of nuclear power
- The risk that CCs will not be commercialised by 2050, and
- The adoption of energy efficient end-use technologies.

The five ACT scenarios are:

The *ACT Map scenario* which is relatively optimistic in all the four technology areas mentioned above. Its assumptions are realistic in the light of the current knowledge of the technologies and historic experience with technological progress. However, significant uncertainties surround each of the four areas identified. The other scenarios are mapped against the results of this scenario.

The *ACT Low Renewable scenario* explores the impact of slower cost reductions for wind and solar energy technologies. In this scenario, costs decline more slowly than in the ACT Map scenario.

The *ACT Low Nuclear scenario* reflects the limited growth potential of nuclear if public acceptance remains low, nuclear waste issues are not satisfactorily addressed and non-proliferation issues remain significant.

The *ACT No CCS* scenario explores what would happen if the technological issues facing CCS are not solved and CCS technologies do not become commercially available.

The *ACT Low Efficiency scenario* assumes that energy-efficiency policies are less effective than in the Map scenario. Global average energy savings are 0.3% per year lower than in the Map scenario.

TECH Plus scenario

The ACT scenarios are based on an accelerated use of technologies that already exist or are under development, whereas the TECH Plus scenario is based on more optimistic assumptions on the rate of progress for renewable and nuclear electricity generation technologies, for advanced biofuels, and for hydrogen fuel cells. The TECH Plus scenario is to some extent speculative, in that it assumes more progress in overcoming technological barriers (cost-related and otherwise) than is considered likely in the ACT scenarios.

Technologies in use

The ACT scenarios and the TECH Plus scenario use a number of different technologies. It is suggested that coal and gas can continue to play an important role even in a CO₂ constrained world. Therefore, more efficient and cleaner gas and coal technologies together with renewables and nuclear power are important means in order to reduce CO₂ emissions.

The technology strategies used in the scenarios related to energy supply are:

Box 1 Technology strategies for a more sustainable energy future

Power generation from Fossil Fuels	Natural gas combined cycle Supercritical Steam Cycle (SCSC) and Ultra-Supercritical Steam Cycle (USCSC) Integrated Gasification Combined-cycle (IGCC) Fluidised Bed Combustion (FBC and PFBC) CO ₂ Capture and Storage Technologies (CCS)
Power generation from Renewables	Hydropower Geothermal Bioenergy Wind energy (on-shore and off-shore) Solar (PV) Ocean Energy (waves, tides, marine currents, thermal energy and salinity gradients)
Nuclear Power Generation	Nuclear fission: Generation III and III+ Nuclear fission: Generation IV

Reduction scenario outputs

The five ACT scenarios demonstrate that the use of technologies that already exist or are under development can return global energy-related CO₂-emission towards today's level by 2050.

CO₂-emission

Given the assumptions in the TECH Plus scenario, CO₂ emission could fall by about 16% below current level in 2050.

Box 2 Global CO₂ emission for all sectors, Gt CO

Baseline Scenario (OECD, Transition economies and Developing countries)		Map	Low Nuclear	Low Renewables	No CCS	Low efficiency	TECH Plus
2003	2050						2050
24.5	58.0	26.0	26.9	26.7	29.7	31.2	20.6
(9.9)*	(26.3)	7.3	(N/A)	(N/A)	(N/A)	(8.8)	(5.1)

* Numbers in brackets show the CO₂ emission share from electricity and heat plants

The CO₂ emission of 24.5 Gt in 2003 is a sum of 13 Gt for the OECD countries, 2.5 Gt for the Transition economies and 9 Gt for the Developing countries.

The significant changes in the ACT scenarios result from strong energy efficiency gains in transport, industry and buildings; from substan-

tial decarbonisation of electricity supply as the power generation mix shifts towards nuclear power, renewables, natural gas and coal with CO₂ Capture and Storage (CCS); and through increased use of biofuels for road transport. Despite, these changes, fossil fuels still supply between 66% and 71% of the world's energy in 2050.

CO₂ capture and storage accounts for between 20% and 28% of the CO₂ emissions reductions in the ACT scenarios (in the scenarios it is assumed to be available); fuel switching for between 11% and 16%; the use of renewables in power generation for between 5% and 16% and nuclear for between 2% and 10%.

Cost implication

Most of the technologies included in the ACT and TECH Plus Scenarios have higher upfront investment costs than incumbent technologies. However, many technologies offer cost savings on a life-cycle basis because of lower fuel or other variable costs.

The box below shows the cumulative increase in power generation investment in the Map scenario, 2005–2050, compared to the Baseline Scenario.

Box 3 Cumulative increase in power generation investments in the Map scenario, 2005 to 2050

Power plants	Additional investment cost (USD trillion)
Wind	3.6
Solar	0.9
Geothermal	1.1
Nuclear	1.4
CSS	0.9
Total additional investment in renewables, nuclear and CCS	7.9
Reduced investment in fossil fuel power plants	-4.5
- of which due to lower electricity demand	-2.9
Total	3.4

Apart from these costs, avoided investment in transmission and distribution networks due to lower demand and the wider use of distributed generation should be taken into consideration. Furthermore, the significant reduction in coal and gas use due to demand reductions and the increased use of renewables and nuclear is noteworthy.

As mentioned earlier, the additional *net discounted* costs in the MAP scenario compared to the Baseline Scenario are relatively small. This illustrates, to a large extent, that the additional costs in the ACT scenarios can be regarded as transitional, leading to significant economic as well as environmental and security benefits in the longer term.

Energy demand and efficiency

Baseline assumptions and emissions

In the Baseline scenario, energy use more than doubles from 2003 to 2050. Most of the growth comes from developing countries.

Reduction scenario parameters and assumptions

All the ACT scenarios and the TECH Plus scenario are based on the same macroeconomic assumptions as in the Baseline Scenario. World economic growth is 2.9% per year between 2003 and 2050. Per capita incomes grow by 2% per year on average, ranging from 1% per year in the Middle East to 4.3% per year in China.

Energy prices in each of the ACT and TECH Plus scenarios respond to changes in demand and supply in that scenario. The underlying demand for energy services is the same in all scenarios. Thus, the study does not consider scenarios for reducing the demand for energy services (such as by reducing indoor room temperatures etc.).

The technology strategies used in the scenarios related to energy demand and efficiency are:

Box 4 Key point - CO₂ reduction

Buildings and appliances	Building Envelope Measures Heating and Cooling Technologies District Heating and Cooling Systems Building Energy Management Systems Lighting Systems Electric Appliances Reducing Standby Losses Solar Heating and Cooling Biomass for Heating and Cooking
Industry	Cogeneration Technologies Motor Systems Steam Systems Enhanced Efficiency Based on Existing Technologies for Basic Materials Production Enhanced Efficiency Based on Process Innovation for Basic Materials Production Fuel Substitution in Basic-materials Production Materials and Product Efficiency Feedstock Substitution CO ₂ Capture and Storage in Industry

Reduction scenario outputs

Improved energy efficiency accounts for between 31% and 53% of the CO₂ emissions reductions in the ACT scenarios.

Box 5 Key point - CO₂ reduction

Energy efficiency plays the most important role in CO₂ emission reductions, accounting for up to 53% of total CO₂ emission reductions.

Transport:*Baseline assumptions and emissions*

Improving energy efficiency in the transport sector is of special importance, since it has the fastest growing emission profile and because finding carbon-free alternatives in the transport sector has proven to be a greater challenge than in e.g. power generation.

Part of the increase in global CO₂ emissions in the baseline reflects an expansion of coal-based transport fuel production. CO₂ emissions from transport in non-OECD countries are projected to increase by more than 300%, while the increase in OECD countries is around 50%.

In the Baseline scenario oil prices increase from USD 39 per barrel in 2030 (2004 prices) to USD 60 per barrel in 2050. This implies that transport fuels produced from coal and gas and coal will begin to play a larger role.

In the Baseline scenario, energy consumption in the transport sector increases by 136% between 2003 and 2050 or 1.84% p.a (pp. 74–76). Oil products account for 94% – of which Fischer Tropsch diesel (syn-gas) produced from coal and gas account for around one fourth. Bio-diesel and ethanol only contribute 3%. The rest is provided by gas, coal and electricity.

There are important reductions in the fuel intensity (e.g. l/km) of light duty vehicles (passenger cars and small trucks) in the Baseline scenario. In OECD regions, the average fuel intensity of the vehicle stock in 2050 is some 13% lower than it was in 2003.

The demand for liquid fuels (defined as including oil products, synfuels and biofuels) in the transport sector in the Baseline scenario is estimated to grow by 1.9% p.a. from 2003 to 2050.

Important: The transport sector covers road, rail, air and water transport as well as energy used for pipelines. However only technologies used in road transport are considered in the scenarios. Road transport accounts for around 80% of total transport demand (see footnote on pp. 87).

Reduction scenario parameters and assumptions

In the five *Accelerated Technology (ACT) scenarios* CO₂-emissions by 2050 return to current levels (2003). The ACT scenarios investigate the potential of energy technologies and best practices aimed at reducing

energy demand and emissions, and diversifying energy sources. The five ACT scenarios are defined on pp. 42.

One of the most interesting in relation to the developments in the transport section is the *ACT MAP scenario*, which represents a relatively optimistic technology outlook. For the transport sector this implies that (pp. 42):

- Biofuels become an increasingly viable alternative to petroleum products. New technologies such as ethanol from ligno-cellulosic feedstocks, increased crop yields and the increased feedstock availability due to agricultural sector restructuring all contribute to reduced costs for biofuels.
- Significant progress is made to reduce the costs of hydrogen fuel-cell vehicles (FCVs), but costs remain high and hydrogen makes only a minor contribution to the transport sector in this scenario.

The sixth scenario – *TECH Plus* – represents a more ambitious scenario where CO₂-emissions is reduced by 16% in 2050 compared to current levels. In this scenario hydrogen and biofuels accounts for 34% of total final transport energy demand in 2050 (returning primary oil demand in 2050 to about 2003 level). The *TECH Plus* scenario is defined on p. 43.

All scenarios are based on the same macroeconomic assumptions (see box 2.1). Energy prices however respond to the demand and supply of each scenario. In all scenarios the underlying demand for energy services is the same. Hence the consequences of e.g. restricting personal travel are not considered in the study.

Reduction scenario outputs

In the transport sector, biofuels and hydrogen fuel-cells offers – as mentioned – two of the few opportunities to reduce emissions.

In all of the *ACT scenarios*, the contribution to CO₂ emission reductions from increased use of biofuels in transport account is around 6%, while the contributions from hydrogen is negligible (see table below for details). In the *MAP* scenario total transport energy demand in 2050 is 17% lower compared to the Baseline scenario.

In the *TECH Plus* scenario, hydrogen and biofuels account provide 34% of total final transport energy demand in 2050 (returning primary oil demand in 2050 to about 2003 level). Hydrogen accounts for savings of 800Mt of CO₂, whereas the fuel-efficiency impact of using fuel cells corresponds to 700 Mt CO₂.

Energy demand in the transport sector is 7% lower than in the *ACT Map scenario* in 2050 due to more efficient fuel cell vehicles (i.e. 23% reduction compared to the Baseline scenario). It however has to be borne in mind that this requires major technological advances in hydrogen pro-

duction and storage as well as fuel cells, which will not be achieved without strong government support and technological breakthroughs.

