CLIMATE CHANGE

Scientific Assessment and Policy Analysis

WAB 500102 020

Oil prices and climate change mitigation

Sensitivity of cost of mitigation options for energy price changes

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Sensitivity of cost of mitigation options for energy price changes

Report

500102 020

ECN-B--09-008

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March 2009

This study has been performed within the framework of the Netherlands Research Programme on Scientific Assessment and Policy Analysis for Climate Change (WAB), project Sensitivity analysis of costs of mitigation options for future oil price variations.

Wetenschappelijke Assessment en Beleidsanalyse (WAB) Klimaatverandering

Het programma Wetenschappelijke Assessment en Beleidsanalyse Klimaatverandering in opdracht van het ministerie van VROM heeft tot doel:

- Het bijeenbrengen en evalueren van relevante wetenschappelijke informatie ten behoeve van beleidsontwikkeling en besluitvorming op het terrein van klimaatverandering;
- Het analyseren van voornemens en besluiten in het kader van de internationale klimaatonderhandelingen op hun consequenties.

De analyses en assessments beogen een gebalanceerde beoordeling te geven van de stand van de kennis ten behoeve van de onderbouwing van beleidsmatige keuzes. De activiteiten hebben een looptijd van enkele maanden tot maximaal ca. een jaar, afhankelijk van de complexiteit en de urgentie van de beleidsvraag. Per onderwerp wordt een assessment team samengesteld bestaande uit de beste Nederlandse en zonodig buitenlandse experts. Het gaat om incidenteel en additioneel gefinancierde werkzaamheden, te onderscheiden van de reguliere, structureel gefinancierde activiteiten van de deelnemers van het consortium op het gebied van klimaatonderzoek. Er dient steeds te worden uitgegaan van de actuele stand der wetenschap. Doelgroepen zijn de NMP-departementen, met VROM in een coördinerende rol, maar tevens maatschappelijke groeperingen die een belangrijke rol spelen bij de besluitvorming over en uitvoering van het klimaatbeleid. De verantwoordelijkheid voor de uitvoering berust bij een consortium bestaande uit PBL, KNMI, CCB Wageningen-UR, ECN, Vrije Universiteit/CCVUA, UM/ICIS en UU/Copernicus Instituut. Het PBL is hoofdaannemer en fungeert als voorzitter van de Stuurgroep.

Scientific Assessment and Policy Analysis (WAB) Climate Change

The Netherlands Programme on Scientific Assessment and Policy Analysis Climate Change (WAB) has the following objectives:

- Collection and evaluation of relevant scientific information for policy development and decision-making in the field of climate change;
- Analysis of resolutions and decisions in the framework of international climate negotiations and their implications.

WAB conducts analyses and assessments intended for a balanced evaluation of the state-of-the-art for underpinning policy choices. These analyses and assessment activities are carried out in periods of several months to a maximum of one year, depending on the complexity and the urgency of the policy issue. Assessment teams organised to handle the various topics consist of the best Dutch experts in their fields. Teams work on incidental and additionally financed activities, as opposed to the regular, structurally financed activities of the climate research consortium. The work should reflect the current state of science on the relevant topic.

The main commissioning bodies are the National Environmental Policy Plan departments, with the Ministry of Housing, Spatial Planning and the Environment assuming a coordinating role. Work is also commissioned by organisations in society playing an important role in the decision-making process concerned with and the implementation of the climate policy. A consortium consisting of the Netherlands Environmental Assessment Agency (PBL), the Royal Dutch Meteorological Institute, the Climate Change and Biosphere Research Centre (CCB) of Wageningen University and Research Centre (WUR), the Energy research Centre of the Netherlands (ECN), the Netherlands Research Programme on Climate Change Centre at the VU University of Amsterdam (CCVUA), the International Centre for Integrative Studies of the University of Maastricht (UM/ICIS) and the Copernicus Institute at Utrecht University (UU) is responsible for the implementation. The Netherlands Environmental Assessment Agency (PBL), as the main contracting body, is chairing the Steering Committee.

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Preface

This report has been commissioned by the Netherlands Programme on Scientific Assessment and Policy Analysis (WAB) Climate Change. This report has been written by the Energy research Centre of the Netherlands (ECN) and the Dutch Environmental Assessment Agency (PBL).

The Steering Committee for this research consisted of Gert-Jan Kramer, (Shell, Eindhoven University), Rob Aalbers (Netherlands Bureau for Economic Policy Analysis), Ronald Flipphi, Frans Duijnhouwer (both Dutch Ministry of Environment), Klaas-Jan Koops, Esther Berden (both Dutch Ministry of Economic Affairs) Dolf Gielen (IEA/OECD), Lars Müller (DG-Environment), and Ralph Samuelson (New Zealand Ministry of Environment). Their helpful comments are greatly appreciated. We also would like to thank Jos Bruggink (ECN) for his review and various other ECN colleagues, particularly Bert Daniëls, Ad Seebregts, Heleen de Coninck and Pieter Kroon, for their valuable inputs.

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List of acronyms

AC	Abatement cost
AEO	Annual Energy Outlook
APS	Alternative policy scenario
APS	Alternative policy scenario
bbl	barrel (of oil)
CCGT	Combined Cycle Gas Turbine
CCS	CO_2 capture and storage
CEF	CO_2 emission factor
CTL	Coal-to-liquids
DOE	Department of Energy
EIA	Energy Information Administration
ETP	Energy Technology Perspectives
ETS	Emission Trading Scheme
EOR	Enhanced Oil Recovery
GHG	Greenhouse gas
GJ	GigaJoule (10^9 Joule)
IEA	International Energy Agency
IMAGE	Integrated Model to Assess the Global Environment
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquefied natural gas
LNG	Liquefied natural gas
MWh	MegaWatthour
NBP	Net Balancing Point
NMVOC	Volatile organic compounds
NO_x	Oxides of nitrogen
NPV	Net present value
O&M	Operation & maintenance
OCF	Oil cost factor
OECD	Organisation for Economic Cooperation and Development
PCC	Pulverised Coal Combustion
PM	Particulate Matter
PRTP	Pure rate of time preference
SO_2	Sulphur dioxide
SoS	Security of Supply
STRP	Social rate of time preference
TIMER	The TIMER IMAGE Energy Regional Model
TPES	Total Primary Energy Sources
TTF	Title transfer facility
TTF	Title transfer facility
VAT	Value-added tax
WEO	World Energy Outlook
WEO	World Energy Outlook
ZJ	Zeta (10^{21}) Joule

Samenvatting

Afbakening

Trends en volatiliteit in toekomstige olieprijzen kunnen een grote invloed hebben op de kosten en baten van CO_2-reductieopties en hun relatieve aantrekkelijkheid ten opzichte van elkaar. Dit rapport analyseert de invloed van verschillende olieprijsscenario's op

- De CO_2-reductiekosten van mitigatieopties in Europa in 2020, bekeken voor afzonderlijke technologieën met een CO_2-reductiekostenmodel van ECN; en
- Het mondiale energiesysteem en CO_2-emissies tot 2050, gebruik makend van het TIMER model.

Onzekerheid in energieprijzen

De meeste studies over kosten en potentiëlen van mitigatie van klimaatverandering gebruiken relatief lage olieprijzen vergeleken met prijzen in 2008. Het B2 scenario in het IPCC Special Report on Emission Scenarios bijvoorbeeld is gebaseerd op een prijs van ongeveer $\$_{1990}$ 23 per vat ($37 in het prijsniveau van 2006). In recentere studies, zoals het IPCC Fourth Assessment Report, wordt $30-60 gebruikt voor berekeningen in de transportsector. Energy Technology Perspectives 2008 gebruikt $62 in 2030 als aanname.

De piek in de olieprijs in 2008, met waarden tot $147 zou veroorzaakt kunnen zijn door een verhoogde volatiliteit, maar in de periode 2000-2008 hebben we ook een doorgaande stijging van de prijs gezien, wat zou kunnen duiden op een meer structurele trend. Het startpunt voor dit rapport is het feit dat de prijzen boven de $100 van 2008 de mogelijkheid van flink hogere prijzen dan aangenomen in de meeste mitigatiestudies hebben laten zien.

Tabel S.1 laat zien welke energieprijsaannamen we hebben gemaakt voor de analyses in deze studie, voor 2020-2040 in het prijsniveau van 2006, in standaardeenheden en €/GJ.

Tablel S.1 Energieprijsaannamen

		Olie	Aardgas	Steenkool
Prijs 2020-2040		\$/vat	€/m^3	€/ton
Scenario	1 (laag)	37	0.12	61
	2 (referentie)	62	0.19	61
	3 (hoog)	150	0.47	61
	4 (hoog, gasprijsontkoppeling)	150	0.19	61
		€/GJ	€/GJ	€/GJ
Scenario	1	5.0	3.7	2.1
	2	8.4	6.1	2.1
	3	20.2	14.8	2.1
	4	20.2	6.1	2.1

Gevoeligheid van mitigatiekosten voor olieprijzen

Voor deze studie heeft ECN een mitigatiekostenmodel opgezet. Hierin zijn gedetailleerde technologiespecifieke gegevens voor de elektriciteit-, industrie- en transportsector opgenomen. The CO_2-reductiekosten zijn gebaseerd op de meerkosten van een mitigatietechnologie vergeleken met één of twee referentietechnologieën. For elektriciteitsopwekking bijvoorbeeld maken we een vergelijking tussen de kosten van kolen- en gasgebaseerde elektriciteit. De geografische focus is Europa. Met dit model hebben de gevoeligheid van reductiekosten bepaald voor veranderingen in olieprijzen voor een serie mitigatieopties.

Gebaseerd op de uitkomsten hiervan geeft Tabel S.2 'vuistregels' volgens 'als de olieprijs $ 10 per vat verschilt van de referentie dan stijgen/dalen de kosten voor mitigatieoptie y met z €/tCO_2. Bijvoorbeeld 2^e generatie biodiesel (vergeleken met diesel) wordt 29€/tCO_2 goedkoper wanneer de olieprijs tussen 2020 en 2040 10 $ per vat hoger is. De koppeling tussen de olie- en gasprijs is belangrijk voor de gevoeligheid voor veel opties waarbij de referentietechnologie op gas gebaseerd is.

Tabel S.2 Olieprijsgevoeligheden van mitigatiekosten

	Gevoeligheid [€/tCO_2 per $10/bbl]	
	gas-olie koppeling	gas-olie ontkoppeling
Wind onshore (PCC)	0	0
Wind onshore (CCGT)	-18	0
Wind offshore (PCC)	0	0
Wind offshore (CCGT)	-18	0
Nucleair (PCC)	0	0
Nucleair (CCGT)	-18	0
CCGT (PCC)	17	0
Biomassa mee/bijstook (PCC)	0	0
WKK (gas) (CCGT)	-18	0
WKK (kolen) (PCC)	0	0
PCC + CCS (PCC)	0	0
CCGT + CCS (CCGT)	4	0
PV (PCC)	0	0
PV (CCGT)	-18	0
Besparing 1 (referentie efficiency)	-17	0
Besparing 2 (referentie efficiency)	-18	0
CCS (EOR) ammoniakproductie (geen CCS)	-16	-17
CCS (geen EOR) ammoniakproductie (geen CCS)	0.4	0.0
Hybride voertuigen (referentie efficiency)	-26	-26
Biodiesel 1e gen (Diesel)	-29	-29
Bioethanol 1e gen (Benzine)	-29	-29
Biodiesel 2e gen (Diesel)	-27	-27
Bioethanol 2e gen (Benzine)	-28	-28

De volgende technologieën blijken lagere CO_2-reductiekosten te hebben bij een hogere olieprijs:

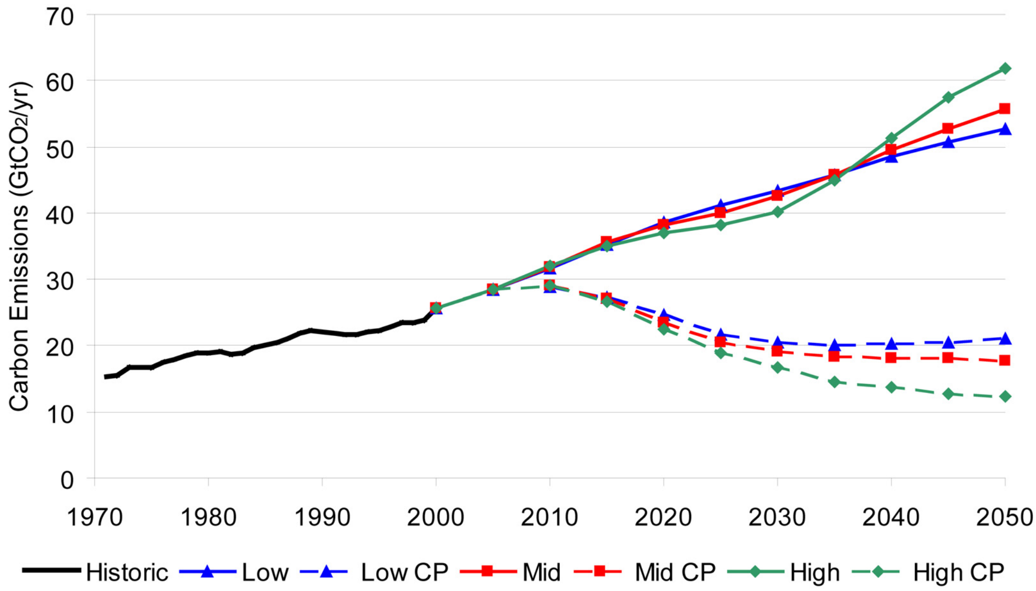
- Hernieuwbare energie, nucleair en gasgestookte Warmte Kracht Koppeling (WKK)
- Besparingsopties in industrie, wanneer deze aardgas gebruikt
- Enhanced Oil Recovery
- Biobrandstoffen (de aanname dat de prijzen hiervan met slechts 10% meestijgen met de olieprijs is cruciaal hier)

Aan de andere kant wordt het duurder om kolengestookte elektriciteit te vervangen door gasgestookte.