Table 7.1 Shares of total CO₂ emission reductions in 2050 by contributing factor

Scenario	Increased use of biofuels in transport	Hydrogen and fuel cells in transport
ACT Map	5.6%	0%
ACT Low Nuclear	5.8%	0%
ACT Low renewables	5.7%	0%
ACT No CCS	6.4%	0%
ACT Low efficiency	6.0%	0%
TECH Plus	6.2%	4.1%

Source: Table 2.2, pp. 51

Well-to-wheels emission estimates are summarised in the table below. It can be seen that some biofuels offer very large CO₂ emission savings, but that there currently is a wide range.

Table 7.2 Well-to-wheel CO₂ emissions by fuel source in the transport sector, 2003

	Grams of CO ₂ per km
Petroleum gasoline	300
Petroleum diesel	220
GTL diesel	260
CTL diesel	460
CNG (compressed natural gas)	230
Biofuels	30–250

Source: Figure 2.32, pp. 88. Note: Reading from graph

IMPORTANT: See also pp. 262–328 for a discussion about “Road transport fuel options”, including a description on their potential for reducing CO₂.

World energy consumption in the transport sector is summarised in the table below. Absolute savings in the transport sector ranges from 5% to 23% compared to the Baseline scenario. In the ACT Map scenario absolute savings is 17% consisting of 20% reductions in OECD countries, 10% in transition economies and 16% in developing countries (source: pp. 77).

Table 7.3 World energy consumption in the transport sector by scenario

	Baseline Scenario		Scenario - 2050		
	2003	2050	Act Map	Low efficiency	TECH plus
Energy consumption (MToe)	1895	4472	3705	4232	3461
Difference from Baseline Scenario in 2050	-	-	-17%	-5%	-23%

Source: Table 2.7, pp. 76.

The figures on pp. 88 provide an overview of total energy use in the transport sector and the composition and figures on the global use of hydrogen and biofuels.

There are, as mentioned, important reductions in the fuel intensity (e.g. l/km) of light duty vehicles (passenger cars and small trucks). The table below summarises the estimates.

About 40% of the improved fuel intensity comes from improvements to the internal combustion engine (see figure 2.34, pp 92). The second most important factor is the use of hybrids, which contribute to 24% of the improved energy efficiency. In the baseline scenario, light and full hybrids each make up 10% of the light-duty vehicle stock in 2050. In the Map scenario, 85% of light duty vehicles on the road in 2050 are powered by a full (20%), mild (20%) or light (45%) hybrid powertrain (see pp. 139 for cost estimates for hybrids). 35% of the medium freight trucks and 75% of buses would have hybrid engines in the Map scenario.

Table 7.4 Fuels intensity of new light duty vehicles and stock - OECD

	New vehicles	Stock
Baseline - 2003	9.3	9.9
Baseline - 2050	8.0	8.3
ACT Map	5.7	5.9
TECH Plus	3.9	4.4

Source: Figure 2.33, pp. 91. Note: Reading from graph

See pp. 258 for historical developments in fuel intensity over time by country

Fact box

* The world liquid fuel and hydrogen supply by scenario is shown at pp. 69.

* Fuels for commercial aircraft are discussed at pp. 271

Brief review of overview studies

Overview study #1: Options for a Low Carbon Future: Review of Modelling Activities and an Update

General/crosscutting remarks

The study is divided into two sections:

- One section summarises the the modelling work undertaken for the 2003 Energy White Paper, which is covered by Key Study #2.
- The second - and main - part of the study provides a summary of findings from other global and national CO₂ mitigation cost modelling studies.
- Three specific studies reviewed in the report are briefly addressed below.

Stabilization wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies

In their article in *Science*, (Pacala 2004), Pacala and Socolow present approaches to reducing world carbon emissions by 7 gigatonnes (= 25.6 GtCO₂) by 2050 compared to a BAU baseline.

The emission reductions are broken down into seven 1 GtC “wedges”. This leads to an emissions trajectory consistent with CO₂ stablization at 500ppm by 2125. According to the authors, there are at least 15 options for wedges each of which are based on technologies that are already deployed on an industrial scale. The wedges highlighted in the overview study are:

- Improved vehicle fuel economy. Assuming four times as many cars on the road in 2054 (i.e. 2 billion cars), doubling of fuel efficiency would achieve one 1 GtC wedge. Hybrid vehicles would be one option for achieving this.
- More efficient buildings. Buildings account for about one-third of energy consumption, and there are known and established approaches to space heating/cooling, water heating and lighting.
- Substitution of natural gas for coal in power generation. As substitution of gas for coal in power generation roughly halves carbon emissions, a fourfold increase in the use of gas would add up to one wedge.
- Carbon capture and storage from fossil power plants

- CCS from plants that produce hydrogen for transport fuels
- CCS from plants that produce liquid fuels (synfuels) from coal. An existing example is the Sasol plant in South Africa.
- Renewable energy from e.g. wind and photovoltaics
- Biofuels to replace fossil fuels for transport
- Nuclear fission

EMF 19

An overview of results from the Stanford Energy Modelling Forum's study on technology and climate change policy (EMF 19) are presented in a paper by Weyant (Weyant 2004). The paper presents results from calculations carried out by a range of different models, comparing the global energy supply structure to the year 2100. A baseline scenario is contrasted with a 550ppm policy scenario. Four categories of options were considered in the modelling:

- Energy supply technologies
- Demand management technologies increasing energy efficiency
- Carbon capture and sequestration
- Biological sequestration (sinks)

The different models show widely differing results, but an interesting common feature is that all studies point toward *increasing diversity* in energy supply and an increasing role for low-carbon technologies even in the absence of climate policy constraints. Given the fact that technologies are close substitutes in the generation of electricity, heat and motive power, converging prices may lead to large substitution effects. A feature of cost optimisation models such as MARKAL is that small differences in cost assumptions may induce significant shifts from one technology to another.

The below figure taken from the overview study shows the results from eight different models as presented in Weyant (2004). Figure (a) shows energy consumption and composition of supply sources in the BaU scenario, while (b) shows results in the 550 ppm policy scenario.

Response from a MARKAL technology model to the EMF scenario assumptions

The study (Smekens et al., 2004) undertaken by ECN covers EU15 plus Norway, Switzerland and Iceland, treated as one single region. It performs a MARKAL modelling exercise for the period until 2100, analysing a number of different climate policy scenarios, with a 550 ppm scenario considered in most detail.

The baseline case implies a continued rise in total energy demand combined with an increase in coal consumption. The 550 ppm scenario leads to fuel switching, increased use of renewables and energy efficiency. There are also some demand reductions due to energy price increases, although there is a continued growth in primary energy consumption, suggesting that little attention is given to the demand side. The emissions in the most stringent scenario are 30% below the 2000 level by 2100. However, most reductions occur after 2050, and the reductions to 2050 are not higher than 10–15%, making the scenario results less relevant.

In the baseline scenario, the share of non-fossil energy declines from 25 to 20% to 2050 due to nuclear phase-out, whereas in the 550 ppm

scenario, it increases to 35% due to an increase in both nuclear, wind and hydro. CCS plays a role, with natural gas conversion to hydrogen combined with CCS, starting in 2025.

Aggregate costs are calculated as annual consumer and producer surplus compared to the reference case. The average costs range from 0.19 to 0.8%.

A clear conclusion that this study shares with most others is that the emission reductions can hardly be achieved by just a single technology or technology group.

Overview study #2: Endogenous Technological Change and the Economics of Atmospheric Stabilisation (Energy Journal Special Issue)

In 2006, the academic journal *The Energy Journal* published a special issue titled “*Endogenous technical change and the economics of atmospheric stabilisation*”. The main question posed by this collection of articles is how today's requirements for GHG emission reductions will influence the costs of tomorrow's reduction efforts. In this report, three overview articles of this special issue are reviewed.⁸

*General/crosscutting remarks*⁹

In the study, 10 models describing the global economics of and investments in GHG mitigating technologies were compared regarding their predictions for a least cost path towards stabilising the atmospheric CO₂ concentrations at 450 and 550 ppm.

Endogenous technical change

All models included so-called endogenous technical change (ETC), i.e. a relation between future costs and historic use of certain GHG mitigating technologies. The very plausible assumption of ETC is that a more extensive use of a given technology in the past, means that this technology will be cheaper today and in the future. 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.

Causality direction?

But what causes this relation between past use and future costs? According to Köhler (2006) it is in essence a chicken-and-egg problem: “Whilst it is entirely possible to assume that the greater market scale leads to cost reductions, it is equally plausible that cost reductions leads to greater

⁸ Grubb et.al. (2006), Köhler et.al. (2006), and Edenhofer et.al. (2006).

⁹ Several of these issues are briefly addressed in section 2.

market scale". The stage in the research and development process may influence the direction of causality somewhat. In e.g. photovoltaics (PV) the present cost reductions are primarily caused by developments in semiconductor technology, and the deployment of PV can be said mainly to follow the costs. Conversely, the most present developments in wind turbines may arguably stem mostly from the learning process.

In case the direction of causality is that the costs drives market penetration some of the economic arguments for early action are diminished. There is no conclusive academic agreement on this topic, but it is most likely that the causality goes both ways.

Crowding out non-energy R&D?

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. Thus, in case only a fixed amount of resources (both in terms of "brains", money and other resources) are available for R&D it will (roughly speaking) be equally costly to perform the emission mitigation, whether or not R&D resources are devoted to energy technologies.

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.

Credible signals?

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."

Baseline assumptions and emissions

The 10 models compared in the study all share the same baseline, namely the Common POLES/IMAGE baseline which describes energy use and emissions from 1995 to 2100. This relies on a world per capita income growth of 1.9 to 2.0 % p.a. and a world population growth from 1995 to 2050 at 0.83 % p.a. Using these projections world energy use is projected

to increase 145 % from 1995 to 2050, while global emissions increase from 32.0 Gt CO₂/year in 1995 to 71.5 Gt/year in 2050. After 2050 the annual emissions are stabilised just below 80 Gt/year. Much of the increase occurs in the developing countries.

Reduction scenario parameters and assumptions

Three reduction scenarios are simulated in the 10 studies, in which the atmospheric CO₂ concentrations are stabilised at 450, 500 and 550 ppm. Each of the reduction scenarios is run both with and without ETC (Endogenous Technological Change) in order to analyse the significance of ETC. The reductions were performed to reach a least-cost.

Correcting market failures?

Two of the reported models yield negative costs for GHG abatement, i.e. the world gains economically from reducing GHG emissions. This is caused by the assumption in the two models concerning market failures in investments in R&D which are supposedly corrected by indirectly forcing more R&D investments through emission reduction requirements.

In one of the models the mechanism is a Keynesian style imperfection in the labour and capital markets (leading to underemployment) which is corrected by higher investments in R&D. While such an assumption sometimes might be appropriate for a very short term model (e.g. 1–3 years) it is quite controversial – at least from a mainstream economist's point of view – for a time span of over 100 years.

In the other model with negative mitigation costs regions generally invest too little in R&D. The assumed mechanism is that they do not accrue all of the benefits of R&D themselves, and are not capable of exerting cooperative behaviour in order to correct this. Forcing R&D through GHG mitigation requirements corrects this market failure and can thus in some circumstances lead to economic improvements as a consequence of GHG mitigation. This assumption may also be regarded as somewhat controversial, albeit not at the scale of the Keynesian assumption mentioned above.

For models incorporating assumptions implying that GHG mitigation can lead to negative mitigation costs by correcting market failures through increased R&D, it may be relevant to compare such model results to a baseline where the R&D effort is spent in other areas than GHG mitigation. Strictly speaking, such models do not analyse GHG mitigation costs, but rather economic inefficiencies in R&D investments, where GHG mitigation is but one option among many for remedying the market failure.

Reduction scenario outputs

The 10 models used for the simulations yields a very broad range of costs. The differences in mitigation costs are very large when technical change is not induced by increased market penetration, i.e. larger deployment of technologies does not lead to technological improvements.

The costs in terms of Gross World Product (GWP) in the period 2000–2100 are estimated to be between zero and 0.5 % of GWP in most simulations. These are for reductions in the magnitude of 700 to 4,000 Mt CO₂e per year. Extreme results are the negative costs, as well as 1% to 6.2% for the large costs. The costs are typically much more dependent on the model used than on the size of the reduction.

A part of the study is to address the reduction costs in absence of ETC. Although the reduction costs in this case are significantly larger (typically from 0.5 % to 3 % of GWP, and some instances above 5%), this part is, however, probably of a more academic interest. The reason is that the baseline technological costs are estimated with ETC but relying primarily on traditional GHG intensive technologies. Thus, this is a worst case scenario where climate policy fails to be credible (thus not creating incentives to learning and R&D) and the only mechanism for bringing about cost reductions is learning and experience (and in particular not R&D policy).

The marginal value of GHG reductions (whether shadow price, allowance price or carbon tax) are increasing through the century in almost all of the simulations. In 2050 the carbon price is between app. 30 and 70 USD per tonne CO₂e in most of the simulations with ITC.

Most of the 10 models evaluated show a tendency towards reducing the carbon intensity instead of relying on reductions in energy intensity, although some of the models have the opposite property. In many cases where the emission intensity is the primary mean of reduction, the abatement is caused by investments in low carbon and carbon free “backstop” technologies, which thus play an important role in the emission abatement efforts.

Overview study #3: The costs of greenhouse gas abatement: a meta-analysis of post-SRES mitigation scenarios

In the survey by Barker et al (2004), estimated costs of achieving different reductions in CO₂ emissions have been compared across a large number of studies. In addition to this, the authors analyse systematically which explanatory factors for differences in model results can be identified.

Costs

The analysis shows that there is a strong correlation between the level of CO2 emissions reduction and GDP loss.

Comparison of the different models shows that results are strongly clustered, with only a few results outside the range -4% to 0% GDP.

The below table shows the estimated per cent global GDP losses for a 50–70 per cent long-term reduction in CO2 emissions compared to *base-line* emissions, (i.e. not compared to a fixed reference year like 1990)

Table 8.1 Number of studies showing different levels of GDP loss for 50–70% reductions in CO2 emissions

< 0 - 1.0	1.0–2.0	.02–3.0	3.0–4.0	4.0–>5.0	Total	Mean, % of GDP
3	7	8	3	7	28	2.6

The below diagram taken from Barker et al. (2004) provides another illustration of the distribution of results.

Explanations

This section of the report revisits earlier analyses carried out by World Resource Institute. Regarding the reasons for differences in modelling results, the meta analysis of the studies shows that 70% of the variation can be explained by a few model attributes and assumptions made. In addition to the CO2 reduction target compared to the baseline (the more ambitious the more expensive) and the number of years to reach the target (the shorter the more expensive) the explanatory factors are the following, ordered by the degree to which their inclusion contributes to explaining differences, so that “1” has the highest impact.

1. CGE models vs. econometric models
CGE models consistently tend to give lower costs than time-series macroeconomic models.
2. The assumed use of carbon tax revenues
Carbon tax revenues are generally assumed to be recycled in economic models. The way in which this recycling takes place has a discernible impact. One option is to return revenues in the form of lump-sum rebates. An alternative is to assume that the revenues collected from the carbon tax will be used in correcting economic distortions in other sectors of the economy which suffer from distortionary taxes. The projected economic impacts turn out to be substantially more positive from the latter approach than if a lump-sum revenue recycling is assumed.
3. The inclusion of non-climate related environmental benefits
Positive environmental benefits beyond climate mitigation include reductions in pollution associated with the burning of fossil fuels, leading i.a. to improvements in local and regional air quality.
4. The inclusion of international emissions trading
When international emissions trading is available (typically modelled by setting a uniform CO₂ tax), reductions will take place where they are most cost-effective and thus contribute to minimizing the overall economic costs of reducing emissions.
5. The availability of a constant-cost backstop-technology in the model
Many models recognise the existence of non-fossil energy sources, but assume that there is limited availability of the resource, implying increasing prices for the use of large amounts. This implies that carbon taxes would have to rise continuously to keep CO₂ emissions constant during economic growth. However, if an energy source becomes perfectly elastic in supply, meaning that there is unlimited supply above a given price, this is termed a *backstop technology*. A carbon tax which is introduced in a situation of non-fossil energy sources being close to competitive, substitution away from conventional fuels can be significant at limited costs. Thus, models without backstop technologies will tend to estimate higher economic impacts from a carbon tax. The estimation of a critical price for the backstop technology is highly uncertain.
6. The inclusion of avoided climate-change damages in the model
The potential economic benefits from avoided climate change are difficult to quantify and associated with very large uncertainties. Obviously including them will reduce the net costs of emission reductions.
7. Whether the model allows for product substitution
The more detailed the production sectors, factors of production and the energy sector of the economy are specified, the more substitution possibilities will be available in the model. Different products have

different level of energy use, and therefore changes in production and consumption patterns will affect them differently. Similarly, different fuels with different GHG emissions should be specified, in order to allow for substitution between them.

In summary, the worst case results come from using a macroeconometric model with lump-sum recycling of revenues, no emission permit trading, no environmental benefits in the model and no backstop technology.

Brief review of selected Nordic Studies

Analysis and Evaluation of the Triptych 6 – case Finland

General/crosscutting remarks

The report “Analysis and Evaluation of the Triptych 6 – Case Finland” covers the second phase of a two-phase study, which focuses on the perspectives for long-term emission reduction pathways and the possible implications for long-term reduction targets by country or by groups of countries.

The objective of the study was to improve the understanding of more complex approaches (burden sharing models), such as Triptych and Multistage. These approaches can be regarded as combined top-down and bottom-up approaches. They start with the GHG stabilisation level and the global emission reductions that are needed to reach that level. The burden sharing is carried out by using a bottom-up approach to take into account the differences between countries and their national circumstances.

In the study critical input data, parameters and assumptions of the global Triptych approach, notably those relevant for Finland, were identified. The sensitivity of the approach was then tested by varying the values for those critical data and parameters in test runs. The results of these test runs were analysed and reviewed, and furthermore, an overall assessment, including conceptual considerations, of the applicability of the Triptych approach for burden sharing in long-term emission reductions was made.

Baseline assumptions and emissions

As a default setting, all Annex 1 countries (including the USA) are assumed to reach their Kyoto target in 2010. The required emission reductions from the reference scenario to reach those targets are assumed to be implemented equally within all sectors.

Reduction scenario parameters and assumptions

The basic input data and the division of the sectors to calculate the emission allowances are based on the Evolution of commitments tool (EVOC). It contains historical and scenario emission data for all green-

house gases considered in the Kyoto Protocol, and for all 192 individual countries. The emission sectors distinguished are as follows:

- The power sector
- Industry
- Domestic sectors
- Fossil fuel production
- The agricultural sector
- Waste disposal and processing
- Land use change and forestry

Reduction scenario outputs

The implemented sensitivity calculations of the Triptych 6 system indicated a variation of less than 10 percentage points from original runs carried out in the first phase of the study. Most of the test runs resulted in decrease, whereas only a few test runs led to increase, of emission allowances of Finland. As regards, the review of the model VTT and VATT identified the following critical methodological features of the Triptych 6 system:

- The chosen representation of CHP in the model
- The sensitivity of base year selection with regard to fuel mix and growth of electricity production
- The lack of distinction between energy-incentive and other manufacturing industry
- Per-capita-based emission indicators as sole drivers for handling the domestic sector

The pre-fixation of all key-drivers (such as growth of GDP and electricity demand) and subsequent adaptation of some key parameters to facilitate target achievement without any recourse to relative cost.

The NORDLEDEN project – Final report from phase II, 2003 (PROFU)

The Nordleden project was an extensive Nordic research project focusing on climate- and energy-policy issues. The project dealt with several strategic and political questions that affect the short- and long-term development of the energy system and its impact on the environment. One important task was to identify cost-efficient developments of the energy supply in Sweden, Norway, Denmark and Finland, adapted to the ongoing internationalization of energy markets and climate policies. Another important

task was to highlight the consequences of different policy measures and their impact on the energy systems in the four Nordic countries.

Two phases

The Nordleden project was carried out as two separate phases. The first phase was conducted between 1996 and 2000, and the other, which was considerably larger in terms of scope, participants and financiers, was carried out between 2000 and 2003.

Participating researchers

The second phase included researchers from different disciplines. The following list summarizes the involved research institutes:

- Energy Systems Technology Division, Chalmers University of Technology, Göteborg
- School of Economics, Göteborg University
- ECON, Stavanger and Oslo
- Centre for Public Sector Research (CEFOS), Göteborg
- Department of Philosophy, Lund University

The project was managed by Profu in Göteborg with assistance from EKAN in Jönköping.

The Nordleden project was also conducted in coordination with the IEA/EU network project for energy systems modeling, ACROPOLIS. Model results and input were, among others, exchanged between the two projects.

Research focus

The analyses were focused on the four Nordic countries Sweden, Norway, Finland and Denmark but within a Northern European context. The parts of the Nordic energy systems that were dealt with included the electricity and district-heating systems, and end use in the industrial, residential and service sectors. Transports were only analyzed briefly. Research issues of central importance were analyses of the impact of different energy- and climate-policy strategies on the development of the Nordic energy systems.

The research questions addressed were grouped into six main areas:

1. The long-term development of the Nordic energy systems and their climate impact
2. The development of the technical sub systems for electricity, district heating, natural gas and biofuels
3. The development of the energy markets for oil, natural gas, electricity, district heating, biofuels and waste fuels

4. The development of national and international policy measures and their impact on the energy systems and their participants
5. Behaviour of different market players and public-acceptance issues - Impact on new investments

Typical research questions that were addressed were, among others:

- What is the benefit and consequence of increased competition and coordination : electricity, gas, CO₂ markets and support for renewables ?
- What are the consequences of introducing “market based” policy measures such as CO₂-emission allowances and tradable green certificates ?
- What can be said about the long-term development of the Nordic energy system ?
- How important is public acceptance when it comes to investments in energy supply ?
- How do market players look upon investments and the future within the energy field ?

Use of energy models

The scientific methodologies included, among others, three energy systems models, namely MARKAL-NORDIC, ECON’s “Kraftmarkedsmodell” and HEATSPOT. The first model covers the stationary energy systems of the four Nordic countries and their long-term development until 2050. The second model is an electricity-market model covering the four Nordic countries, Germany, Poland and the Netherlands. The third model is a district-heating model that includes locally described district-heating systems of one country. HEATSPOT was applied to the Swedish, Danish and Finnish district-heating systems.

Conclusions and findings

A very brief and condensed summary of the most important findings of the Nordleden project may be summarized into the following:

- Increased international coordination of energy and climate policies is beneficial
- Under given environmental considerations, increased competition in the energy markets is beneficial
- Meeting the targets cost-efficiently requires flexibility and a multitude of measures
- The energy-system change is continuous and involves bridging technologies towards a (fully) renewable energy supply
- The interplay between the markets for electricity, CO₂-emissions allowances and tradable green certificates is highly complex

- Public acceptance and driving forces of market players for new investments are crucial for the long-term development of the energy systems

Continued work

Further information of the Nordleden project may be found at www.nordleden.nu and in the final report (ISBN 91-631-4327-5). In 2005 it was agreed that the Nordleden project was to be continued, namely as the “Nordic energy perspectives” (NEP) project with a further extension in terms of participants. The first phase of the NEP project will be concluded and reported in September 2006. More information is available at www.nordicenergyperspectives.org.