Als we aannemen dat de prijs van kolen ook meestijgt met de olieprijs dan worden de elektriciteitstechnologieën met kolen-gestookte centrales als referentie 4 €/tCO_2 goedkoper bij een $10 olieprijsstijging.

Invloed van olieprijzen op energietechnologieën en CO_2-emissies

Naast de aanpak via individuele technologieën hebben we ook een mondiaal energiemodel (TIMER) gebruikt om de invloed van olieprijzen op het mondiale energiesysteem en CO_2-emissies te bepalen (zie Figuur S.1).



Figuur S.1 CO_2-emissies met en zonder klimaatbeleid (CP, 100 \$/tCO_2) voor lage, midden, en hoge olie- en gasprijzen.

De manier waarop energieconsumptie reageert op stijgende olieprijzen (dus de transitie naar alternatieven voor olie) is onzeker en projecties variëren sterk tussen verschillende modellen. Projecties van het TIMER-model laten zien dat hogere olieprijzen over de langere termijn leiden tot een dalend oliegebruik en meer inzet van alternatieven. Deze reactie op hogere olieprijzen is sterker in de TIMER-berekeningen dan, bijvoorbeeld, in de World Energy Outlook van het IEA.

In de afwezigheid van een CO_2-prijs zouden emissies kunnen dalen over de middellange termijn maar sterk kunnen stijgen over de lange termijn door toenemende inzet van kolen. Met een sterk klimaatbeleid (gemodelleerd als een 100 \$/tCO_2-prijs) kunnen hogere olieprijzen resulteren in duidelijk lagere CO_2-emissies bij dezelfde kosten, vooral na 2030. Hiervoor zijn drie redenen:

- In de elektriciteitssector hebben hernieuwbare bronnen en nucleair een betere positie
- Hogere energieprijzen leiden tot een hogere efficiency en lager finaal energiegebruik
- Wanneer waterstof wordt toegepast in de transportsector is er een groot extra potentieel voor CO_2 afvang en opslag. Dit geldt ook voor emissies van coal to liquids (CTL) en elektrische voertuigen, maar deze technologieën zijn niet expliciet meegenomen in TIMER.

Conclusies

Uit de voorgaande analyses trekken we de volgende conclusies:

- Energieprijzen zijn kritische inputs voor berekeningen van kosten van CO_2-reductieopties en energie en emissiescenario's. Gezien het feit dat vele bestaande mitigatiestudies zijn gebaseerd op relatief lage olieprijzen vergeleken met waarden uit 2008, moeten we de resultaten van deze studies voorzichtig interpreteren.
- De CO_2-reductiekosten van veel mitigatieopties gaan sterk omlaag bij stijgende olieprijzen. Dit geldt in het bijzonder voor de duurdere opties (vooral in de transportsector) die zich aan de bovenzijde van de marginale kostencurves bevinden. Hierdoor zal de CO_2-prijs die nodig is om ambitieuze klimaatdoelstellingen te halen substantieel lager zijn wanneer energieprijzen hoger zijn over een langere periode.
- Wat echter niet geconcludeerd kan worden is dat hogere olieprijzen automatisch leiden tot lagere emissies – wat duidelijk blijkt uit Figuur S.1. Op de korte termijn zal er besparing plaatsvinden, maar overstap van gas naar kolen wordt ook aantrekkelijker. Op de langere termijn kunnen hogere olieprijzen leiden tot meer waterstof en elektriciteit in de transportsector. Klimaatbeleid is nodig om ervoor te zorgen dat CCS wordt toegepast, anders zal deze verandering leiden tot significant hogere CO_2-emissies. Als we een CO_2-

prijs van \$ 100 aannemen kan een hogere olieprijzen leiden tot duidelijk lagere emissies, vooral na 2030.

- De relaties tussen prijzen van olie, gas en kolen zijn essentieel in het bepalen van de gevoeligheid van mitigatiekosten bij verschillende olieprijzen. In deze studie hebben we aangenomen dat de gasprijs aan de olieprijs gekoppeld blijft, maar de kolenprijs niet. Vindt er ontkoppeling tussen de gas- en olieprijs plaats dan veranderen de resultaten sterk. Mocht de kolenprijs meestijgen met de olieprijs volgens de zwakke correlatie in de afgelopen decennia dan zullen de mitigatieopties met kolen als referentietechnologie enigszins goedkoper worden.
- De gevonden olieprijsgevoeligheden voor de elektriciteit- en industriesector kunnen worden geëxtrapoleerd naar andere regio’s in de wereld, aangezien de aannamen voor deze opties ook geldig zijn buiten Europa. Voor de transporttechnologieën (biobrandstoffen en hybride voertuigen) is het moeilijker te bepalen in hoeverre de kwantitatieve resultaten ook geldig zijn buiten Europa, maar duidelijk is dat deze opties goedkoper worden onafhankelijk naar welke regio worden gekeken.
- Hogere energieprijzen kunnen de kosten van materialen zoals staal en aluminium beïnvloeden. Doordat energietechnologieën verschillen in het gebruik van deze materialen kunnen hierdoor ook mitigatiekosten veranderen. Recent onderzoek echter toont aan dat dit effect waarschijnlijk erg klein is, en binnen de algemene onzekerheid van technologieën valt.

We laten zien dat de kosten van belangrijke mitigatie-opties sterk afhangen van olieprijzen, welke sterk variëren. Dit impliceert een risico voor de betaalbaarheid van klimaatbeleid, en we bevelen aan dat klimaatbeleid meer olieprijsresistent wordt gemaakt. Een logische keuze is het beleid te richten op die opties die emissies én olieafhankelijkheid reduceren, zoals besparing. Beleidsmakers kunnen ook overwegen meer prikkels te geven aan sector die veel olie consumeren en die welke een hogere CO_2-uitstoot geven bij hoge olieprijzen. Een voorbeeld hiervan is CO_2-afvang en –opslag, die een verhoogde uitstoot kunnen voorkomen wanneer in de transportsector coal to liquids (CTL), waterstof en elektrische voertuigen belangrijk worden. Daarnaast zou er meer zekerheid voor investeerders kunnen worden bewerkstelligd wanneer beleid olieprijsrisico’s op zich zou nemen, hoewel dit natuurlijk de onzekerheid voor het beleid verhoogt. Constructies waarbij het risico wordt gedeeld zouden kunnen worden geprefereerd. Onze belangrijkste beleidsaanbeveling is dat prijsrisico’s (van olie en eventueel andere composities) expliciet moeten worden meegenomen in beleidskeuzes.

Deze studie geeft meer inzicht in de invloed van olieprijzen op CO_2-reductieopties. Er zijn ook beperkingen aan deze studie, waar toekomstig onderzoek zich op zou kunnen richten.

- De effecten van volatiliteit van energieprijzen hebben we in dit onderzoek niet goed mee kunnen nemen doordat hier nog geen wetenschappelijk toepasbare methoden voor zijn gevonden. Dit effect zou heel belangrijk kunnen zijn en zelfs kunnen toenemen naarmate de prijzen stijgen, wat heel belangrijk is voor zowel publieke als private investeerders. Mogelijke richting van aanpak zou kunnen zijn het toepassen van verschillende discontovoeten voor technologieën aan de hand van investeringsrisico en een risicopremie voor brandstoffen met een hoge volatiliteit. Op deze manier kunnen externaliteiten van energievoorzienings-zekerheid worden meegenomen in sociale kosten-batenanalyse van mitigatieopties.
- Hoge energieprijzen en klimaatbeleid kunnen leiden tot een lagere vraag naar olie, en op deze manier de prijs van olie weer doen dalen. Een kwantitatieve analyse van deze 2^{e} orde-effecten was buiten het blikveld van deze studie. Meer onderzoek is nodig om te komen tot een consistentie analyse van de interacties tussen olieprijzen en klimaatbeleid.

Executive Summary

Scope
Future oil price trends and oil price volatility have a major impact on the economic attractiveness of distinct mitigation options and their mutual unit cost rankings. This report assesses the impact of different oil price scenarios on:

- the abatement costs of mitigation options in Europe in 2020, using a technology-by-technology approach with an ECN Abatement Cost model; and;
- the global energy system and CO_2 emissions until 2050, using the TIMER model.

Energy price uncertainty
Most studies related to cost and potential of climate change mitigation are using relatively low oil prices compared to prices prevalent in 2008. For instance the B2 scenario in the IPCC Special Report on Emission Scenarios is based on approximately $\$_{1990}$ 23 per barrel, or $ 37 in 2006 price levels. In more recent calculations, such as the IPCC Fourth Assessment report $30-60 is used for the transport sector. The IEA Energy Technology Perspectives 2008 uses $\$_{2006}$ 62 in 2030. The oil price spike in 2008 with values up to $147 could be due to increased price volatility, however in the period 2000-2008 we have also seen a steady increase in price which could point to a more structural trend. The starting point for this report is the fact that the prices more than $100 in 2009 show the possibility of substantially higher energy prices than assumed in the published mitigation studies.

The next table shows the energy price assumptions in four scenarios used in the current study, for 2020-240 in 2006 price levels, in traditional units and in €/GJ.

Table S.1 Energy price assumptions (2006 price indices)

		Oil	Natural gas	Coking coal
Price 2020-40		$/barrel	€/m^3	€/tonne
Scenario	1 (low)	37		61
	2 (baseline)	62	0.19	61
	3 (high)	150	0.47	61
	4 (high, gas decoupling)	150	0.19	61
		€/GJ	€/GJ	€/GJ
Scenario	1	5.0	3.7	2.1
	2	8.4	6.1	2.1
	3	20.2	14.8	2.1
	4	20.2	6.1	2.1

Sensitivity of abatement cost to oil prices
For the purpose of this study, ECN developed an Abatement Cost model (AC model). This includes detailed technology-specific data on technologies in the electricity, industry and transport sector. The abatement costs are based on the incremental cost of a mitigation technology compared to one or two reference technologies in 2020. For electricity generating options, for instance, a comparison is made with pulverised coal combustion (PCC) and Combined Cycle Gas Turbines (CCGT). The geographical scope is Europe. With this model we have estimated the sensitivity of the CO_2 abatement cost of a range of options for changes in oil prices.

Table S.2 gives 'rules of thumb' according to the format: 'if the oil price departs from the reference by 10 $/bbl, then mitigation option y will cost z €/tCO_2-eq less or more', e.g. 2nd generation biodiesel (reference diesel) becomes 29 €/tCO_2 cheaper when the oil price between 2020 and 2040 is $10 per barrel higher. For abatement cost of option using a gas-based reference technology it is clear that the linkage between gas and oil prices is key to the sensitivities.

Table S.2 Oil price sensitivities: 'if the oil price departs from the reference by 10 \$/bbl, then mitigation option y will cost z \$/tCO$_2$-eq less or more compared to the baseline estimate'

	Sensitivity [€/tCO$_2$ per \$10/bbl]	
	gas-oil coupling	gas-oil decoupling
Wind onshore (PCC)	0	0
Wind onshore (CCGT)	-18	0
Wind offshore (PCC)	0	0
Wind offshore (CCGT)	-18	0
Nuclear (PCC)	0	0
Nuclear (CCGT)	-18	0
CCGT (PCC)	17	0
Biomass co-firing (PCC)	0	0
CHP (gas) (CCGT)	-18	0
CHP (coal) (PCC)	0	0
PCC + CCS (PCC)	0	0
CCGT + CCS (CCGT)	4	0
PV (PCC)	0	0
PV (CCGT)	-18	0
Efficiency 1 (Baseline efficiency)	-17	0
Efficiency 2 (Baseline efficiency)	-18	0
CCS (EOR) ammonia (no CCS)	-16	-17
CCS (no EOR) ammonia (no CCS)	0.4	0.0
Biomass feedstock (Fossil feedstock)	0	0
Hybrid light duty cars (Baseline efficiency)	-26	-26
Biodiesel 1st gen (Diesel)	-29	-29
Bioethanol 1st gen (Gasoline)	-29	-29
Biodiesel 2nd gen (Diesel)	-27	-27
Bioethanol 2nd gen (Gasoline)	-28	-28

Based on this, assuming coupling between gas and oil prices, it appears that technologies that may benefit significantly from higher oil prices are:

- Renewable electricity, nuclear and gas-based CHP compared to CCGT
- Energy efficiency options in industry, using natural gas as primary energy input
- Enhanced Oil Recovery
- Biofuels may benefit the most (but the assumption that biofuel price elasticity for oil prices is 10% is critical here).
- However fuel switch from coal to gas becomes more expensive.

In case it is assumed that coal prices would be coupled to oil prices, the electricity options with PCC as a reference option become 4 €/tCO$_2$ cheaper when the oil price increase by \$10 per barrel.

Impact of oil prices on energy technologies and global CO$_2$ emissions

In addition to this technology-by-technology approach we have used a global energy model (TIMER) to assess impacts of different oil prices on the global energy system and the resulting CO$_2$ emissions (see Figure S.1).