Information of relevance to the study phase

Crosscutting

Baseline assumptions

In table 10.1 a number of general baseline assumptions used in the three key studies are listed.

Table 10.1 General baseline assumptions

	Key Study # 1	Key Study # 2	Key Study # 3
GDP growth	EU 15: 2.3% p.a., EU10 3.5% p.a.	UK: 2.25% p.a.	Global: 2.9% p.a.
Population	Stable	65 million in 2050	
Global energy consumption	2½ times 2000 consumption in 2030	N.a.	More than 2 times 2005 level
Fuel price	30 \$/b in 2020 35\$/b in 2030	Approximately 25 \$/b for the whole period	39 \$/b in 2030 60 \$/b in 2050

Modelling methodology

Different models have been used for the three key studies, including the PRIMES partial equilibrium model for EU, the POLES global energy model and different versions of the MARKAL model. All these models can be characterised as bottom up models. In table 10.2 below the models used in the different studies are indicated.

Resulting cost indication

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 the indication on the costs and the associated emission reduction.

Table 10.2 Cost indication in selected studies

Study	Model	Cost indication	Emission reduction target	Coverage of cost indication
Key Study #1 EEA	PRIMES, POLES and others	MAC: 65€/t CO2 GDP: 1%	CO2 content: 550 PPM 65% reduction by 2050 compared to 1990. Some reductions through use of flexible mechanisms.	EU 25
Key Study #2 DTI	MARKAL	MAC: 80–400 EUR/t CO2 GDP: <1%	45–70% of 2000 emission	UK
Key Study #3 IEA	ETP–MARKAL	CO2 Price: 25 - 40 \$/t 0.1% of world GDP	Stabilisation of global emissions in 2050 at 1990 level (30% OECD reduction)	World
Overview Study # 1 Stanford EMF ECN	Different plus MARKAL	Costs: 0.19– 0.8% reduced annual consumer and producer surplus (MARKAL 2100)	CO2 content 550PPM	EU 15 plus Norway, Switzerland and Iceland
Overview Study # 2 Energy Journal special edition	Different models	MAC: 30–70 \$/t CO2 Costs: 0.5% of Global GDP, but extremes scenarios up to 6%	CO2 content: 450–500–550 PPM	World

Energy supply (with CCS)

Fuel mix and CHP

Although electricity and steam production is reduced with only app. 4% from 2000 to 2030 in Key Study #1, this sector delivers app. 80% of the reductions in energy related CO2 emissions. This is to a large extent driven by shifts from coal to natural gas. In Key Study #2, however, the baseline already features the shift from coal to gas (because of a rather low natural gas price), so reductions from fuel mix shifts are very limited. In Key Study #3, coal is the main fuel of choice, as the reduction requirements in this study are quite lax (zero to app. 15% relative to 2000 corresponding to a CO2 price of app. 25 USD/tonne in 2050). *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

All three key studies illustrate the effects of significant expansions of the nuclear electricity generation capacity. Because of the uncertainty of future use of nuclear power, additional analyses of the significance of nuclear power in emission abatement are also presented in all three key

studies. In Key Study #1, nuclear power expands from 17 to 22 % of electricity generation from the baseline to the reduction scenario, and up to 30 % in an accelerated nuclear power scenario. In a nuclear decommissioning scenario the share falls to 13 %. In the reduction scenario the average production cost of electricity increases with 26%. Accelerating nuclear power will lead to an increase of only 24%, while the decommissioning scenario states an increase of 35% in electricity generation average costs.

In Key Study #2 nuclear power acts as a part of the backstop technology, so the effect of decommissioning depends strongly on the availability of other backstop technologies. With a 60% reduction requirement nuclear power does not make any difference for the total reduction. Without CCS, the absence of nuclear investments doubles the reduction costs. In the 70% reduction case, the absence of nuclear investment doubles the reduction costs even with CSS, while the cost quadruples without CCS.

In Key Study #3, there is no absolute target for GHG emissions. Instead, different technology and policy setups cause different emissions. If the reduction scenario is altered to a low reliance on nuclear power, world emissions increase by 900 Mt/year, equivalent to a 3.4% reduction.

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).

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.

In Key Study #1, the baseline consumption of renewable energy is 8.6% of total energy consumption, increasing to between 12.5% and 13.9% in the reduction scenarios. With extra efforts concerning renewable energy, this share can increase to 21.5%. The share of electricity production increased from 18.2% to 27 to 30%, and with extra efforts to 39%.

The corresponding figure for Key Study #2 is an increase from little above 10% to 25–35% of electricity production. In the scenarios without nuclear expansion and CCS the share of renewables in electricity production could increase up to 70%.

In Key Study #3, the baseline renewable electricity generation is 16.4% increasing to 31.3% in the “Map” reduction scenario. Hydropower generation accounts for 5.9 percentage points of this increase, while biomass accounts for app. 2.5%. Two thirds of the rest of the increase is

attributable to wind power, the rest to solar and geothermal power. Increasing the efforts concerning renewable energy is primarily reflected in increases in wind, solar and geothermal power.

All three studies conclude that especially *wind power is an important source for reductions in CO₂ 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

In Key Study #1 CCS is not present as it is anticipated that this technology will be large scale commercially available only after 2030, which is the time horizon of the study.

In Key Study #2 CCS together with nuclear power plays an important role as backstop technology. Excluding only one of these has a limited effect on reduction costs. CCS is applied both in coal fired electricity generation and in natural gas based production of hydrogen for transport.

In Key Study #3, CCS delivers app. 20% of the emission reductions in electricity generation. Without CCS the world emissions will become 14% higher than in the “Map” reduction scenario.

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*.

Energy demand and efficiency

In the baseline projection of energy use, Key Study #1 departs from the assumption that the final energy intensity of industry, services, households and transport decreases with 33% to 50%. Imposing the ambitious reduction targets adds further reductions in final energy intensity of app. 2 to 6 percentage points. Thus, most of the emission reductions are found outside final energy use.

In Key Study #2 the decrease in final energy use are somewhat more outspoken. Imposing a 60% and 70% reduction requirement causes final energy demand to fall by 14% and 20%. The role of energy efficiency improvements decrease when the reduction requirement is more ambitious.

In Key Study #3, the most significant source of emission reductions is improvements in energy efficiency. It must be noted that this study does not investigate as ambitious reductions as the two other studies. As energy efficiency improvements tend to be relatively cheap, it is no surprise that they are dominant in low reduction scenarios such as those presented in Key Study #3.

The demand side efficiency measures are not explicitly described, but the report notes that the measures described in most research are potential short-term improvements, while longer term improvements are not researched very often.

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.

Transport

The key messages from the literature review is summarised below.

Baseline parameters and assumptions

The key messages for the definition of the baseline scenario are:

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.

Oil products account for the largest share of the energy demand from the transport sector (in *Energy Technology Perspectives* oil products account for 94% in the baseline scenario – of which Fischer Tropsch diesel (syngas) produced from coal and gas account for around one fourth. Biodiesel and ethanol only contribute 3%. The rest is provided by gas, coal and electricity).

There are varying views on the time scale in which hydrogen could be introduced. The results show that hydrogen fuel cell vehicles most likely will show (virtually) no market penetration in the baseline scenario as it remains too costly.

Key estimates on well-to-wheel emission factors are shown in the table below (source: *Energy Technology Perspectives*).

Table 10.3 Well-to-wheel CO₂ emissions by fuel source in the transport sector, 2003

	Grams of CO ₂ per km
Petroleum gasoline	300
Petroleum diesel	220
GTL diesel (gas to liquids)	260
CTL diesel (coal to liquids)	460
CNG (compressed natural gas)	230
Biofuels	30–250

Reduction scenario parameters and assumptions

The key messages for the definition of the emission reduction scenario(s) are:

The demand for transport services is insensitive to increased costs of transports

Modal shift effects are very small

In most scenarios, CO₂ 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

Other sources and sinks*Modelling methodology*

Other sources and sinks present an expanded set of opportunities to reduce GHG emissions across sectors and over time. A growing amount of studies indicate that a significant portion of these reductions could be highly cost-effective, thereby supplementing reductions of energy-related CO₂ emissions.

Baseline parameters and assumptions

On the basis of our review of other sources and sinks analyzed in Key Study #1 (including the background report by Bates et al., 2004), the following observations can be made with respect to the baseline scenario for the Nordic countries up to 2050:

- Key Study #1 contains fairly detailed emissions and cost estimates for non-energy CO₂, non-CO₂ GHGs, and sinks.

- Baseline emissions are based on a bottom up technology assessment of relevant activities and emissions factors. They are projected until 2030 for EU-15, EU-10, and the wider Europe.
- The bottom up technology approach makes the results for other sources (and sinks) comparable to those obtained from MARKAL.
- Separate figures for the Nordic countries are reported, and may be used in combination with the National Communications to the UNFCCC, in order to estimate baseline emissions until 2030 and beyond.
- However, baseline emissions from the Nordic countries are reported only for broad categories of non-energy CO₂ and non-CO₂ GHGs. This makes it difficult to extend the time horizon to 2050 on the basis of changes in underlying activities.
- Completing the analysis of other sources and sinks in the second phase of this project on the basis of Key Study #1 would therefore be quite demanding, as it would require an elaboration of the methodology and the data used for estimating costs and emissions reductions in Bates et al. (2004).

Reduction scenario parameters and assumptions

With respect to the GHG emissions reductions and their costs, we note that:

- Non-CO₂ 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
- F-gases appear to have a particularly large potential for GHG reductions
- For sinks, a considerable potential exists, but the estimates are highly uncertain
- Against this background, it is important that other sources and sinks are included in a strategy for considering ambitious reduction targets in the Nordic countries until 2050
- 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

References

- Barker et al: The costs of greenhouse gas abatement: a meta-analysis of post-SRES mitigation scenarios, *Environmental Economics and Policy Studies* vol. 5, 2002
- Bates et al. (2001), *Economic Evaluation of Emission Reductions of Nitrous Oxides and Methane in Agriculture in the EU*, (contribution to *Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change*), Commission for the European Union, Directorate General Environment, Brussels.
- Bates et al (2004): *SoEOR2005: Greenhouse gas emission projections and costs 1990–2030*. EEA–ETC/ACC. 2004/1.
- Bates, J. and A. Haworth (2001), “Economic Evaluation of Emission Reductions of Methane in the Waste Sector in the EU”, (contribution to *Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change*), Commission for the European Union, Directorate General Environment, Brussels.
- Bates, J., M. Adams, A. Gardiner, J. Cofala, J. van Minnen, H. Eerens, N. Kouvaritakis, L. Mantzos, M. Zeka-Paschou (2004), “SoEOR2005: Greenhouse Gas Emission Projections and Costs 1990–2030”, EEA-ETC/ACC Technical Paper 2004/1, European Topic Centre on Air and Climate Change, European Environment Agency, Copenhagen, Denmark.
- Blok, K., D. de Jager and C. Hendriks (2001), “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change: Summary Report for Policy Makers”, Commission for the European Union, Directorate General Environment, Brussels.
- Bruinsma, J. (2003), *World Agriculture Towards 2015/2030: An FAO Perspective* (London, UK: Earthscan).
- Commission of the European Communities: *Winning the Battle against Global Climate Change*, 2005
- Criqui et al: *Greenhouse gases reduction pathways in the UNFCCC process up to 2025*, 2003
- DTI: *Our energy future – creating a low carbon economy*. UK Energy White Paper, 2003
- DTI: *Options for a Low Carbon Future: Review of Modelling Activities and an Update*, 2003
- Energy Journal Special Issue: *Endogenous Technological Change and the Economics of Atmospheric Stabilisation*. 2006
- European Environment Agency: *Climate Change and a European low-carbon energy system*, 2005
- European Climate Change Programme, ECCP (2001), *Mitigation Potential of Greenhouse Gases in the Agricultural Sector*, Final Report of Working Group 7, European Climate Change Programme.
- FAPRI, *US and World Agricultural Outlook*, Food and Agricultural Policy Research Institute, Iowa, USA. 2003
- Hendriks, C. and D. de Jager (2001), *Economic Evaluation of Methane Emission Reduction in the Extraction, Transport and Distribution of Fossil Fuels in the EU* (contribution to *Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change*), Commission for the European Union, Directorate General Environment, Brussels.
- International Energy Agency: *Energy Technology Perspectives*, IEA 2006
- International Panel on Climate Change, IPCC: *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (Bracknell, UK: IPCC, OECD, IEA), 1997
- IPCC: *Good Practice Guidance and Uncertainty Management in national Greenhouse Gas Inventories* (Institute for Global Environmental Strategies, Japan: IPCC), 2000
- IVM: *Ex-post estimates of costs to business of EU environmental legislation*, 2006
- Mantzou et al: *European energy and transport Trends to 2030*, 2003
- Mantzou et al: *European energy and transport: trends to 2030*. European Commission, 2003
- Pacala and Socolow: *Stabilization Wedges: Solving the Climate Problem for the next 50 Years with Current Technologies*. Science Vol. 305, 2004
- PROFUT: The NORDLEDEN project, Final report from phase II, 2003
- RAINS WEB (2003), *The RAINS WEB Model*, IIASA; Laxenburg, Austria.
- Soimakallio et al: Analysis and Evaluation of the Triptych 6 - case Finland, VTT 2006

van Vuuren et.al: *Regional costs and benefits of alternative post Kyoto climate regimes*, 2003.

van Vuuren et al.: *Multi-gas scenarios to stabilize radiative forcing*, Energy Economics 28, 2006

Weyant, J.P., F.C. de la Chesnaye, and G.J. Blanford (2006), "Overview of

EMF-21: Multigas Mitigation and Climate Change", *Energy Journal*, forthcoming.

Weyant: *Introduction and overview (to the EMF 19 study on technology and climate change policy*, Energy Economics, 26, 2004

Sammendrag

Formålet med denne gennemgang af litteraturen er at give et overblik over de studier, der har set på storskala reduktioner af drivhusgasser. Fokus har været på

- basis emissioner scenarier, dvs. den sandsynlige udvikling af emissioner i fraværet af ambitiøse mål og dertil hørende politikker og tiltag for at nå målene
- reduktions scenarier hvor der bruges politiske virkemidler for at reducere emissionerne

For både basis og reduktions scenarier bestemmer et antal drivkræfter størrelsen af fremtidige emissioner og omkostningerne ved reducere emissionerne. De forskellige studier har vidt forskellige tilgange til at modellere basis og reduktions scenarier og de resulterende omkostninger.

Udvalg af studier

Tre typer af studier er blevet gennemgået:

- Nøglestudier er omfattende studier, der giver væsentlig information om emissioner og reduktionsomkostninger i forskellige sektorer
- Overblikstudier gennemgår og sammenligner de mange forskellige studier, der er blevet lavet.
- Nordiske studier omfatter et mindre antal studier, der er lavet for de nordiske lande

Gennemgangen har fokuseret på tre udvalgte nøglestudier lavet af Det Europæiske Miljøagentur (EEA 2005), Department of Trade and Industry i UK (DTI 2003) og Det Internationale Energi Agentur (IEA 2006).

Basis antagelser

Der er specielt set på set på forudsætningerne for basis scenarier i de gennemgåede nøglestudier. Disse forudsætninger er meget vigtige for de resulterende omkostningsestimater, som altid må ses i forhold til de bagvedliggende forudsætninger. Særligt er udviklingen i energiforbrug (som igen afhænger af udviklingen i BNP, befolkning m.v.), priserne på fossil energi og niveauet af de ønskede reduktioner af stor betydning for de estimerede omkostninger.

Da nøglestudierne dækker forskellige geografiske områder, varierer antagelserne bag de forskellige studier noget, specielt med hensyn til

reduktionernes størrelse og priser på fossil energi. Et overblik over nogle af disse antagelser er vist i tabel 3.1.

Tabel S1. Basis forudsætningerne i de undersøgte nøglestudier

	EEA	DTI	IEA
Geografisk område	EU25	UK	Verden
BNP vækst	EU15 2,3% p.a., EU10 3,5% p.a.	2,25% p.a.	2,9% p.a.
Befolkning	Stabil	65 mill. i 2050	
Globalt energiforbrug	2½ gange 2000- forbruget i 2030	N.a.	Mere end 2 gange 2005-niveauet
Olie pris	2020: 30 \$/btl 2050: 35 \$/btl	ca. 25 \$/btl	2030: 39 \$/btl 2050: 60 \$/btl

\$/btl: dollar per tønde olie

Omkostningsestimer

De forskellige studier er baseret på forskellige antagelser og modeller, og har forskellige reduktionsmål og forskellige opgørelser af omkostningerne. Det betyder at det er svært at sammenligne omkostningerne på tværs af studierne.

En sammenligning af de estimerede omkostninger for ambitiøse reduktioner af udslip af drivhusgasser giver alligevel mening, når man kun sammenligner størrelsesordenen. Et overblik over de estimerede omkostninger er vist i tabel S2:

Tabel S2. Omkostningsestimer i litteraturen

Studie	Model	Omkostning	Reduktions mål	Geografisk område
EEA	Bottom-up	MAC: 65€/t CO2 BNP: 1 %	CO2: 550 ppm 65 % reduktion i 2050 i forhold til 1990. Brug af fleksible mekanismer	EU 25
DTI	Bottom-up	MAC: 80-400 €/t CO2 BNP: <1 %	45–70 % af 2000-emission	UK
IEA	Bottom-up	MAC: 25-40 \$/t BNP: ~0.1 %	Stabilisering af de globale emissioner i 2050 på 1990 niveau (30 % OECD reduktion)	Verden
Overblik 1 Stanford, EMF, ECN	Forskellige modeller	Velfærdstab; 0,2–0,8 %	CO2: 550 ppm	EU 15 plus Norge, Svejts og Island
Overblik 2 Energy Journal, special edition	Forskellige modeller	MAC: 30–70 \$/t CO2 BNP: ~0.5 % men op til 6 %	CO2: 450 ppm 500 ppm 550 ppm	Verden

Energikilder

De gennemgåede studier viser sammenfaldende nogle generelle resultater omkring energikilder:

Fosille brændsler: der er en ret stor variation i de relative priser af naturgas og kul. Dette påvirker resultaterne i forhold til brændselstype en hel del, som f. eks. med et stort skifte fra kul til gas enten i basis- eller i reduktionsscenariet. En nøgleantagelse for omkostningerne er i alle studier derfor den relative pris af kul i forhold til olie og specielt naturgas.

Kernekraft: på grund af usikkerheden omkring anvendelsen af kernekraft i fremtiden er der i alle tre nøglestudier særlige analyser af betydningen af kernekraft i forhold til CO₂-reduktion. De gennemgåede studier tyder på, at kernekraft har en ret stor betydning for omkostningerne ved CO₂-reduktioner. Imidlertid vil betydningen af kernekraft for reduktionsomkostninger være begrænset, hvis der er andre erstatningsmuligheder (som tilstrækkelig billige CCS-teknologier, dvs. kernekraft er en potentiel ret vigtig bagstopper teknologi).

Vedvarende energi: for alle tre nøglestudier er vindkraft den dominerende vedvarende energi teknologi, mens biomasse for opvarmning og i nogen grad CHP også er vigtig. Andre teknologier har ingen betydning i studierne. Alle tre studier konkluderer at specielt vindkraft er en vigtig metode til reduktioner af CO₂-emissioner.

CCS¹⁰: det kan konkluderes at CCS kan blive en vigtig metode til reduktioner af CO₂-emissioner. Det er bemærkelsesværdigt at nogle studier påpeger at fraværet af både CCS og kernekraft kan føre til meget større omkostninger eller mindre reduktioner. Med andre ord, CCS og kernekraft indgår som supplerende bagstopper teknologier.

Energiefterspørgsel og energieffektivitet

Tiltag der forbedre energieffektiviteten er de billigste reduktionsmetoder i alle tre studier. Men for meget ambitiøse reduktions mål er potentialet for forbedring af effektiviteten udtømt og reduktioner på forsyningssiden bliver vigtige. Denne konklusion kan delvis forklares ved en egenskab ved energimodellerne, som lægger vægt på energiforsyningen og mindre vægt på sideeffekten af lang-tids forbedringer af teknologierne.

Transportsektorens emissioner

Selv uden klimatiltag vil transportsektorens teknologiforbedringer i form af øget brændstofeffektivitet være ganske væsentlig (-10 % til -20 %). Forbrændingsmotoren vil stadig være dominerende i køretøjer i 2050, og stadig hovedsagelig bruge benzin eller diesel. Dertil vil brugen af hybridbiler øges.

Klimapolitikken vil generelt have lille betydning for transportbehovet, da det ikke er særlig følsomt overfor øgede omkostninger. I de fleste reduktions scenarier opnås CO₂-reduktioner i transportsektoren ved øget brug af biobrændsler og forbedret energieffektivitet.

¹⁰ CCS: Carbon capture and storages (Opsamling og lagring af CO₂)

Forbedringen af brændselseffektiviteten vil øges i takt med de internationale bestræbelser på at mindske udslippet af drivhusgasser. Effektiviteten kan øges med omkring 40 %. I de fleste scenarier trænger hydrogen brændselsceller ikke igennem på marked.

Andre kilder end energi og transport

For andre drivhusgasser end CO₂ (non-CO₂ GHG) er der en bred vifte af muligheder for reduktioner med lave omkostninger. De kan spille en væsentlig rolle for at nå ambitiøse reduktionsmål med lavest mulige omkostninger, specielt F-gasserne har et særligt stort potentiale.

Der er et stort potentiale for dræn (sinks, optag af CO₂ i planter), men estimerne er meget usikre. Samtidig er emnet meget kompliceret, fordi drænene er spredte og svage, mens vurderingerne af reduktionsmulighederne og -omkostninger afhænger af kilde for kilde estimer.

Appendix A: Energy Sector Analysis Report

Abbreviations

boe	Barrels of Oil Equivalent
CCS	Carbon Capture and Storage
MAC	Marginal Abatement Cost
MWh	Mega Watt hour
Solar PV	Solar Photo Voltaic

Summary and Conclusions

When talking about achieving ambitious 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 schemes will lead to a shift in electricity generation towards technologies with lower CO₂-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 CO₂-emission, which is also the aim of the scheme. 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.

Business-as-Usual scenario

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/boe¹¹ 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 biomass¹² 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 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

¹¹ Barrel of oil equivalents

¹² The assumption regarding constant prices for biomass may be optimistic in a scenario where international demand for low-emission fuels is expected to be increasing.

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 CO₂ 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.

Reduction scenarios

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 CO₂ 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.