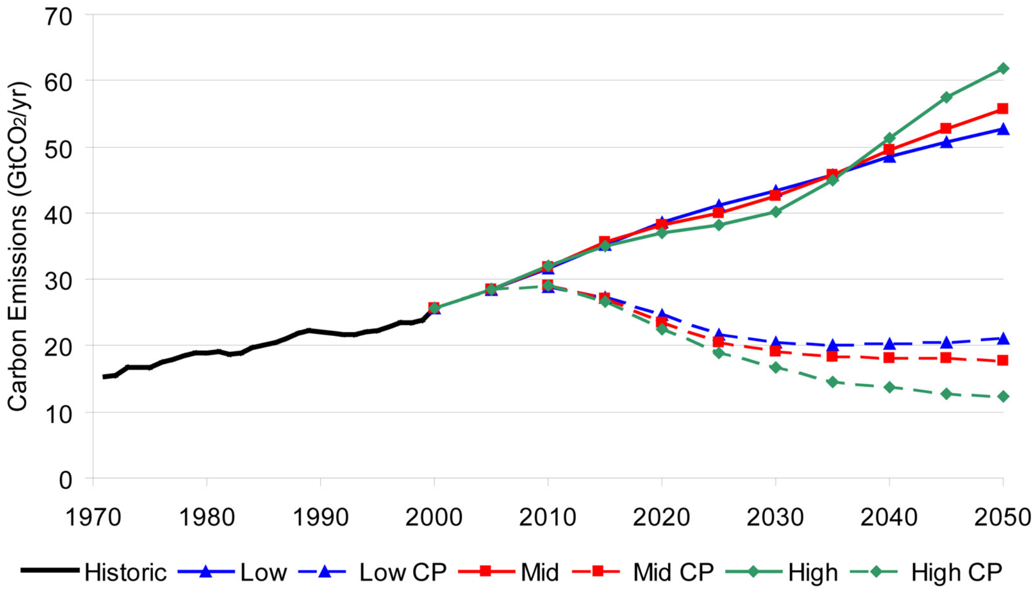


Figure S.1 CO_2 emissions with and without climate policy (CP, 100 \$/tCO_2) for medium, low and high oil/gas prices (which correspond to Scenario 1, 2 and 3 in Table S.1)

The response of consumption patterns to rising oil prices (i.e. the transition away from oil towards alternative options) is uncertain and projections vary widely between different models. Projections of TIMER show that long-term high oil prices lead to an increased use of alternative fuels and a decreasing use of oil. This response to oil price increases is much stronger in the TIMER calculations than in, for instance, the IEA World Energy Outlook.

In the absence of a carbon price, emissions may decrease in the medium term, but increase significantly in the long term due to the increased use of coal. With a strong climate policy (modelled as a \$100 CO_2 price) higher oil prices result in substantially lower CO_2 emissions at the same costs, particularly after 2030. There are three major reasons for this:

- In electricity production, there is an improved position of renewable energy sources and nuclear energy
- Higher energy prices lead to an increase in efficiency and hence, lower final energy use
- Once hydrogen enters the transport sector, there is a large additional potential for CCS. This holds also, at least to a large extent, for emissions from CTL or electric vehicles, technologies that are not explicitly considered in TIMER.

Conclusions

Based on the preceding analyses we draw the following conclusions:

- Energy prices are a key input for the calculation of abatement costs of mitigation options as well as energy and CO_2 emission scenarios. As many existing mitigation studies are based on low energy prices compared to 2008 levels, the results of these should be interpreted with care.
- In terms of CO_2 abatement costs, many mitigation options become significantly cheaper with higher oil prices. In particular the more expensive (i.e. transport) options, which are at the margin of the cost curves, become substantially cheaper at higher oil prices. Therefore carbon prices that are needed to achieve ambitious mitigation targets will be lower at sustained high oil prices.
- It should however not be concluded that high oil prices will automatically lead to lower emissions, as shown in Figure S.1. In the short term energy efficiency is likely to increase, but a switch from natural gas to coal also is more attractive. In the longer term high oil prices may lead to more hydrogen and electricity in the transport sector. Climate policy is needed to ensure that CCS is deployed; otherwise, this could lead to a large increase in emissions.

When assuming a \$100 CO_2 price on the other hand, a higher oil price could lead to substantially lower emissions, particularly after 2030.

- Relations between prices of oil, gas and coal are crucial in sensitivity assessment of mitigation options for different oil price levels. In this study we have assumed that gas prices are coupled to oil, but coal prices are not. If the gas-oil coupling will not continue in the future the results would change. If coal prices rises with oil price according to historic correlation the mitigation options with coal as reference will benefit to some extent.
- Oil price sensitivities for mitigation options in the power and industry can be extrapolated to other world regions, as assumptions are valid outside Europe as well. For transport options assessed (i.e. biofuels and hybrid vehicles) it is more difficult to assess to what extent the quantitative results are valid outside Europe, but it is clear that these options will also strongly benefit from higher oil prices.
- High energy prices may also influence the costs of other commodities, like steel or aluminium. Because some energy technologies are more steel-intensive than others (e.g. CCS, Wind or PV), this might change the cost differences between energy options as well. However recent research shows that this impact is likely to be small, as the cost of energy determines these commodity prices only to a limited extent.

We have shown that the costs of several essential climate mitigation options depend heavily on the oil prices, and oil prices fluctuate greatly. This could pose a significant risk for the affordability of climate policy and it is recommended that climate policy is made more oil-price resistant. A logical choice is to focus policy on measures and technologies that both reduce emissions and reduce oil dependence, such as energy efficiency. Policymakers could also consider providing more incentives in those sectors that are particularly oil-dependent and that would see deployment of climate-unfriendly technologies in the case of high oil prices. An example is CCS, which could prevent increasing emissions due to transport technologies such as CTL, hydrogen and electric vehicles, as well from a switch from gas to coal. In addition, policies that take on risks in oil price developments would give certainty to investors, but uncertainty for government budgets. Risk-sharing constructions might be preferable. The main policy recommendation is that oil (and potentially other commodity) price risks need to be made explicit in choosing policies.

The current study sheds light on the issues related to oil price impacts on mitigation technologies. However some important limitations need to be noted. These could be addressed by future research.

- Effects of volatility of energy prices have not been included in the analysis in this study due to lack of scientific methods at our disposal that could assess this properly. Volatility may however increase as fuel prices rise and are an important factor of uncertainty both for national governments as well as the private sector. Possible approaches could include applying different discount rates to technologies according to risk investor risk and a fuel risk premium for fuels with particularly high volatility. This could be a way of including externalities of energy supply security into social cost-benefit analysis of mitigation options.
- High prices as well as climate policy may lead to lower demand for oil, and thereby reduces oil prices. A quantitative assessment of these possible 2nd order price effects was outside of the scope of this study. More analysis may be needed to come up with a more consistent assessment of the interaction between oil prices and climate policy.

1 Introduction

This report focuses on the impact of the evolution of the world oil price on the cost of future GHG mitigation measures. Projections of the cost of mitigation policies are a key input for national and international negotiations on future mitigation of GHG emissions among public policy makers and other stakeholders.

Future oil price trends and oil price volatility have a major impact on the economic attractiveness of distinct mitigation options and their mutual unit CO_2 abatement cost rankings. Consider, for instance, the net cost of the option of CCS (carbon capture and storage) in combination with enhanced oil recovery in case of a surge in oil prices. Such event may trigger the costs of CCS in a significant downward direction.

Most studies related to cost and potential of climate change mitigation are using relatively low oil prices compared to prices prevalent today. For instance the B2 scenario in the IPCC Special Report on Emission Scenarios is based on approximately $\$_{1990}$ 23 per barrel (IPCC, 2007), or \$ 37 in 2006 price levels. More recent calculations, such as in the IPCC Fourth Assessment report \$30-60 is used in the abatement cost calculations for the transport sector (IPCC, 2007). The Energy Technology Perspectives 2008 (IEA/OECD, 2008b), uses $\$_{2006}$ 62 in 2030.

However virtually throughout the year 2008 oil prices have been higher than \$100 per barrel, with a maximum of \$147. In the fourth quarter of 2008 the oil price has plummeted to values around \$40 per barrel, where it still is as of February 2009. An important question is whether the higher oil prices in 2008 are a result of increased volatility or whether there could be a more structural trend. In this regard we note the steady increase in prices from approximately \$20 in 2000 to over \$80 in early 2008 (DOE/EIA, 2008a).

This report however does not focus on this question. What is important is that the 2008 prices have shown at least the theoretical possibility of substantially higher energy prices than assumed in the published mitigation studies. Therefore it would be helpful for policymakers if it is possible to say ‘when the oil prices is x \$/bbl higher than assumed in an existing study, the cost of mitigation option y will be reduced/increased by z €/tCO_2-eq. This study therefore aims to shed light on the impact of changes in energy prices on the CO_2 abatement cost of different mitigation options. In addition, the impact of oil prices on energy and emission scenarios needs further attention.

After discussing several published oil price scenarios (Chapter 2), this report therefore assesses the impact of different oil price scenarios on:
1. the abatement costs of mitigation options in Europe in 2020 (Chapter 3 and 4), using a technology-by-technology approach with an ECN Abatement Cost model; and;
2. the global energy system and CO_2 emissions until 2050 (Chapter 5), using the TIMER model.

These two parts use different models and are distinct in nature, and thereby may use different technology assumptions. Only the energy price scenarios are aligned. The appendices, where the methodology and assumptions for the abatement cost sensitivity analysis is explained, only applies to the analysis in Chapter 3 and 4.

2 Energy price scenarios

This chapter aims to give an overview of published oil price scenarios, and its impacts on prices of natural gas and coal. Also the energy price scenarios selected in the analysis are explained.

Oil price scenarios
The IEA World Energy Outlook (WEO) is a comprehensive analysis of global energy-related trends. Its scenarios are the most widely used in energy analysis. The latest WEO was issued in November 2008. Table 2.1 shows energy prices used in the WEO 2008 and 2007 (assumptions in the latter are also used in the Energy Technology Perspectives 2008 (IEA/OECD, 2008b).

Table 2.1 Fossil energy prices in the IEA WEO 2007 and 2008 Reference scenario

		WEO	2006	2007	2010	2015	2020
2007 IEA crude oil imports	$\$_{2006}$/bbl	2007	62		59	57	62
	$\$_{2007}$/bbl	2008		69	100	100	110
Gas European imports	$\$_{2006}$/MBtu	2007	7.3		6.6	6.6	7.3
	$\$_{2007}$/MBtu	2008		7.0	11.1	11.5	12.7
OECD steam coal imports	$\$_{2006}$/tonne	2007	63		56	57	61
	$\$_{2007}$/tonne	2008		72.8	120	120	116.7

In the Alternative Policy Scenario (APS), various policies related to climate and energy security are implemented. These policies would yield substantial improvements in energy efficiency and reductions in energy imports. Oil and gas prices in the APS are similar however to the Reference Scenario. Only for coal, the price in 2030 would be lower: $55 per tonne.

The Annual Energy Outlook is prepared by the US Energy Information Administration, and includes long-term projections of energy supply, demand and prices. Its projections are based on EIA's National Energy Modeling System. Table 2.2 contains energy price projection from AEO 2008 (DOE/EIA, 2008a), where the Reference, High and Low scenarios refer to the oil price scenarios given in Figure 2.1.

Table 2.2 Fossil energy prices in the AEO 2008 scenarios (US$\$_{2006}$)

	Scenario	2006	2010	2015	2030
IEA crude oil imports ($/bbl)	Reference	59	65	52	70
	High			93	119
	Low			34	42
Natural gas wellhead price ($/MBtu)	Reference	6.2	6.2	5.2	6.5
	High		6.2	5.9	7.9
	Low			4.5	5.7
OECD steam coal imports ($/tonne)	Reference	53	55	52	52
	High			53	54
	High coal cost			59	78

The oil price scenarios are also given in Figure 2.1.

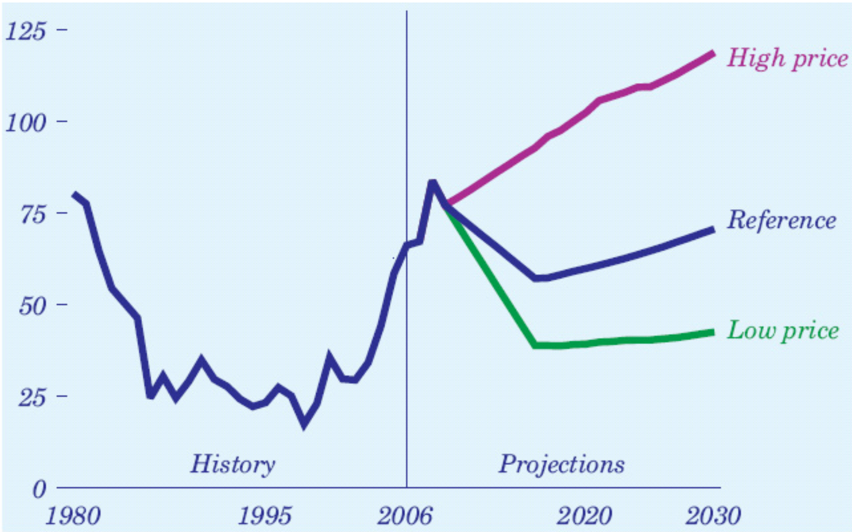


Figure 2.1 Oil price scenarios in the AEO2008 ($2006)(DOE/EIA, 2008a)

It can be observed that the prices for each of the three fossil energy sources the prices scenarios differ considerably. The AEO2008 states: “The low and high price cases reflect a wide band of potential world oil price paths, ranging from $42 to $119 per barrel in 2030, but they do not bound the set of all possible future outcomes. The high and low oil price cases are predicated on assumptions about access to and costs of non-OPEC oil, OPEC supply decisions, and the supply potential of unconventional liquids. Combining those assumptions with different assumptions about the demand for oil would produce a wider range of oil price paths” (DOE/EIA, 2008a).