MAC curves

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 figures below.

2020 MAC curve, energy sector

2050 MAC curve, energy sector

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 CO₂-emissions relatively more competitive. Another reason is an assumed technological development decreasing costs of renewable energy technologies.

Technology shifts

For the reduction scenarios concerned with the size of the 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 CO₂ emissions become more expensive. See the figure below.

Electricity generation technology composition and allowance price (2020)

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.

In the BaU as well as the reduction scenarios, all potential for wind and hydro power are 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. This demand is met by increasing solar PV and wave capacity. See the figure below.

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 CO₂ (an reduction rate of 85% has been assumed), 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.

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 CO₂, 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.

Introduction

This report presents the quantitative analyses of the energy sector which have been carried out as part of the project “Klima 2050 - veien til 60–80 prosent reduksjoner i klimagassutslippene”. The purpose of the project has been to analyse the consequences of ambitious long term reductions in the emissions of CO₂ by Nordic countries.

Apart from the energy sector also the transport sector as well as other sources and sinks have been included in the analyses. The results of these analyses are presented in separated reports.

Methodology and assumptions

The MARKAL-NORDIC model

The energy sector analyses have been carried out by the MARKAL-NORDIC model which is an optimisation model with perfect foresight. In simple terms, the model satisfies, at the least possible cost, demand for energy through a complex combination of energy conversion modules, energy distribution chains and fuel-supply systems under a large number of constraints. Fuel switching, co-production of heat and power, and conservation and efficiency measures are considered, among other factors. Investments are, thus done endogenously in the model.

The MARKAL-NORDIC model includes a database describing the entire stationary energy system for the four Nordic countries Sweden, Norway, Finland and Denmark. Energy demand is divided into roughly 60 sectors distributed among the four Nordic countries. The division between sectors is based on nationality, sector (industry, residential housing and commerce etc.), and purpose of energy use (lightning, heating etc.). The annual load duration for electricity is divided into six periods, including diurnal representation of winter, summer and an intermediate season. The corresponding load duration for district heating is divided into only three periods, one for each season, while demand for all other energy carriers is expressed on an annual basis.

The time horizon in the model is from present date until 2050. All technologies in the model are described in terms of technical efficiency, availability, investment costs, operation and maintenance costs, fuel delivery costs, and life lengths. For existing technologies, capital costs are considered as sunk costs, and the time dependence of the residual capacity is expressed as an “age curve” based on estimations of remaining technical lifetime (assumed identical to the economic lifetime).

Fuels are associated with exogenously given costs and potentials. For fossil fuels, potentials are unlimited, mimicking global markets. Natural gas is, however, supplied through a transmission and distribution grid associated with investment and O&M costs. Domestic fuels such as biomass are divided into several cost classes yielding a supply curve.

Several important energy and carbon taxes are included in the MARKAL-NORDIC model depending on the scenario analysed (see section 4.3 Approach. This also applies to wind-power subsidies in the Nordic countries and the existing TGC scheme in Sweden.

The MARKAL-NORDIC model has been used for a number of analyses of the Nordic energy system. In the recently finalised first phase of the Nordic Energy Perspectives project, see Rydén et al. (2006), MARKAL-NORDIC was used as one of eight energy system models with the purpose of analysing a wide range of problem issues. The eight models were of different types, MARKAL-NORDIC being one of the “Engineering-economic models” together with e.g. the Balmorel model.

Today's power generation in the Nordic electricity market

The table below shows the electricity generation in the Nordic electricity market as it is today.

Table A1 Electricity generation mix in the Nordic electricity market in 2005, GWh

	Denmark	Finland	Iceland	Norway	Sweden	Nordel
Total generation	34,353	67,862	8,679	137,948 ²	154,729	403,571
Nuclear power	.	22,334	.	.	69,461	91,795
Other thermal power	27,715	31,764	8	976	12,195	72,658
- Condensing power		5,680	.	0	513	6,193
- CHP, district heating	25,886 ¹⁾	14,446	.	89	6,315	46,736
- CHP, industry	1,829	11,623	.	531	5,336	19,319
- gas turbines, etc.	0	15	8	356	31	410
Hydro power	23	13,597	7,013	136,465	72,143	229,241
Windpower	6,615	167	.	507	930	8,219
Geothermal power	.	.	1,658	.	.	1,658
Total generation 2004	38,370	82,155	8,621	110,545 ²	148,758	388,176
Change as against 2004	-10,5 %	-17,4 %	0,7 %	24,8 %	4,0 %	4,0 %

¹⁾ Includes condensing production

²⁾ Gross production

Source: Nordel (2005)

It appears that nuclear generation accounts for approximately 23%, other thermal power (coal and gas) for 18%, hydro power for 57%, and wind power for 2%. Furthermore, it appears how there are large differences in power mix between the countries.

The analyses carried out within this project have included Denmark, Finland, Norway and Sweden.

Approach

The approach regarding the energy sector analyses has been to simulate the marginal abatement costs under different assumptions by use of the MARKAL-NORDIC model. The main assumptions concerns:

- Energy demand from industry, services and households, by different source (e.g. should industries produce steam and electricity by themselves or rely on grid-connected energy?)
- Bio-fuel prices, i.e. an ambitious international climate policy is likely to increase the international demand for biofuels, and hence the price of bio-fuels;
- Fossil fuel prices: With a strong international demand for energy, both bio and fossil fuel prices will be high
- Technological development in terms of investment costs, efficiency of production etc.;
- Nordic CO₂-reduction target (an analysis of individual reduction targets for each of the Nordic countries is outside the scope of this project)
- Other policy measures, concerning among others energy efficiency measures;
- Investment discount rate: with a lower rate, future costs (in particular high abatement costs of ambitious future climate policy) are weighted more in the investment decisions, furthering investments in climate friendly technologies.

The main purpose of the analyses has been to estimate the marginal abatement costs of future generation patterns. The description includes investments in new units and future development in electricity and heat prices depending on different reduction targets. By analysing the allowance price using a wide range of assumptions the robustness in results are underpinned in the sense that drivers of costs and savings of climate policy are made more explicit.

Baseline scenario assumptions

The final energy demand is projected to increase with 0.45 % p.a. between 2002 and 2050 in the baseline scenario. The MARKAL Nordic model distinguishes between industrial final energy demand and residential and other commercial energy demand. Industrial final energy demand grows with 0.63 % p.a. while residential and commercial demand grows somewhat slower with 0.20 % p.a. The use of electricity is projected to increase with 0.29 % p.a. in the projection period.

The raw energy prices of the projections are characterised by a marked increase in the price of easily available hydrocarbon energy sources, as the world supply is expected to become scarcer while the world demand is expected to increase. The coal price is expected to in-

crease only moderately during the projected period. The price of biofuels is endogenously determined by supply and demand for it modelled in MARKAL Nordic. It is however assumed that biofuels are also available on an international market. It is here assumed that the price of biofuels will be constant during the projection period. The fuel prices are described in the table below.

Table A2 Baseline fuel prices in the projected period (USD/boe)

	2010	2020	2030	2050
Coal	13	14	15	20
Oil	45	48	57	92
Natural gas	34	37	45	72
Biomass (max)	42	42	42	42

Note: boe means barrel of oil equivalents

As can be seen the fuel prices may tend to favour the use of biomass in the longer term. It is inherently difficult to make reasonable very long term projections concerning the use of biomass versus hydrocarbons. It should however be noted that the considerable geopolitical uncertainty of the Russian supply of gas at present tends to incline the major energy companies not to invest in gas-fired generation plants. Besides the considerable uncertainty of the long term natural gas price, the monopolistic position of Russian gas supply may mean that natural gas may be priced at least at the level of other relevant alternatives (coal not considered). As the MARKAL Nordic model does not describe these matters, a reasonable way to capture them anyway is to use a not too low price for natural gas.

The international price for biomass is assumed to remain constant. This assumption will hold true if the international land and forest resources will remain relatively abundant. While the European land and forest resources are rather scarce¹³ due to Europe's relatively high population density, less densely populated parts of the world (e.g. Russia, North America, and perhaps even Africa) may become important suppliers of bio energy. This argument is primarily valid for biomass for the energy sector, and may not be appropriate for biocrops for transport sector fuel.

Regarding the future climate policy it is assumed that the Kyoto agreement is continued in the baseline scenario. In model terms this is implemented as a CO₂ tax of 20 Euro/tonne CO₂e. In the model simulations the effect of this tax will be to impede the use of coal.

¹³ It is estimated that at least 10 % of the EU25 primary energy supply can be based on bio crops, see "How much bio energy can Europe produce without harming the environment", EEA report No 7/2006

Results of analyses

The inclusion of green house gas reduction schemes in the energy sector implies that production is shifted from some production technologies to others. For instance an ambitious reduction scheme may make biomass more competitive than coal, even though the fuel price for biomass (and other costs) may be higher. This will have an influence on the CO₂ emissions, which is also the aim of the scheme. Furthermore, it will influence on e.g. electricity and heat prices, production and transmission patterns, final energy use, system costs, and emissions of other pollutants (e.g. NO_x and SO₂).

The analyses within this project have in particular focused on:

- Energy sector MAC curve;
- Electricity generation and investments in new technologies;
- Other combustion of fossil fuels
- Electricity and heat prices.

Energy sector MAC curves

Figure A1 and A2 below show the relation between the CO₂ reduction level and the CO₂ prices in 2020 and 2050, which is equal to the marginal reduction costs in the system.

Figure A1: MAC curve 2020, energy sector (electricity and heat)

Figure A2: MAC curve 2050, energy sector (electricity and heat)

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 CO₂-emissions relatively more competitive. Another reason is an assumed technological development decreasing costs of renewable energy technologies.

Further analyses (not shown in figure) show that the marginal abatement costs increase if the technological development is slower. A lower investment discount rate (3 % p.a. instead of 7 % p.a.) decreases the marginal abatement cost with approximately 20 %. A lower discount rate means that future costs weigh more in the investment decision. Hence, the energy firms are more concerned about the higher future costs of emissions, and subsequently invest in more GHG friendly technologies.

Electricity generation and investments in new technologies

The long term model simulations have been carried out taking also investments in new production facilities into consideration. Thereby, production is not only shifted among existing technologies, where the flexibility is limited, but the reduction scheme also influence on the types of new investments. The following reduction technologies have been included:

- Biomass technologies;
- Wind power;
- Wave power;
- Fossil fuel plants with carbon capture;
- Solar PV;
- Fuel cells.

Apart from these technologies, the model can also choose to invest in conventional power generation technologies such as coal and gas fired power plants without carbon capture. However, investments in new nuclear power facilities have not been included as an option.

The choice of investment depends among others on the technological development, the development in fuel prices, and the reduction level which have been combined in the different scenarios.

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 A3 below shows the relative reduction over time in the investment costs of key technologies.

Table A3: Development in investment costs for key energy technologies

Baseline scenario					
	2005	2010	2020	2030	2050
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%

The cost estimates for CCS are based on IEA (2004) “Prospects for CO₂ capture and storage”. According to IEA, the estimated costs are 20–25 USD/tCO₂ for coal-based generation and 25–30 USD/tCO₂ 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 modeling 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.

Figure A3 below shows the electricity generation pattern in the BaU scenario.

Figure A3: Electricity generation, BaU scenario

It appears from the figure that the hydro power generation remains at a stable level during the analysed period whereas the share of electricity from fossil fuels decreases considerably. After 2030, gas is totally phased out, and in 2050 coal only accounts for 5% of the electricity generation. This is mainly a consequence of the assumptions on the relative prices of natural gas and biofuels, combined with the assumption of a continuation of the Kyoto efforts which prevents the use of coal fired generation.

The by the model chosen reduction technologies in the BaU scenarios includes only biomass and wind power.

In the reduction scenarios, some other reduction technologies come into play, in particular investments in solar PV. In Figure A4 it can be seen that increasing emission costs tend to squeeze out coal (especially around 2020) and natural gas in 2050. In 2020 wind power replaces coal. In 2050 the potential for wind power has been exhausted, and therefore solar PV and (to a small extent wave power) replaces natural gas in the electricity generation system.

Figure A4 Electricity generation technologies in 2020 and 2050 (TWh)

Note: The second axis has been shortened to emphasise the marginal technologies. The base load technologies are hydro and nuclear power.

The reason for the phase out of fossil fuels is that prices on fossil fuel increase considerable during the analysed period, which in combination with the high reduction targets makes fossil fuel technologies uncompetitive in the market.

With respect to carbon capture storage (CCS), the model calculations in general indicate, that this might not play any important role in the future Nordic energy system. Since CCS is assumed to have a capture efficiency of 90% (and not 100%), and since the CCS reduces the electric plant efficiency, fossil fuel technologies with CCS still face relatively high CO₂ costs. This, in combination with the assumed fossil fuel price increase and the assumed technological development during the period, means that investments in CCS do not appear in any of the analysed scenarios.

However, in addition to the scenarios described in this report, two sensitivity analyses regarding CCS were carried out; one assuming a capture efficiency of 100% instead of 90%, and another assuming a price increase in biomass during the period due to limited domestic resources. In both these two situations, investments in CCS come up indicating that the entrance of CCS in the Nordic power system is very sensitive toward a few but important assumptions set up in this matter.

With respect to reduction technologies, it appears that the technologies that come into play are biomass, wind and solar PV. The potential for hydro power is assumed to be almost fully utilised already today, and therefore new investments in hydro power has not been included as an option. Investments in fuel cells do not appear in any of the scenarios indicating that this technology may not be competitive in the market (with the assumptions used).

Figure A5: Industrial, commercial and residential use of fuels (TWh/year)

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 CO₂, 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.

It should be noted that like many other energy models, the MARKAL model has certain limitations on the demand side. There is more emphasis on energy supply and less on long-term demand side efficiency improvements. This means that the model output is likely to underestimate the demand-side response to higher energy prices. As there is likely to be more energy-efficiency measures available, the model outputs will, all else being equal, tend to overstate the abatement costs.

References

Nordel (2005): Annual Report 2005,
Nordel.	first phase of the Nordic Energy Perspectives project. Elforsk. Stockholm. September 2006.
Rydén et al. (2006): Ten Perspectives
on Nordic Energy. Final report of the	

Appendix B: Projections of transport demand and CO₂ emissions from transport 2010–2050

This appendix gives a brief graphic presentation of the forecast of CO₂ 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”. For 2030–50 COWI has assumed the same profile as for 2020–30.

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 there is not included any biomass in the baseline. This is done in order to focus on alternative transport fuels compared to a simple baseline with conventional fuels only – reflecting the situation as of today.

The development in transport demand in the projection is shown in Figure B1 and Figure B2 and Figure B3 and Figure B4 show how the CO₂ emissions develop over time.

Figure B1 Passenger transport activity (Gpkm)

Figure B2 Freight transport activity (Gtkm)

Figure B3 CO₂ Emissions (Mt of CO₂)

Figure B4 CO₂-Emissions (Index)

Appendix C: Other Greenhouse gasses

The contents of the appendix is organized as follows.

Section 1 provides the detailed tables for the GHG emissions inventories in the Nordic countries for the year 2006. The emissions are reported mainly at a 3-digit level, following the UNFCCC common reporting format. These tables form the basis of the baseline projections and the estimation of costs and emission reductions related to non-CO₂ GHGs.

Section 2 presents a summary table of the study by Bates et al. (2004), which has been used for the projections from 2004 to 2020. Assumptions used for the projections until 2050 are shown in section 3.

Section 4 presents a table on the cost estimates of non-CO₂ GHG reductions from the studies by the Energy Modelling Forum-21 and the USEPA (2006). The reductions are reported as total annual reductions at varying level of prices. These prices are “breakeven prices” for the technology options involved in each group of emissions reductions. See the study by the USEPA (2006) for a careful elaboration of the cost estimates.

The cost estimates are available at the homepage of the USEPA: [US EPA - Non-CO₂ Gases Economic Analysis and Inventory: Projections and Mitigation Costs](#) under the section of “International Analysis of All Non-CO₂ GHGs”.

Cost estimates are also available at the Stanford Energy Modelling Forum-21 homepage: [EMF 21 Multi-Gas Mitigation and Climate Change](#). The results of multi-gas modelling by the EMF-21 will be published in the November 2006 edition of the Energy Journal. These results rely on the abatement cost figures reported on the pages indicated, and used in this study, although some revisions have been made to the more recent version of USEPA (2006).

Section 4 presents disaggregated figures of the marginal abatement cost curves for reductions of CH₄, N₂O and F gases, as they are applied in this study.¹ National Communications to UNFCCC

Table C1 GHG Emissions in Denmark, 2004 (Gg)

Greenhouse gas source	CO ₂	CH ₄	N ₂ O	HFCs	PFCs	SF ₆
	(Gg)	(Gg)	(Gg)	CO ₂ eq. (Gg)		
Energy						
Fuel Combustion						
Energy Industries	25.388	15	0			
Manufacturing Industries	5.841	2	0			
Transport						
Other Sectors	7.159	8	0			
Other (military transport)	239	0	0			
Transport						
Civil Aviation	128	0	0			
Road Transportation	12.024	3	1			
Railways	216	0	0			
Navigation	490	0	0			
Other Transportation						
International Bunkers						
Aviation Bunkers	2.447	0	0			
Marine Bunkers	2.545	0	0			
Fugitive Emissions from Fuels						
Solid Fuels						
Coal Mining and Handling						
Solid Fuel Transformation						
Other (flaring)						
Oil and Natural Gas						
Oil		4				
Natural Gas		0				
Venting						
Flaring	608	0	0			
Industry						
Mineral Products						
Cement Production	1.539					
Lime Production	110					
Limestone and Dolomite Use	64					
Soda Ash Production and Use						
Asphalt Roofing	0					
Road Paving with Asphalt	2					
Other	13					
Chemical Industry						
Ammonia Production						
Nitric Acid Production			2			
Adipic Acid Production						
Carbide Production						
Other	3					
Metal Production						
Iron and Steel Production						
Ferroalloys Production						
Aluminium Production						
SF ₆ Used in Al and Mg						
Other						
Other Production						
Pulp and Paper						
Food and Drink						
Consumption of HFC, PFC and SF ₆						
Refrigeration and Air Conditioning Equipment				596	16	
Foam Blowing				144		
Fire Extinguishers						
Aerosols/ Metered Dose Inhalers				9		
Solvents						
Other applications using CFC substitutes						
Semiconductor Manufacture						
Electrical Equipment						10
Other (double glaze windows, labs.)						23
Other						
Solvent and Other Product Use						

Greenhouse gas source	CO ₂	CH ₄	N ₂ O	HFCs	PFCs	SF ₆
	(Gg)	(Gg)	(Gg)	CO ₂ eq. (Gg)		
Paint Application	21					
Degreasing and Dry Cleaning	27					
Chemical Products and Processing	2					
Other	63					
Agricultural Livestock						
Enteric Fermentation						
Dairy Cattle		71				
Non-Dairy Cattle		39				
Sheep		1				
Goats		0				
Horses		3				
Swine		14				
Other						
Manure management						
Dairy Cattle		11				
Non-Dairy Cattle		2				
Sheep		0				
Goats		0				
Horses		0				
Swine		34				
Poultry		0				
Other livestock		1				
Anaerobic Lagoons						
Liquid Systems			0			
Solid Storage and Dry Lot			2			
Other AWMS						
Agricultural Soils						
Direct Soil Emissions						
Synthetic Fertilizers			4			
Animal Manure Applied to Soils			4			
N-fixing Crops			1			
Crop Residue			1			
Cultivation of Histosols			0			
Other Direct Emissions						
Pasture and Range Manure			1			
Indirect Soil Emissions						
Atmospheric Deposition			1			
Nitrogen Leaching and Run-off			6			
Other						
Industrial waste as fertilizer			0			
Sewage sludge as fertilizer			0			
Waste						
Solid Waste Disposal on Land						
Managed Waste		51				
Unmanaged Waste						
Other						
Waste Water Handling						
Industrial Wastewater						
Domestic and Commercial Waste Water		13	0			
Other						
Waste Incineration						
Other (Gasification of biogas)	2					

Source: UNFCCC, Common Reporting Format (2006), Annex I Party GHG Inventory Submissions.

Table C2 GHG Emissions in Sweden, 2004 (Gg)

Greenhouse gas source	CO ₂	CH ₄	N ₂ O	HFCs	PFCs	SF ₆
	(Gg)	(Gg)	(Gg)	CO ₂ eq. (Gg)		
Energy						
Fuel Combustion						
Energy Industries	12.291	3	1			
Manufacturing Industries	11.400	2	2			
Transport						
Other Sectors	5.765	11	1			
Other (military transport)	278	0	0			
Transport						
Civil Aviation	667	0	0			
Road Transportation	18.319	2	0			
Railways	68	0	0			
Navigation	567	0	0			
Other Transportation	265	0	0			
International Bunkers						
Aviation Bunkers	1.772	0	0			
Marine Bunkers	6.503	0	0			
Fugitive Emissions from Fuels						
Solid Fuels						
Coal Mining and Handling						
Solid Fuel Transformation						
Other (flaring)	838					
Oil and Natural Gas						
Oil	2	0				
Natural Gas						
Venting						
Flaring	45					
Industry						
Mineral Products						
Cement Production	1.284					
Lime Production	537					
Limestone and Dolomite Use	141					
Soda Ash Production and Use	30					
Asphalt Roofing						
Road Paving with Asphalt						
Other	8					
Chemical Industry						
Ammonia Production						
Nitric Acid Production			1,378			
Adipic Acid Production						
Carbide Production	53					
Other		0	0			
Metal Production						
Iron and Steel Production	1.798	0				
Ferroalloys Production	256					
Aluminium Production	145				263	
SF ₆ Used in Al and Mg						40
Other	323					
Other Production						
Pulp and Paper						
Food and Drink						
Consumption of HFC, PFC and SF ₆						
Refrigeration and Air Conditioning Equipment				601	5	
Foam Blowing				107		
Fire Extinguishers				6		
Aerosols/ Metered Dose Inhalers				30		
Solvents						
Other applications using CFC substitutes						
Semiconductor Manufacture				0		1
Electrical Equipment						30
Other (double glaze windows, labs.)						12
Other		0	0			

Solvent and Other Product Use

Greenhouse gas source	CO2	CH4	N2O	HFCs	PFCs	SF6
	(Gg)	(Gg)	(Gg)	CO ₂ eq. (Gg)		
Paint Application	48					
Degreasing and Dry Cleaning	0					
Chemical Products and Processing	2					
Other	87		0			
Agricultural Livestock						
Enteric Fermentation						
Dairy Cattle		52				
Non-Dairy Cattle		70				
Sheep		4				
Goats		0				
Horses		5				
Swine		3				
Other		2				
Manure management						
Dairy Cattle		7				
Non-Dairy Cattle		7				
Sheep		0				
Goats		0				
Horses		0				
Swine		6				
Poultry		1				
Other livestock		0				
Anaerobic Lagoons						
Liquid Systems			0			
Solid Storage and Dry Lot			1			
Other AWMS			0			
Agricultural Soils						
Direct Soil Emissions						
Synthetic Fertilizers			2			
Animal Manure Applied to Soils	3					
N-fixing Crops			1			
Crop Residue			1			
Cultivation of Histosols			3			
Other Direct Emissions			0			
Pasture and Range Manure			1			
Indirect Soil Emissions			3			
Atmospheric Deposition						
Nitrogen Leaching and Run-off						
Other						
Industrial waste as fertilizer						
Sewage sludge as fertilizer			2			
Waste						
Solid Waste Disposal on Land						
Managed Waste		99				
Unmanaged Waste						
Other						
Waste Water Handling						
Industrial Wastewater						
Domestic and Commercial Waste Water			0			
Other			0			
Waste Incineration	140					
Other (Gasification of biogas)						

Source: UNFCCC, Common Reporting Format (2006), Annex I Party GHG Inventory Submissions.