The High Oil Project (HOP!, Fiorello et al (2008)) has considered the impact of a range of high oil price scenarios on energy policies. Figure 2.2 shows the scenarios they analysed in €$_{2000}$[1].

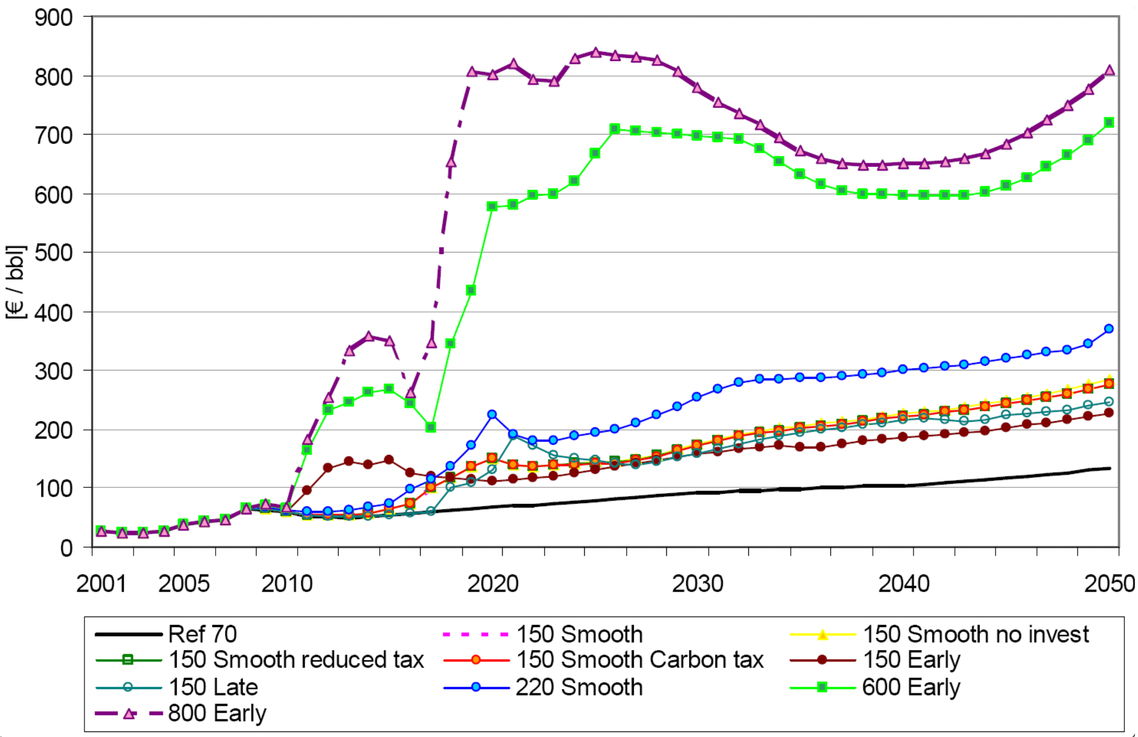


Figure 2.2 Oil price scenarios in the HOP! Project (Fiorello et al, 2008)

[1] E.g. a price of 150 €$_{2000}$/bbl would correspond to 179 €$_{2008}$/bbl.

Jesse and Van der Linde (2008) analyse the oil price outlook for the coming decade. They argue that $110 per barrel could be price floor. This price consists mainly of the marginal cost of production, but other factors are supply-demand fundamentals, a short-term risk premium, and long term scarcity and policy. Prices of over $ 200 dollars are considered possible, a conclusion shared by Goldman Sachs (2008).

Other comprehensive oil price scenarios were not found. Though the OPEC produces a World Oil Outlook (OPEC, 2007) with an outlook for oil supply and demand up to 2030, this does not contain price projections.

2.1 Gas and coal price scenarios

A key issue in this study is the linkage between prices of oil, natural gas and coal. In Appendix A the relation between gas and oil prices is analysed. There has been a correlation in the past and this could continue, but in the long run it seems inevitable that over the long term gas prices will be less strictly linked to oil prices, and a relation to coal prices is also possible.

The WEO 2007 (IEA/OECD, 2007; pp 64-65) assumes that the natural gas price follows the oil price trend, because of inter-fuel competition and widespread oil-indexation in long-term gas supply contracts. Index for gas to oil is 0.63, while for coal the correlation factor to oil is 0.22. In the WEO 2008 this correlation slowly declines after 2020, i.e. the oil price rises faster than the price of coal.

Annex B gives an analysis of the historical correlation between coal and oil prices. It appears there has been a correlation in the past until the 1970s, but since then coal prices have not changed significantly with oil price changes, which showed much more volatility. DOE/EIA (2008b) projects no substantial change in coal prices until 2030 compared to historical levels, even though oil price projections are much higher than prices over the past decade. The role of substitution effects between oil, gas and coal remains a matter of debate. In summary, literature shows a variety of possibilities regarding correlation between coal and oil prices.

Scenarios selected
For the purpose of this study (i.e. analysing the sensitivity of GHG abatement cost to oil prices), it is desirable to have at least the following three oil price scenarios

1. a relatively low price that is in line with major baseline mitigation cost studies such as the IPCC Special Report on Emission Scenarios (i.e. lower than $40)
2. a middle scenario that is in line with authoritative price projections from the IEA (such as $62 from the World Energy Outlook 2007)
3. a price scenario that is significantly higher than most official projections (that tend to be conservative) but still credible

For prices of natural gas we assumed coupling with the oil price as has been the case till date. However, as this could change in the future we added a scenario:

4. high oil price but decoupling of natural gas price.

Another important uncertainty is the relation with coal prices, as analysed in Annex B. Analysing historical data, it could be concluded there is statistical relation. However the nature of this relation is very different from the gas-oil coupling, which has been explicitly established. In other words, the oil-coal relation cannot be explained by fundamental factors. Therefore we deem it unreasonable to assume a constant quantitative coal-oil factor for our scenarios: there is no reason that the coal price would double were the oil price to double (even though it is likely that the coal price would rise by a certain amount). The coal price is therefore assumed to be the same in all four scenarios. On the other hand, looking at the relative prices of coal compared to oil, a factor 10 between them in 2030 seems very unlikely, given that in the future stronger substitution options are viable (e.g. coal-to-liquids).

The next table shows the energy price assumptions in the four scenarios, for 2020-240 in 2006 price levels, in traditional units and in €/GJ.

Table 2.3 Energy price assumptions (2006 price indices)

Price 2020-40		Oil $/barrel	Natural gas €/m^3	Coking coal €/tonne
Scenario	1 (low)	37	0.116	61
	2 (baseline)	62	0.194	61
	3 (high)	150	0.47	61
	4 (high, gas decoupling)	150	0.194	61
		€/GJ	€/GJ	€/GJ
Scenario	1	5.0	3.7	2.1
	2	8.4	6.1	2.1
	3	20.2	14.8	2.1
	4	20.2	6.1	2.1

In order to estimate the impact of these assumptions we will include some extra ‘sensitivity’ cases, one of which will include a high coal price that is linked to the high oil price.

3 Baseline cost of selected mitigation options

3.1 Selection of mitigation options

In this study the focus in on CO_2 reduction options in the electricity, industry and transport sector in Europe. In the selection of mitigation technologies to be included in the analysis we used the following criteria:

- They should cover different ‘groups’, i.e. different sensitivities to oil prices;
- Data availability should be good in order to provide a meaningful analysis;
- The mitigation potential the overall list of options covers should be large.

Table 3.1 shows the mitigation technologies as well as the reference technologies included in the sensitivity analysis in Chapter 3 and 4. The CO_2 abatement figures shown refer to the global emission reductions in 2030 the Blue MAP scenario (IEA/OECD, 2008b), which is consistent with a 550 ppmv GHG stabilisation scenario. The total CO_2 abatement compared to the baseline is 42 $GtCO_2$. The abatement of the options included in our study adds up to 20-22 $GtCO_2$, excluding CHP (for which no figures were found).

Table 3.1 Mitigation options selected in further analysis and 2030 mitigation potentials

Sector	Mitigation option/ *Reference option*	Blue MAP abatement ($GtCO_2$/yr)	Remarks
electricity	Wind on-shore / offshore	2.14	
	Photovoltaics	1.32	
	Nuclear	2.8	
	Fuel switch coal to gas (new-build)	1.07	Potential[2]
	Biomass co-firing	1.45	Incl. gasification
	CHP (gas-based and coal-based)	no data found	
	PCC + CCS and CCGT + CCS	4.85	
	PCC	-	
	CCGT	-	
Industry	Energy efficiency package 1 and 2	1.3-4.0	Potential[3] IPCC, 2007
	Baseline efficiency	-	
	CCS (with and without EOR) in ammonia production	0.15	Potential IPCC, 2007
	Ammonia production without CCS	-	
	Biomass feedstock in chemical industry[4]	0.1	
	Oil-based feedstock	-	
Transport	Biodiesel 1st generation	n/a	
	Biodiesel 2nd generation	2.16	Total biofuel 1st and 2nd generation[5]
	Diesel	-	
	Bio-ethanol 1st generation	n/a	
	Bio-ethanol 2nd generation		
	Gasoline	-	
	Hybrid light-duty vehicles	2.00	Electric + plug-in
	Baseline diesel vehicle	-	

n/a: not applicable (1st and 2nd biofuels compete with each other, therefore the potential can only be given for bioethanol or biodiesel in general)

2 Abatement potential in IPCC (2007), including efficiency improvements.
3 Includes process emission reductions.
4 Not included in further analysis due to data limitations.
5 IPCC (2007) reports a potential of 0.6 - 1.5 $GtCO_2$/yr reduction in 2030 up to \$25/tCO_2.

Notes to Table 3.1:

- Fuel switch in the power sector is covered by new CCGT compared to new PCC plants
- CCS in the electricity sector entails storage in saline aquifers or empty hydrocarbon fields, CCS in ammonia production is both with and without Enhanced Oil Recovery in order to clearly show the sensitivity to oil prices in the further analysis.
- Energy efficiency in industry covers two sets (package 2 more extensive and expensive than package 1) of small options in industry sectors included in the EU ETS. These only include technologies that reduce final energy-related fuel consumption, i.e. electricity saving options are excluded.
- Four biofuel options are included in order to cover both 1st and 2nd generation, and the gasoline and diesel 'routes'.

The buildings sector is excluded because of:

- Limited data availability
- Large differences between different countries in Europe, which would result in a very large range of abatement costs and sensitivities
- Costs are not likely to be the determining factor in mitigation in buildings, as indicated by the negative costs of most options. Therefore conclusions regarding sensitivity to oil prices are of limited use for policymaking.

For energy efficiency in cars only hybrid cars are included because this is a technology for which mitigation cost can be calculated specifically. Other efficiency improvements are more diverse (engine downsizing, use of brake energy, energy-efficient tyres, etc), making quantitative analysis more complicated. However, the sensitivity to oil prices is likely to be comparable.

Non-CO_2 greenhouse gases are excluded because of (a combination of) limited potential and limited sensitivity to oil prices. Other sectors are outside the scope of this report due to time constraints.

Even though our sensitivity analysis focuses on Europe, we hereby indicate that the options included cover more than half of the global potential for CO_2 reduction. In addition, several mitigation options are similar to others not included in the analysis: for CCS in ammonia production (with or without enhance oil recovery (EOR)), the abatement cost and the sensitivity to oil prices can be extrapolated to other industry sectors such as ethylene and hydrogen production and refineries.

3.2 Abatement cost calculation methodology

CO_2 abatement cost of mitigation technologies can be calculated in different ways. In this section we briefly describe our methodology and approach.

CO_2 abatement costs are calculated by the difference between the cost of a mitigation technology compared to a baseline (divided by the difference in CO_2 emission factors). Establishing a consistent baseline across all sectors for the studied region can be done using energy-economic modelling (e.g. as done in Daniels and Farla (2006) and in model runs in Chapter 5). This is however beyond the scope of this part of the study. Therefore we use a simple approach: we calculate abatement cost based on the cost of a mitigation technology (e.g. on-shore wind power, T1) and the cost of one specific reference technology (e.g. coal-fired power, R1), divided by the difference in CO_2 emission factor (also used in e.g. McKinsey, 2009).

$$AC_{M1} = \frac{Cost_{T1} - Cost_{R1}}{CEF_{R1} - CEF_{T1}} = \frac{60-40[€/MWh]}{0.85-0[tCO_2/MWh]} = 23.5€/tCO_2 \quad \text{(Eq. 3.1, example only)}$$

With:

AC_{M1}	Abatement cost of Mitigation option (M)
Cost	Cost of technology (T) or reference (R)
CEF	CO_2 emission factor

The timeframe is 2020 – 2040, using the annuity method to depreciate investments, and geographical scope Europe. Annex E, F and G show more specifically the approach for the different sectors.