Table C3 GHG Emissions in Norway, 2004 (Gg)

Greenhouse gas source	CO ₂	CH ₄	N ₂ O	HFCs	PFCs	SF ₆
	(Gg)	(Gg)	(Gg)	CO ₂ eq. (Gg)		
Energy						
Fuel Combustion						
Energy Industries	12.406	4	0			
Manufacturing Industries	3.886	0	0			
Transport						
Other Sectors	3.576	8	0			
Other (military transport)	330	0	0			
Transport						
Civil Aviation	945	0	0			
Road Transportation	10.003	2	1			
Railways	44	0	0			
Navigation	2.398	0	0			
Other Transportation	691	0	0			
International Bunkers						
Aviation Bunkers	847	0	0			
Marine Bunkers	1.875	0	0			
Fugitive Emissions from Fuels						
Solid Fuels						
Coal Mining and Handling	8	3				
Solid Fuel Transformation						
Other (flaring)						
Oil and Natural Gas						
Oil	1.320	17				
Natural Gas	14	2				
Venting	87	15				
Flaring	1.220	1	0			
Industry						
Mineral Products						
Cement Production	726					
Lime Production	92					
Limestone and Dolomite Use	21					
Soda Ash Production and Use						
Asphalt Roofing						
Road Paving with Asphalt						
Other						
Chemical Industry						
Ammonia Production	497					
Nitric Acid Production			6			
Adipic Acid Production						
Carbide Production	101	0				
Other	3	0				
Metal Production						
Iron and Steel Production	343					
Ferroalloys Production	2.711	1	0			
Aluminium Production	2.084				880	
SF ₆ Used in Al and Mg						206
Other	89					14
Other Production						
Pulp and Paper	10					
Food and Drink	232					
Consumption of HFC, PFC and SF ₆						
Refrigeration and Air Conditioning Equipment				367	1	
Foam Blowing				28		
Fire Extinguishers				5		
Aerosols/ Metered Dose Inhalers						
Solvents						
Other applications using CFC substitutes						
Semiconductor Manufacture						1
Electrical Equipment					0	55
Other (double glaze windows, labs.)						
Other						
Solvent and Other Product Use						

Greenhouse gas source	CO ₂	CH ₄	N ₂ O	HFCs	PFCs	SF ₆
	(Gg)	(Gg)	(Gg)	CO ₂ eq. (Gg)		
Paint Application	24					
Degreasing and Dry Cleaning	1					
Chemical Products and Processing	15					
Other	87	0	0			
Agricultural Livestock						
Enteric Fermentation						
Dairy Cattle		38				
Non-Dairy Cattle		25				
Sheep		22				
Goats		0				
Horses		1				
Swine		1				
Other		3				
Manure management						
Dairy Cattle		5				
Non-Dairy Cattle		5				
Sheep		1				
Goats		0				
Horses		1				
Swine		1				
Poultry		1				
Other livestock		0				
Anaerobic Lagoons						
Liquid Systems			0			
Solid Storage and Dry Lot			0			
Other AWMS						
Agricultural Soils						
Direct Soil Emissions						
Synthetic Fertilizers			2		4	1
Animal Manure Applied to Soils			1		1	1
N-fixing Crops			0		0	0
Crop Residue			0			
Cultivation of Histosols			1			
Other Direct Emissions						
Pasture and Range Manure			1			
Indirect Soil Emissions						
Atmospheric Deposition			0			
Nitrogen Leaching and Run-off			1			
Other						
Industrial waste as fertilizer						
Sewage sludge as fertilizer			0			
Waste						
Solid Waste Disposal on Land						
Managed Waste						
Unmanaged Waste		69				
Other						
Waste Water Handling						
Industrial Wastewater						
Domestic and Commercial Waste Water		1	0			
Other						
Waste Incineration	20	0				
Other (Gasification of biogas)						

Source: UNFCCC, Common Reporting Format (2006), Annex I Party GHG Inventory Submissions.

Table C4 GHG Emissions in Finland, 2004 (Gg)

Greenhouse gas source	CO ₂	CH ₄	N ₂ O	HFCs	PFCs	SF ₆
	(Gg)	(Gg)	(Gg)	CO ₂ eq. (Gg)		
Energy						
Fuel Combustion						
Energy Industries	32.820	1	1			
Manufacturing Industries	11.191	1	1			
Transport						
Other Sectors	5.931	10	0			
Other (military transport)	1.569	0	0			
Transport						
Civil Aviation	332	0	0			
Road Transportation	11.811	2	2			
Railways	140	0	0			
Navigation	523	0	0			
Other Transportation	651	0	0			
International Bunkers						
Aviation Bunkers	1.252	0	0			
Marine Bunkers	1.679	0	0			
Fugitive Emissions from Fuels						
Solid Fuels						
Coal Mining and Handling						
Solid Fuel Transformation						
Other (flaring)	838					
Oil and Natural Gas						
Oil	1	0				
Natural Gas	6	2				
Venting						
Flaring	62					
Industry						
Mineral Products						
Cement Production	560					
Lime Production	528					
Limestone and Dolomite Use	116					
Soda Ash Production and Use	20					
Asphalt Roofing						
Road Paving with Asphalt	2					
Other						
Chemical Industry						
Ammonia Production						
Nitric Acid Production			1			
Adipic Acid Production						
Carbide Production						
Other	172	0	0			
Metal Production						
Iron and Steel Production	2.551	0				
Ferroalloys Production						
Aluminium Production					263	
SF ₆ Used in Al and Mg						40
Other	0					
Other Production						
Pulp and Paper	13					
Food and Drink	4					
Consumption of HFC, PFC and SF ₆						
Refrigeration and Air Conditioning Equipment				601	5	
Foam Blowing					2	
Fire Extinguishers					107	
Aerosols/ Metered Dose Inhalers					6	
Solvents					61	
Other applications using CFC substitutes						
Semiconductor Manufacture				0		1
Electrical Equipment					3	30
Other (double glaze windows, labs.)						12
Other	0	0				

Solvent and Other Product Use

Greenhouse gas source	CO ₂	CH ₄	N ₂ O	HFCs	PFCs	SF ₆
	(Gg)	(Gg)	(Gg)	CO ₂ eq. (Gg)		
Paint Application	48					
Degreasing and Dry Cleaning	0					
Chemical Products and Processing	2					
Other	87	0				
Agricultural Livestock						
Enteric Fermentation						
Dairy Cattle		52				
Non-Dairy Cattle		70				
Sheep		4				
Goats		0				
Horses		5				
Swine		3				
Other		2				
Manure management						
Dairy Cattle		7				
Non-Dairy Cattle		7				
Sheep		0				
Goats		0				
Horses		0				
Swine		6				
Poultry		1				
Other livestock		0				
Anaerobic Lagoons						
Liquid Systems			0			
Solid Storage and Dry Lot			1			
Other AWMS						
Agricultural Soils						
Direct Soil Emissions						
Synthetic Fertilizers			2			
Animal Manure Applied to Soils			3			
N-fixing Crops			1			
Crop Residue			1			
Cultivation of Histosols			3			
Other Direct Emissions			0			
Pasture and Range Manure			1			
Indirect Soil Emissions						
Atmospheric Deposition						
Nitrogen Leaching and Run-off						
Other						
Industrial waste as fertilizer						
Sewage sludge as fertilizer			0			
Waste						
Solid Waste Disposal on Land						
Managed Waste		99				
Unmanaged Waste						
Other						
Waste Water Handling						
Industrial Wastewater			0			
Domestic and Commercial Waste Water			0			
Other						
Waste Incineration	140					
Other (Gasification of biogas)						

Source: UNFCCC, Common Reporting Format (2006), Annex I Party GHG Inventory Submissions.

C2 Data for baseline projections

Table C5 Baseline emissions in study by Bates et al. (2004)

	1990	2000	2010	2020	2030
Nordic countries					
Denmark	18	17	17	17	17
Finland	15	14	15	15	14
Norway	17	16	23	24	25
Sweden	19	17	18	18	17
Greenhouse gases					
CO ₂	186	187	191	208	245
Non-energy CO ₂	5	4	5	5	5
CH ₄	25	24	29	30	29
N ₂ O	33	31	32	28	28
F-gases	6	5	7	11	11
Sinks	0	0	0	0	0
Total	255	251	264	282	318
Other GHGs/Total	0	0	0	0	0
Baseline Denmark					
CO ₂					
Non-energy CO ₂	1	1	1	1	1
CH ₄	6	6	5	5	5
N ₂ O	11	9	9	8	8
F-gases	0	1	2	3	3
Sinks	0	0	0	0	0
Total	18	17	17	17	17
Baseline Finland					
CO ₂					
Non-energy CO ₂	1	1	1	1	1
CH ₄	6	5	5	5	4
N ₂ O	8	7	8	7	7
F-gases	0	1	1	2	2
Sinks	0	0	0	0	0
Total	15	14	15	15	14
Baseline Norway					
CO ₂					
Non-energy CO ₂	1	1	1	1	1
CH ₄	6	7	13	14	15
N ₂ O	5	6	6	5	5
F-gases	5	2	3	4	4
Sinks	0	0	0	0	0
Total	17	16	23	24	25
Baseline Sweden					
CO ₂					
Non-energy CO ₂	2	1	2	2	2
CH ₄	7	6	6	6	5
N ₂ O	9	9	9	8	8
F-gases	1	1	1	2	2
Sinks	0	0	0	0	0
Total	19	17	18	18	17

Source: Projections based on EU study by Bates et al, (2004).

C3 Assumptions in baseline scenario

Table C6 Global Warming Potentials (GWP) used in study

CO ₂ equivalents	CO ₂	CH ₄	N ₂ O	HFCs	PFCs	SF ₆
(Gg = Mt)						
100 year global warming potentials (GWP)	1	23	310	140-1.170	6.500-9.200	23.900

Table C7 Growth rates in the baseline scenario (Gg)

Baseline growth rates		Non-Energy	CH ₄	N ₂ O	HFCs	PFCs	SF ₆
		CO ₂			F gases		
2000-2020	(% per year)	1,3%	1,3%	-0,5%		6,0%	
2004-2020	(% total change)	20,0%	20,0%	-7,7%		96,0%	
2020-2050	(% total change)	0,0%	0,0%	0,0%		0,0%	

C4 Marginal abatement cost curves

Figure C1 MAC curve for methane (CH₄)

Figure C2 MAC curve for nitrous oxide (N₂O)

Figure C3 MAC curve for F gases (HFCs, PFCs and SF₆)