The costs of technologies can be calculated in different ways. In this study we distinguish three different cost approaches[6,7]:

- Economic cost. This approach looks at technologies from national point of view, i.e. transfers between producers and consumers, and between governments are excluded (taxes and subsidies are not taken into account). Also the discount rate is set a 'social' level.
- Private cost, or the investor point of view. In this case the discount rate is set at a level applicable to investment decision common in the private sector. Also taxes and subsidies are being included[8].
- Social cost. Here the assumptions of the economic cost approach are used, but in addition externalities (cost borne by society but not taken into account in the investment decision) are included.

In the calculations in Chapter 3 and 4 only the first two approaches are used.

In order to take due account of the inherent uncertainties in the assumptions for the cost calculations, we use a Monte Carlo analysis (@RISK add-on in Excel). The ranges for the input values (e.g. investment cost for wind on-shore between 1250 and 2100 Euro/kW_e) refer to the 95% confidence interval. In the Monte Carlo analysis all the input values are varied in a large number of simulations, which results in an output value distribution (e.g. 38 – 70 €/MWh for off-shore wind).

Outside of the scope of this study is:

- Second order effects, e.g. increase in renewable is likely to reduce demand for fossil fuels and thereby may decrease fossil fuel prices. In that regard oil prices and climate policy interact with each other. This study however assumes constant fossil fuel prices over the period 2020-2040 in order to make the conclusions from the oil price sensitivity analysis as clear as possible. In the modelling analysis in Chapter 5 however an evolution of prices is assumed.
- Impact of uncertainty/volatility in fuel prices on investment decisions; strong volatility for e.g. gas prices could decrease attractiveness for investments in gas-fired power stations. This issue is however excluded for no proper method to include this in the calculations was found.
- Changes in commodity prices: changes in prices for materials such as steel may alter the cost of technologies. Ongoing research however suggests that this impact is likely to be small: the investment cost for gas and coal-fired power stations may increase several percent, up to 11% for wind turbines, with a doubling or tripling of metal and cement prices (Keppo, 2009). The overall uncertainty in investment cost however is much larger than these figures and thereby we believe that the uncertainties in the assumptions (which are already taken into account) do cover these impacts. Also the specific uncertainty for commodity prices would be very difficult to distinguish from other uncertainties. Moreover, no reliable sources projecting commodity prices for the period 2020-2040 are available. Only for biofuels this effect is taken into account by an elasticity factor (called 'Oil Cost Factor', OCF) of 0.10: a doubling of the price of oil results in a 10% increase in the price of biofuels.

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6 For a more elaborate description see Annex C

7 Consistent with Egenhofer et al (2006) and Daniels and Farla (2006); in the latter study the economic cost approach is called 'national cost' and private cost 'end-user cost'.

8 Taxes and subsidies vary greatly and estimates for any future year are uncertain.

3.3 Assumptions

The analysis in Chapter 3 and 4 is based on the basic principle that in 2020 an investment decision has to be made as to whether use the reference technology or the mitigation technology. The economic lifetime may differ, but for each technology in the power and industry sector this is normalised to 20 years. For technologies in the transport sector a shorter lifetime (13 years) is assumed.

All costs are expressed in $€_{2006}$. The geographical focus is Europe.

For the discount rate the following ranges are used (see also Annex C):
- Discount rate economic cost: 3-5%
- Discount rate private cost: 6-10%.

Assumptions related to the electricity, industry and transport sector are given in Annex E, F and G respectively. The most important sources are:
- Electricity: Jansen et al (2008), Energy Technology Perspectives (IEA/OECD, 2008b) and the 'Cost Assessments of Sustainable Energy Systems' project (CASES, 2008). These studies have either a European or a global perspective.
- Industry: Option Document for GHG reduction in The Netherlands (Daniels and Farla, 2006) for energy efficiency. The industry sector in Europe may be diverse across countries when it comes to energy efficiency, however the Dutch industry is characterised by high efficiency therefore the results presented in this study can be regarded as conservative. For CCS, IPCC (2005), the Option Document, Bhandzha and Vajjhala (2008) and other sources are used.
- Transport: TNO (2006), European Commission (2007b), ACEA (2006, 2008), Refuel (Londo et al, 2008) and Eurostat (2008) focus on the European level. Uyterlinde et al. (2008) focuses mainly on The Netherlands, however many of the data that have been used in this study refer to European data or can be used at a European scale.

3.4 Baseline cost

Figure 3.1 shows economic CO_2 abatement costs of the mitigation options in our baseline price assumptions (Scenario 2), with the reference option in brackets. The vertical bars show the 95% uncertainty range. The dots indicate the 'mean' values. Figure 3.2 shows abatement costs based on the private cost approach, in the baseline price scenario. It should be noted that this report is about sensitivity of abatement cost to oil prices, rather than the absolute abatement cost figures. The results presented in this chapter have been calculated based on recent literature and validated using in house expertise, but differences with other sources may arise. They should be interpreted with care.

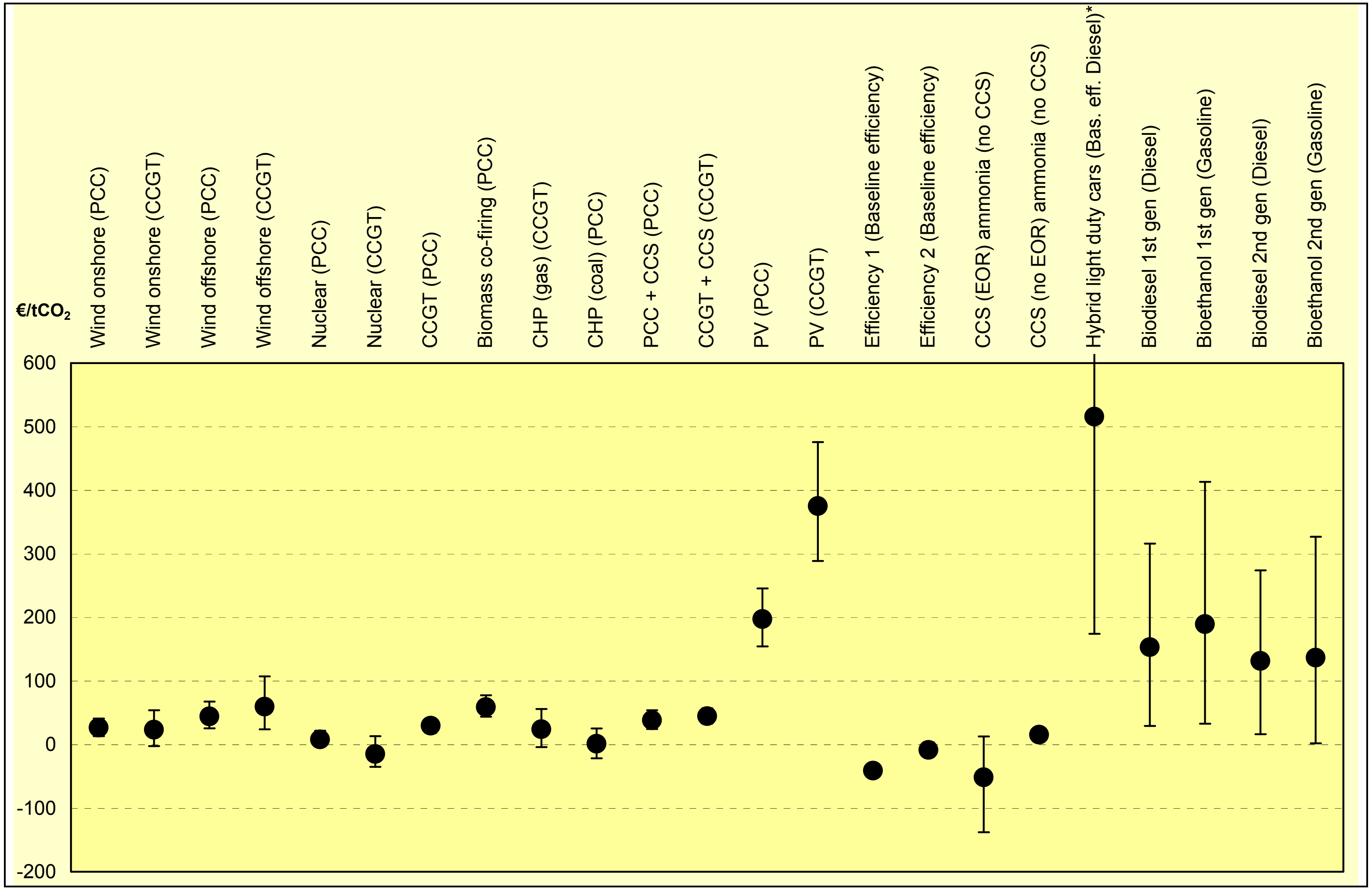

Figure 3.1 Economic abatement cost in baseline price scenario (ECN calculations)

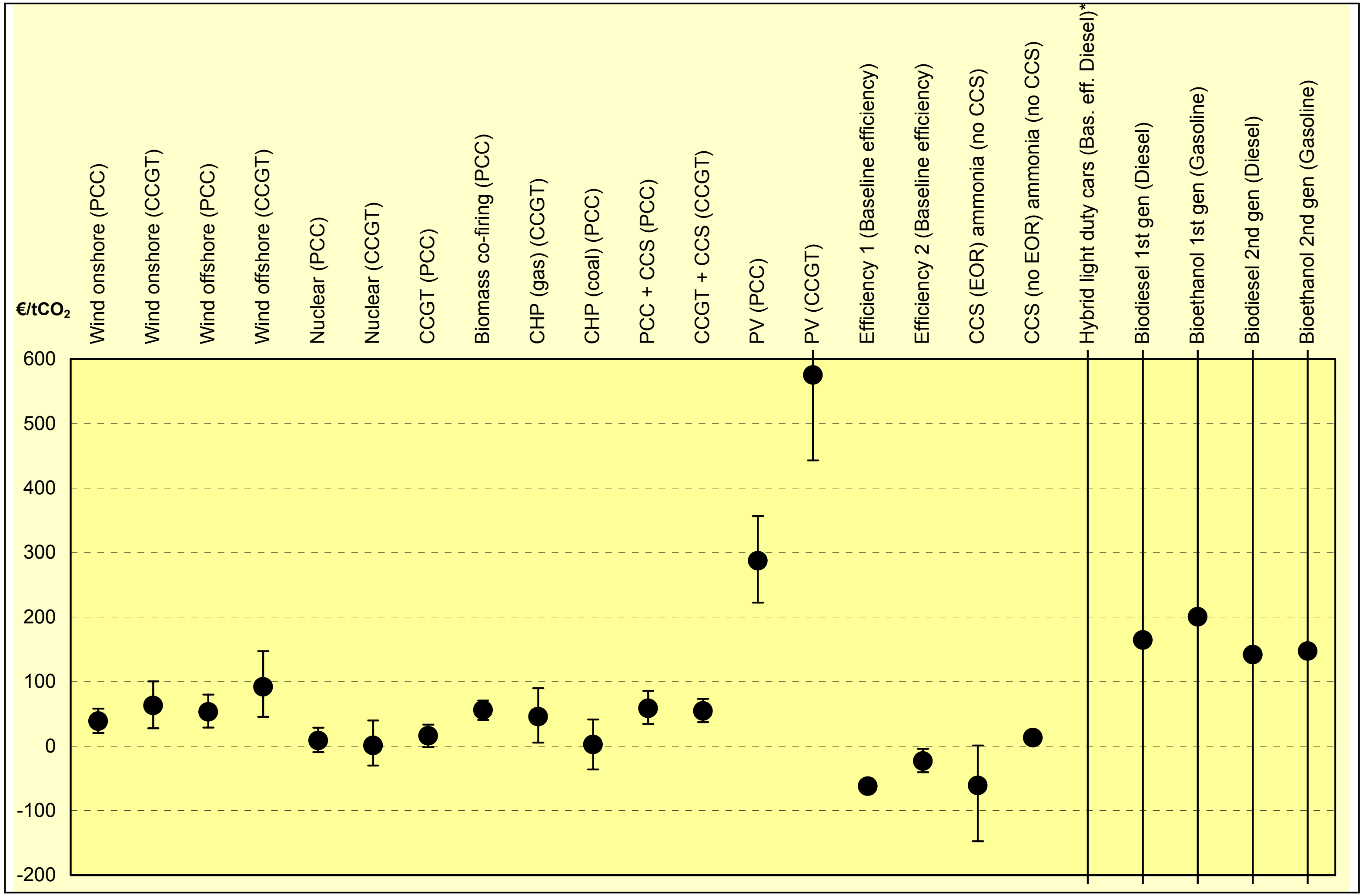

*Figure 3.2 Private abatement cost in the baseline scenario (ECN calculations) * Mean value 924 €/tCO_2*

Some observations for the baseline price scenario:

- For most electricity sector options the (mean) cost are between 0 and 100 €/tCO_2, and the results are in line with other studies such as Jansen et al (2008) and CASES (2008). For nuclear, possible cost for reduction of the lifetime of high radioactive waste are not taken into account.
- In the industry sector there are several options with cost lower than 20 €/tCO_2. The results for CCS are comparable to IPCC (2005), while for energy efficiency in industry the figures are lower than in Daniels and Farla (2006), which can be explained by the higher energy prices assumed in our baseline scenario.
- Biofuels are likely to be more expensive than 100 €/tCO_2, but the uncertainties are large. These results match with major studies mentioned in section 3.3.
- EOR appears to be cost-effective even at medium oil prices ($62/bbl). The potential however is likely to be limited as point sources (in this case ammonia plants) may not be close to the storage sites. The abatement cost figures should therefore be interpreted with care.
- For capital intensive options, such as wind, nuclear, photovoltaics and hybrid vehicles private abatement costs are significantly higher than the economic costs. This can be explained mainly by the higher discount rate that the private sector uses (6-10% vs 3-5%). For hybrids the additional costs are also subject to taxation, which increases the abatement cost. Fuel switch appears to be more attractive from the private compared to the economic point of view. For biofuels the uncertainty in the abatement cost has increased significantly due to uncertainty in tax levels.

3.5 Major uncertainties

Inherently the major input parameters (investment cost, operation and maintenance, discount rate, economic lifetime, conversion efficiency, etc) have a degree of uncertainty or variation due to technological development, commodity and labour cost, difference in time preference, spatial differences, etc. These uncertainties are reflected in the cost of each technology. In the case of abatement cost these uncertainties are amplified as the difference in cost for two technologies is being examined. More specifically the uncertainty range is large for mitigation options where the difference between (either or both) the cost and the CO_2 emission factor of the mitigation and reference technology is small. This is the case for e.g. for hybrid vehicles compared to diesel vehicles, and to a lesser extent CHP and wind compared to CCGT. For biofuels it is not clear at this point why the cost range is so large.

For EOR our calculations are mainly based on Bhandzha and Vajjhala (2008), which carried out a comprehensive analysis for the EOR in the US. We have assumed that their data can be used for Europe as well. Our results are in line with those from a European study (Hustad et al, 2004), that show EOR in the North Sea could be cost-effective at oil prices higher than $28/bbl. However whether EOR in Europe is an attractive option depends on some factors not taken into account such as volatility of oil prices, uncertainty in the oil recovery rate, and the large amount of capital required to build the CO_2 infrastructure.

It should be noted here that in our model calculations there is no uncertainty regarding the fossil energy prices included, i.e. each of the four price scenarios has one fixed price for oil, gas and coal. Therefore the uncertainty ranges reported here do not include fossil energy price uncertainty. The reason is that this uncertainty (i.e. the sensitivity of mitigation cost for energy price changes) is the very topic of this report, which will be investigated in Chapter 4.

4 Impact of oil prices on mitigation costs

This chapter discusses the sensitivity of the cost of mitigation for energy price changes.

4.1 Review of relevant studies

This section briefly discusses other recent studies that have analysed the impact of high energy prices on mitigation technologies and energy policy.

The HOP! project (Fiorello et al, 2008) includes oil price scenarios of € 150 per barrel in 2020 and higher, up to € 800 (see Figure 2.2). The impacts on the EU economy, employment and transport are assessed, of which the most important conclusions are:
- Significant downward pressure on economic growth
- Substantial decrease in EU employment in the short to medium term for the very high oil price scenarios
- Sharp decrease in CO_2 emissions from transport in the medium term even in the moderate (i.e. € 150 /bbl) scenarios, which is maintained in the longer term.

The IPCC Fourth Assessment report (IPCC, 2007) uses a range of sources for abatement cost. For new light duty vehicles with higher efficiency for example, the abatement cost in 2030 change from -14 $/tCO_2$ to -88 $/tCO_2$ when the oil price changes from $30 to $ 60 per barrel.

In the Energy Technology Perspective 2008 (IEA/OECD, 2008b) the baseline scenario includes an oil price of $65 per barrel in 2050, as marginal oil production cost in 2050 are in the range of 30 to 60 $/bbl. In the 50% energy-related CO_2 mitigation scenario the price is estimated to be $45 per barrel, due to a 27% drop in oil demand compared to current levels.

The marginal abatement cost to achieve this target is $200-500/t$CO_2$-eq, depending on assumptions regarding technological progress. The marginal cost is determined by transport technologies, as these are generally in the more expensive part of the abatement cost curves. The figure of $200/t$CO_2$-eq is equal to an additional oil cost of $80 per barrel for end-users (IEA/OECD, 2008b).

McKinsey (2009) published their Global GHG Abatement Cost Curve v2.0 for 2030 using an oil price of $60 per barrel. They provide a brief sensitivity analysis for $120 per barrel which results in an average reduction in abatement cost of €19 per tonne of CO_2-eq. For no-regret options (energy efficiency) the reduction however is €40-80, while for other options the cost reduction is less than 10 €/tCO_2-eq.

In Daniels and Farla (2006) a detailed assessment of cost and potentials for climate mitigation options (the so-called Option Document) for 2010 and 2020 for the Netherlands is given. The results are based on an oil price $29/bbl, but a sensitivity analysis with an oil price of $40 was also carried out. Table 4.1 shows the changes in abatement cost (economic cost approach, see next section) due to the increased oil price for selected options compared to the baseline. It is clear that for many technologies the abatement cost is very sensitive to the oil price, and that some become cheaper while the costs for others increases.

Table 4.1 Oil price sensitivities in the Option Document 2006 ($40/bbl compared to $29)

Mitigation option	Abatement cost change ($€_{2000}/tCO_2$-eq)
Biomass co-firing in existing PCC	0
Biomass co-firing in existing CCGT	-32
New nuclear power	-14
Fuel switch existing PCC to CCGT	35
Wind on/offshore	-13
Electricity saving commercial buildings	-15
Solar boilers commercial buildings	-27
Heat pumps commercial buildings	-45
Electricity saving household through behaviour change	-14
PV	-14
CCS in ammonia production	1
CCS in large scale existing CHP	8
Electricity saving industry	-15
Large scale CHP	0
Aluminium recycling	-16
Steel recycling	3
Heat demand reduction industry	-32
Biofuels in transport	-15
Reduction of highway maximum speed	-34

Matthes et al (2008) analyse the impact of oil prices on energy consumption and CO_2 emissions in Germany, using energy and economic modelling. The high scenario includes $82.5 per barrel in 2030 compared to $ 37 in the reference scenario. The following impacts are observed for 2030:

- 7% reduction in total primary energy consumption
- Increase in renewables in the electricity sector, partly compensated by increase in coal-based production. No change for nuclear.
- Increase in renewables in the transport sector
- Gas and oil consumption reduction by 30% and 11% respectively
- Total CO_2 emission reduction by 11%, spread rather evenly across the sectors

From these studies it can be concluded that energy prices are likely to have a profound impact on the energy system and cost of CO_2 abatement. The remaining part of the current report sets out to quantify the impact of oil prices of more than $100/bbl.

4.2 Results of sensitivity analysis

Figure 4.1 gives the results for the economic abatement cost for the different mitigation options in the four energy price scenarios with constant prices for 2020-2040 described in section 2.3:

1. $37/bbl;
2. $62/bbl;
3. $150/bbl;
4. $150/bbl and decoupling of gas price.

In all scenarios the coal price is equal to € 61/tonne.

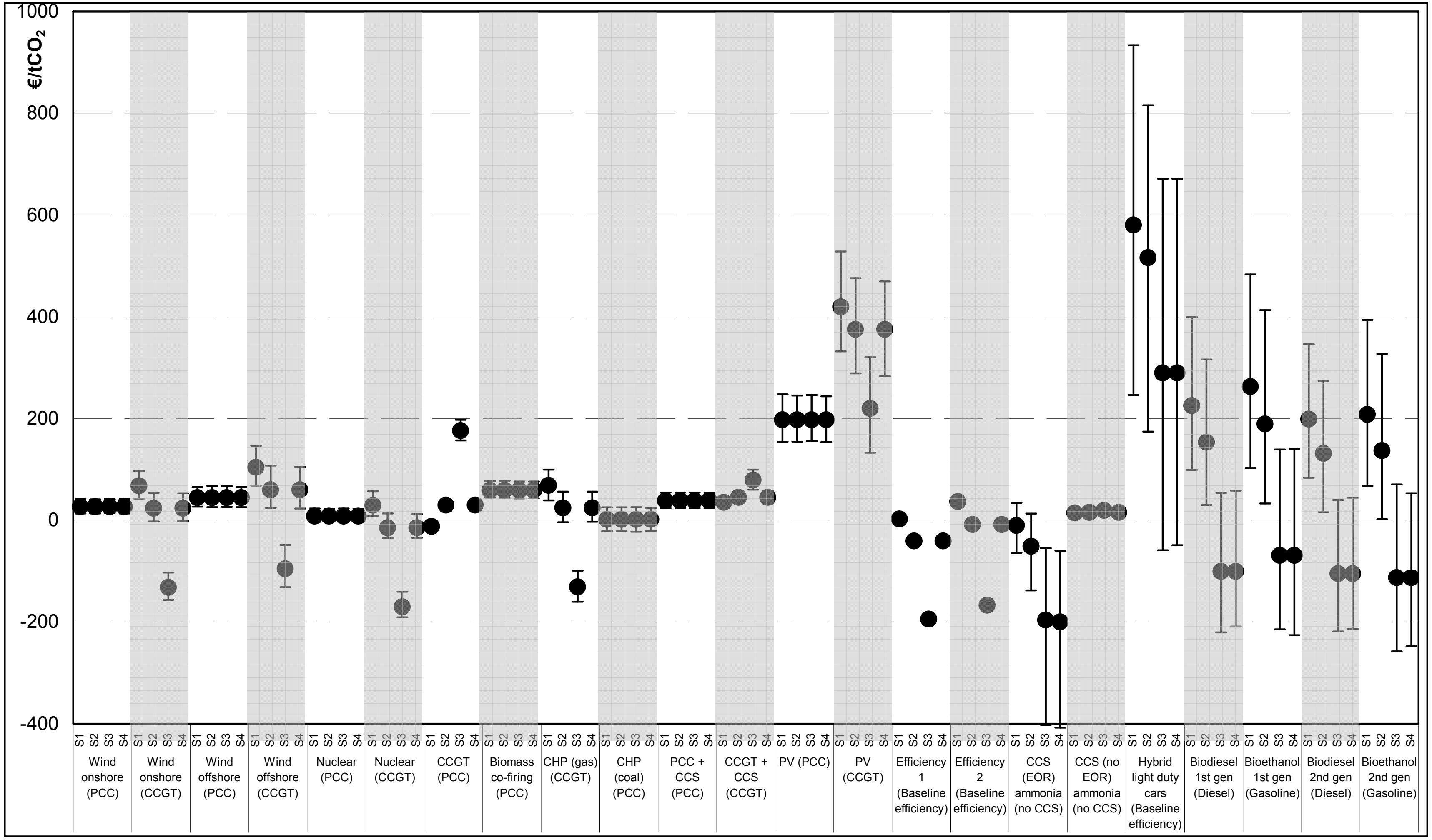

Figure 4.1 Sensitivity of economic abatement cost to energy prices (ECN calculations

4.3 Discussion of results

In the previous section we have shown results of CO_2 abatement cost in 2020 for a range of mitigation technologies compared to reference technologies for different fossil fuel price scenarios. The costs are looked at from the economic and private point of view, and are based on standard calculation methods.

4.3.1 Rules of thumb

Table 4.2 gives 'rules of thumb' according to the format: 'if the oil price departs from the reference by 10 $/bbl, then mitigation option y will cost z $/tCO$_2$-eq less or more compared to the baseline estimate', e.g. 2nd generation biodiesel (reference diesel) becomes 29 €/tCO$_2$ cheaper when the oil price between 2020 and 2040 is $10 per barrel higher. For abatement cost of the electricity options it is clear that the linkage between gas and oil prices is key to the sensitivities.

Table 4.2 Oil price sensitivities: 'if the oil price departs from the reference by 10 $/bbl, then mitigation option y will cost z $/tCO$_2$-eq less or more compared to the baseline estimate'

	Sensitivity [€/tCO$_2$ per $10/bbl]	
	scenario 2-3	scenario 2-4
Wind onshore (PCC)	0	0
Wind onshore (CCGT)	-18	0
Wind offshore (PCC)	0	0
Wind offshore (CCGT)	-18	0
Nuclear (PCC)	0	0
Nuclear (CCGT)	-18	0
CCGT (PCC)	17	0
Biomass co-firing (PCC)	0	0
CHP (gas) (CCGT)	-18	0
CHP (coal) (PCC)	0	0
PCC + CCS (PCC)	0	0
CCGT + CCS (CCGT)	4	0
PV (PCC)	0	0
PV (CCGT)	-18	0
Efficiency 1 (Baseline efficiency)	-17	0
Efficiency 2 (Baseline efficiency)	-18	0
CCS (EOR) ammonia (no CCS)	-16	-17
CCS (no EOR) ammonia (no CCS)	0.4	0
Biomass feedstock (Fossil feedstock)	0	0
Hybrid light duty cars (Baseline efficiency)	-26	-26
Biodiesel 1st gen (Diesel)	-29	-29
Bioethanol 1st gen (Gasoline)	-29	-29
Biodiesel 2nd gen (Diesel)	-27	-27
Bioethanol 2nd gen (Gasoline)	-28	-28

Based on this, assuming coupling between gas and oil prices, it appears that technologies that may benefit significantly from higher oil prices are:
- Renewable electricity, nuclear and gas-based CHP[9] compared to CCGT
- Energy efficiency options, assuming gas-fuelled
- Enhanced Oil Recovery

[9] The results for CHP should be treated with care, as its profitability and attractiveness as a mitigation option depend strongly on other variables including demand and supply of power and heat.

- Biofuels may benefit the most (assuming biofuel price elasticity for oil prices is 10%; if this elasticity is much higher the benefits will decrease accordingly).
- Fuel switch from coal to gas becomes more expensive

The relation between oil prices and abatement cost between scenario 1 and 3 ($ 37 to $ 150 with gas price coupling) is linear (even though scenario 1 is not shown in Table 4.2).

4.3.2 Sensitivity to coal prices

Possible coal price increases due to higher oil prices is not taken into account here; if there is a positive relation between the two, the options that have coal as a reference would also increase their attractiveness. To quantify this effect we carried out one additional sensitivity run which assumes a historical coupling of 0.25 between coal and oil prices. This linear relation means that a doubling of oil prices also results in a doubling of coal prices. Results show that the electricity options with PCC as a reference option become 4 €/tCO_2 cheaper when the oil price increase by $10 per barrel. Thereby the sensitivity to oil price changes is much lower. This can be explained by 1) the relatively low correlation factor (for gas/oil it is 0.73) and 2) the relatively low contribution of coal price in the cost of electricity, i.e. the investment cost are more important.

4.3.3 Comparison to other studies

Comparing our results those report in Daniels and Farla (2006) in Table 4.1, it appears that most of the sensitivities are comparable. For the electricity sector minor differences can be explained by the fact that in their scenario study the baseline emissions are determined by a combination of coal and gas-fired power stations, while in our approach the baseline is either one of these technologies. Striking is however the higher sensitivity – compared to our findings - for fuel switch (gas to coal) and energy efficiency in industry, and the lower sensitivity of the biofuel options.

The Energy Technology Perspectives 2008 (IEA, 2008) – see 4.1 – notes that an increase in oil prices has a substantial downward effect on the marginal cost of abatement. As the marginal options are generally in the transport sector (e.g. biofuels) this is in line with our findings, where the transport options are the most sensitive to oil price changes.

4.3.4 Uncertainties

While we assumed constant energy prices over the period 2020 – 2040, in practice they vary. Higher energy prices in the future than previously expected may also increase the likelihood of more price volatility and thereby uncertainty for both society and investors. This may be an advantage for renewables, nuclear and coal compared to oil and gas based technologies. However this effect is not covered in this study.

The choice for the discount rates to be applied to future cost and benefits is always a debatable matter, as discussed in 3.3. It is a key input for the calculation of technology costs and abatement cost of mitigation options. However as we are applying the same discount rate to each mitigation option and then vary the energy price inputs, the effect of the discount rate on the outcomes in this chapter are not very significant.

4.3.5 Extrapolation to other world regions

The previous analysis has focused on Europe. The assumptions for the input of the cost calculations are based on European studies. An important question is to what extent the results of the sensitivity analysis can be used to draw conclusions for other world regions.

In general it can be said that for other world regions these assumptions are likely to be valid as well. For power and industry, the most important assumptions are investment cost, operation & maintenance cost, economic lifetime, full load hours, conversion efficiency and discount rate. Only the latter two may differ significantly across different regions.

For developing countries, in particular Least Developed Countries, conversion efficiency for reference options may be lower, though the difference with industrialised countries is likely to be smaller in 2020 than it is now (IEA/OECD, 2006). However the impact of conversion efficiency on oil price sensitivity is low, which can also be seen from the nearly equal sensitivities: -17 and -18 [€/tCO_2]/[10$/bbl] for the two different energy efficiency option packages 1 and 2 respectively.

The (economic) discount rate could be higher in developing countries due to a preference of society for more short term return compared to long-term benefits, which may be important for strong economic development. However the impact of a different discount rate on the oil price sensitivity is very limited.

It is more important to note that for the industry options the calculations are based on natural gas: for coal-based options the sensitivity to oil price changes is much lower (as also discussed above). This is particularly important for China, but also for Japan, China and Indonesia, whose industry sector is to a large extent based on coal. For North America, Europe and Australia natural gas is the dominant fuel (see Figure 4.2).

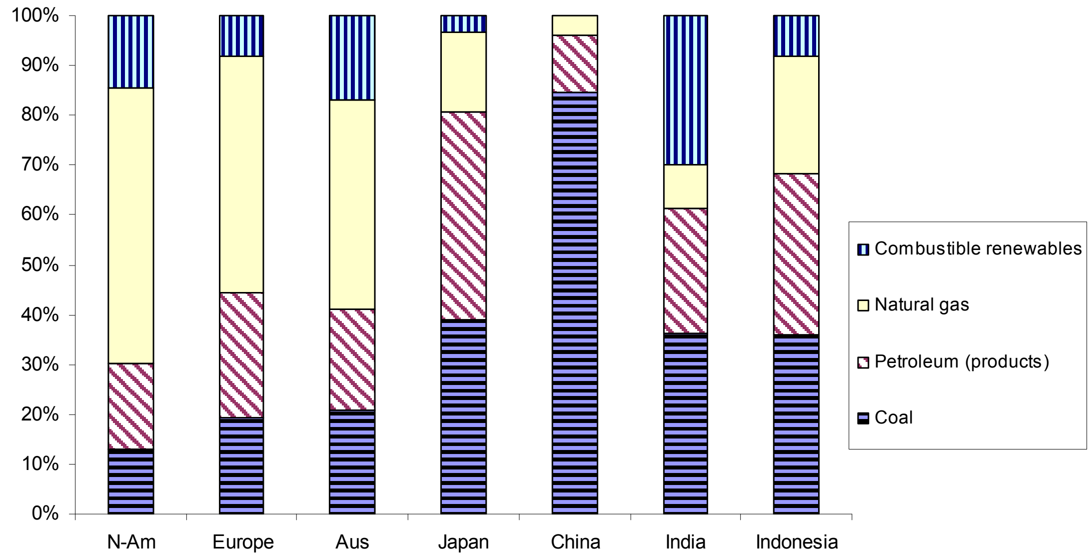

Figure 4.2 Primary fuel mix in 2004 in the industry sector in world regions (Kessels et al (2008))

The transport sector is more diverse across the globe, because of individual preference that influence e.g. the weight of a car and its fuel efficiency, cost of vehicles as well as the discount rate. Therefore it is not possible to extrapolate the findings for the transport sector directly to other world regions, in particular developing countries. However it is clear that all covered transport options benefit from higher oil prices.

The next chapter uses a different approach to estimate impacts of different oil prices. A global energy model is employed to determine changes in the global energy system and CO_2 emissions from today till 2050.

5 Impact of oil prices on mitigation scenarios

The impact of high energy prices on mitigation options can also be assessed in the dynamic context of an energy model. Compared to an analysis that is focused on the costs of different technologies, as done in Chapter 3 and 4, this allows to take dynamic factors in account. This includes for instance limits to the implementation potential of different options, impacts on depletion, technology development dynamics and delayed responses due to capital stock turnover. However, using a model for such analysis also increases uncertainty.

As this chapter uses an existing model to calculate changes in the energy system, the technology assumptions may be different from those in Chapter 3 and 4. The energy price assumptions in Chapter 5 however are aligned with those in the previous chapters (except that in these chapters constant prices are assumed, while here price paths are described).

5.1 The TIMER model

In this analysis we have used the TIMER world energy model (van Vuuren et al., 2006), which is a part of the Integrated Assessment Model IMAGE (Integrated Model to Assess the Global Environment). The model was used in various assessments of mitigation strategies and costs, including the IPCC Fourth Assessment Report. TIMER describes the long-term dynamics of the production and consumption of about 10 primary energy carriers for 5 end-use sectors in 26 global regions (Figure 5.1). In the model, long-term energy prices are determined by resource depletion and technology development. These prices, combined with preferences, are used in a multinomial logit model to allocate the investments to a combination of technologies. Generally, the multinomial logit model assigns a larger share of investments to low-cost technologies, though also some investments are made into more expensive options. Emissions of the energy system are obtained by multiplying energy consumption and production flows with emission factors. A carbon tax can be used to induce a dynamic response such as increased use of low or zero-carbon technologies, energy efficiency improvement and end-of-pipe emission reduction technologies.

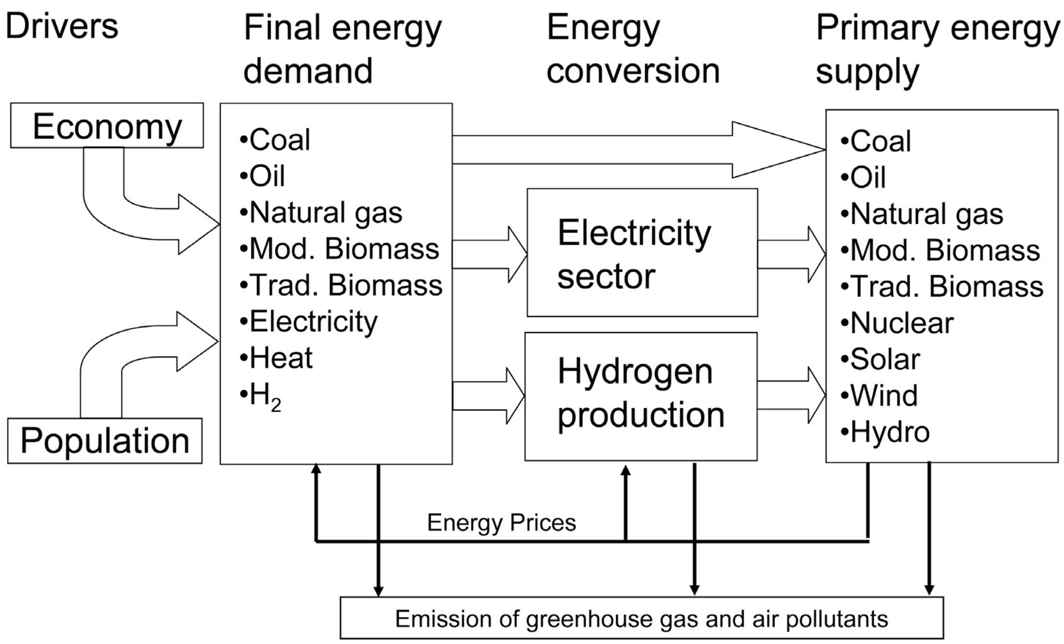

Figure 5.1 Overview of the general structure of the TIMER model

5.2 Fossil fuel resources and price paths

To model resource depletion of fossil fuels and uranium, several resource categories are defined that are depleted in order of their costs (12 categories for oil, gas and nuclear fuels, 14 for coal). Hence, production costs rise as each subsequent category is exploited. TIMER includes three fossil-fuel production sub-models for respectively solid, liquid and gaseous fuels. For each region these sub-models calculate the demand for secondary energy carriers, electricity generation, international transport (bunkers) and the demand for non-energy use and feedstocks. The calculated fuel demand accounts for losses (e.g. refining and conversion) and energy use within the energy system. In a next step, demand is related to potential supply, both within the region and in other regions by means of the international trade model.

The size of the different resources in TIMER is based on data from the US Geological Survey (as reported by Mulders et al., 2006) and Rogner (1997). Table 5.1 provides an overview of the assumed available resources in default model conditions (aggregated from regional estimations into 5 global categories). The table indicates that under default assumptions, supply of natural gas and oil is limited to only 2-8 times 1970-2005 production for the sum of current reserves, other conventional resources, and reserves of unconventional resources (oil from tar sands and oil shales). The last category of unconventional resources is much larger (especially for natural gas) but it is far from certain that this resource will ever become economically attractive. For coal even the current reserves equal several times the production of the last 3 decades.

Table 5.1 Fossil fuels in TIMER under default assumptions aggregated into 5 global supply categories (ZJ) based on Rogner (1997) and Mulders et al. (2006)

	Oil	Natural gas	Underground coal	Surface coal
Cum. 1970-2005 production	4.4	2.1	1.6	1.1
Reserves	4.8	4.9	23.0	2.2
Other conventional resources	6.6	6.9	117.7	10.0
Unconventional resources (reserves)	6.1	16.5	25.0	233.5
Other unconventional resources	37.2	496.4	1.3	23.0
Total	59.1	515.9	168.6	270.0

An alternative way of presenting this information is by showing the information aggregated into a long-term supply curve. In case of full global trade and perfect markets, the costs of oil would more or less follow such global curve. In reality, however, many factors imply that prices are significantly different from marginal production costs and that the actual marginal production costs are higher than the lowest points on Figure 5.2. Factors that contribute to prices (and costs) being higher than the point most to the left on the global production curve include: 1) strategic behaviour of oil producing countries, 2) underinvestment in production and refining capacity due to inertia and uncertainty, 3) market uncertainties in response to political uncertainty in oil producing countries, 4) rapid increases in demand, 5) limitations in the production rate of low-costs fields, 6) energy security policies in oil consuming countries (limiting import), 7) limitation in the rate at which new oil resources can be brought into production (e.g. unconventional sources).

Some of these factors have been included in the TIMER model (and other energy models) – but many have not. If somehow the global curve could be followed, prices would increase slowly. In standard scenarios the oil consumption in the next 50 years would be about 2000 billion bbl, resulting in a price increase due to depletion in the range of 30 up to nearly 200 $/bbl. Because many of the factors mentioned above are not easy to include dynamically in a long-term energy system model, they are implemented by including an additional exogenous “price factor” to the production costs. Setting this factor at zero implies that energy prices more or less equal the marginal production costs, while including much higher numbers would allow us to create high oil price scenarios. This does not mean that the prices become fully exogenous, since the dynamics of long-term depletion are still included (there is only an exogenous price-factor added). However, because this price-factor is exogenous and not the result of model-dynamics it does not involve any model feedbacks. This implies, for instance, that if oil demand decreases as reaction to high prices, there will be no response in oil prices, which consequently remain high.

We have used this exogenous price factor to implement different price-paths of oil and natural gas in line with the scenarios of Chapter 2 (Figure 5.2) - but have left the coal price unchanged (hence, coal prices are determined only by depletion dynamics). The reason is that large coal resources exists, so that potentially in the long-run coal and oil prices are not coupled as new resources can be brought under production (coal and oil prices have been correlated in the past, but in this interpretation this has been a result of short-term constraints in current production capacity). We assume that gas prices are fully coupled to the oil prices.

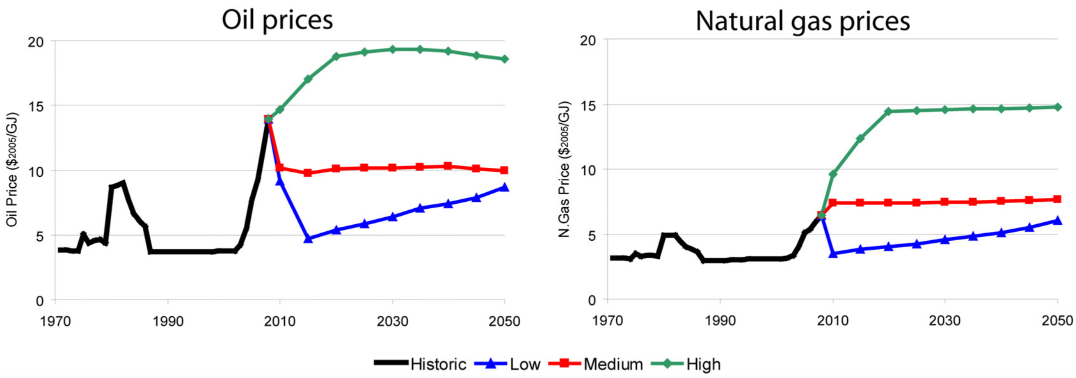

Figure 5.2 Development of oil prices (world market) and natural gas prices (western European market) in the low, medium and high price scenarios developed in Chapter 2

5.3 Dynamics of electricity production

Before discussing the results of the model experiments, we first discuss fuel choices in the power sector, as assumed in the TIMER model. In order to gain insight in the (model-) response to fuel price changes, we perform a static analysis, focussing on four major uncertainties: the prices of coal, oil and natural gas and the carbon tax. In this analysis, we use the default technology assumptions for new installed capacity in the TIMER model for 2020[10]. This static analysis does not take account of depletion impacts or increased costs from large scale penetration of intermittent power options; dynamics that are included in the TIMER model. The assumptions are derived from endogenous calculations in the TIMER model (for instance on technology learning, cost development of CCS) and might therefore deviate from the calculations in Chapter 3 and 4 of this report.

The left graph of Figure 5.3 shows electricity production costs as a function of coal, oil and natural gas prices, in the absence of climate policy. Although no coupling takes place in the model analysis, we here combine the energy prices, because the prices of fossil fuels have historically been coupled. We use coupling factors for natural gas and coal of 0.73 and 0.22 respectively (see Chapter 2; it should be noted that the other parts of this report assumes no coupling between oil and coal prices).

Obviously, the results show that all fossil-based technologies are sensitive to energy prices, but at a different rate. Oil responds most directly to energy price changes, whereas natural gas and coal react at lower rates. At low oil prices, natural gas is the preferred electricity production option, but above oil prices of 5 $/GJ (or 30 $/bbl), coal becomes more attractive. The price level of 5$/GJ is on the lower side of the range of scenarios that will be explored further in this chapter (see Figure 5.2).

[10] Using the low price scenarios as reference with 2.1, 5 and 3.7 $/GJ for coal, oil and natural gas (see Table 2.3)

The left graph combines all fossil energy prices coupled to the oil price with coupling-factors of 0.73 and 0.22 for natural gas and coal respectively. It should be noted that the other parts of this report assumes no coupling between oil and coal prices. The right graph shows the influence of carbon taxes.

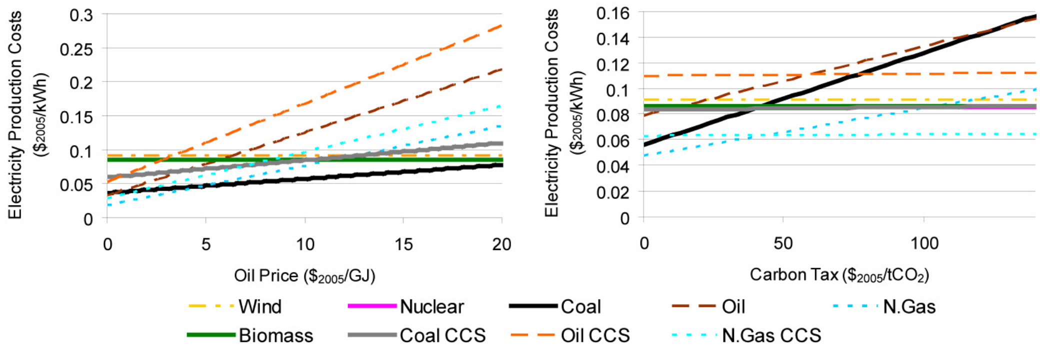

Figure 5.3 Costs of electricity production options at different energy prices and carbon taxes

So far, we have not included climate policy. We will now do so, by plotting the costs of different technologies as a function of the carbon price (Figure 5.3, right graph). The response of different technologies depends on the carbon content of the feedstock and the specific efficiency of electricity production. Carbon intensive coal responds strongly to a carbon tax, whereas the costs of natural gas based electricity increase more slowly. The fossil-based options with CO_2 capture and storage (CCS) show only some slight reaction to a carbon tax (note that there is still some CO_2 emitted, thus also taxed) and the non-fossil options (wind, nuclear and biomass) are irresponsive to a carbon tax. Using the default prices of 2.1 $/GJ for coal, 5 $/GJ for oil and 3.7 $/GJ for natural gas, conventional natural gas plants are competitive at very low carbon taxes. With a carbon tax above 45-50 $/tCO_2$ natural gas with CCS becomes competitive.

Figure 5.4 combines the variation in fossil energy prices and carbon taxes, showing the cheapest electricity production options under different circumstances. The graph shows different areas where certain technologies are economically the most attractive. We determined two variants: in the left graph, coal prices are coupled to the oil price (compare to Figure 5.3, left graph); in the right graph, coal prices remain constant at 2.1 $/GJ.

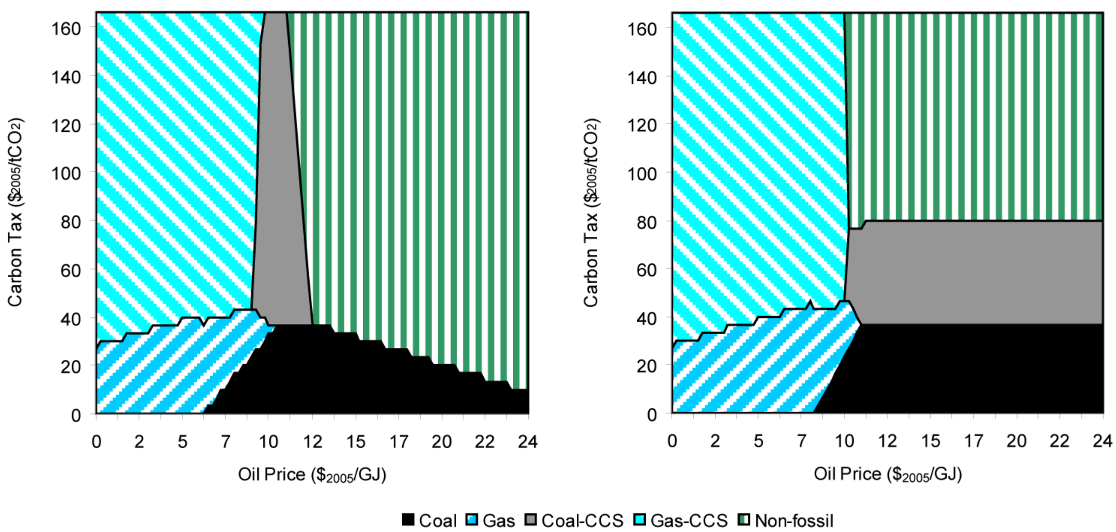

Figure 5.4 Cheapest electricity production options with different oil/gas/coal prices and carbon tax levels

Without carbon tax, the left graph of Figure 5.4 follows the lower left graph of Figure 5.3. At low oil prices natural gas is the most attractive electricity production option. At higher prices, coal is more attractive (both with coupled and constant prices) because gas responds more rapidly to oil price changes (see also Figure 5.3). The situation changes if a carbon tax is introduced. If such carbon tax is high enough, low carbon emitting options become attractive in all cases. At very low oil prices, the carbon tax required to make the shift to low GHG emitting technology is around 30-35 US\$/tCO_2 – and it rises somewhat with higher oil prices (due to a high penalty function for additional natural gas use from decreased efficiency with CCS). At oil prices of about 5-7 \$/GJ coal based power becomes more attractive than natural gas (both with and without CCS). Interestingly, if coal prices are coupled to oil prices, coal with CCS is only the lowest-cost technology at a narrow band with carbon prices above 40 \$/tCO_2 and oil prices of 9-12 \$/GJ. If coal prices are assumed constant, coal with CCS is attractive at high oil prices and with a carbon tax between 35 and 80 \$/tCO_2. At high carbon taxes and high fossil energy prices, the non-fossil options are most attractive. The electricity production costs of all these options (wind, nuclear, biomass) are within a narrow range (see Figure 5.3) – therefore we have chosen to show them as a single group.

These figures are, of course, highly sensitive to input assumptions. Issues like capital cost development, conversion efficiencies or costs of CCS are very uncertain and estimations in literature vary over a broad range. Therefore, the exact numbers of the turning points (either as oil prices or carbon taxes) between different technologies deviate from estimations in Chapter 3 of this report. However, the impact on electricity production dynamics remains clear: at low fossil energy prices, natural gas is the most attractive technology, either with or without CCS, depending on the carbon tax. At higher energy prices coal, eventually with CCS, becomes more attractive. With both high fossil energy prices and high carbon taxes, non-fossil options are most attractive. The attractiveness of coal with CCS depends closely on the coal price, taxes on remaining emissions and the price development (and public support) of non-fossil alternatives.

5.4 Influence of different price paths on energy system development (baseline, without climate policy)

We first explore the impact of different fossil fuel prices in a dynamic model in the absence of climate policy, in order to distinguish the impacts of energy prices and climate policy. Figure 5.5 shows the influence of energy prices on primary energy use in TIMER, using the price paths from Figure 5.4. It shows clearly that the use of oil and natural gas decreases with higher prices. This impact of the different price paths is rather strong. In TIMER the high oil path leads to a strong substitution away from oil over a period of 50 years. In the transport sector, medium and high oil prices lead to an increase of bio-energy use, and in the longer-term hydrogen also becomes an option (see Figure 5.6). As this hydrogen is mostly produced from coal, this causes a substantial shift to coal in primary energy use (Figure 5.5). In electricity production, natural gas is substituted by coal and wind in the higher price scenarios (Figure 5.7). Another important impact of the higher energy prices is efficiency increase. Especially in the transport sector, it can be seen that final energy use is about 10% lower in the high price scenario than with low oil prices (note that final energy use is only comparable until 2030, because hydrogen is more efficient in final application, but needs more primary energy at production).

It is important to note here that hydrogen is the only option in the TIMER model to apply coal in the transport sector. Alternative routes, like coal-to-liquids (CTL) or electric vehicles are not considered explicitly. Both CTL and electricity have a comparable position in the energy system: coal is converted to an end-use energy carrier for the transport sector (with all related efficiency losses). However, the costs of infrastructure developed and vehicles are likely to be lower than from those of hydrogen. Hence, it might be expected that coal is competitive in the transport sector at lower oil prices as well. Another issue is how the carbon emissions of CTL, electricity and hydrogen relate to each other. This is fully understood, though they might be expected in the same order of magnitude.

In terms of global primary energy supply, the substitution away from oil with high prices, leads to a strong increase in bio-energy and coal consumption (Figure 5.5). The former is mainly used in transport while the latter is used in industry and power generation – and on the longer term to produce hydrogen. It should be noted that we did not explore high coal prices but as most coal technologies are much less sensitive to the feedstock price (see also Figure 5.3) this general result is expected to remain (although dampened).

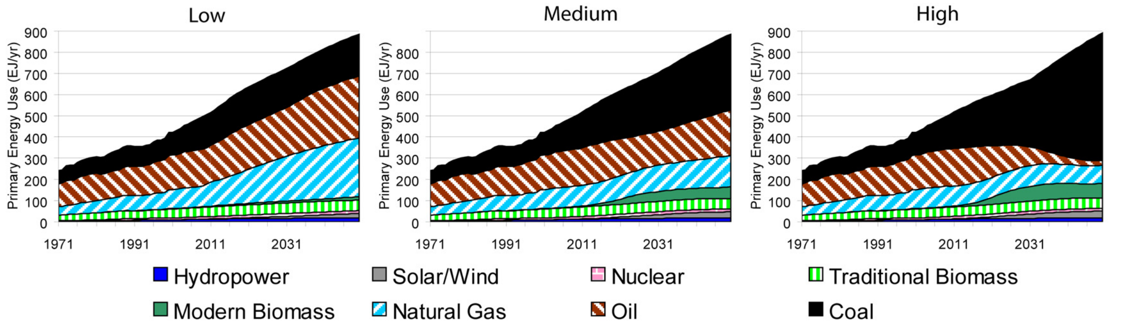

Figure 5.5 Global primary energy use with low, medium, and high oil and natural gas prices without climate policy

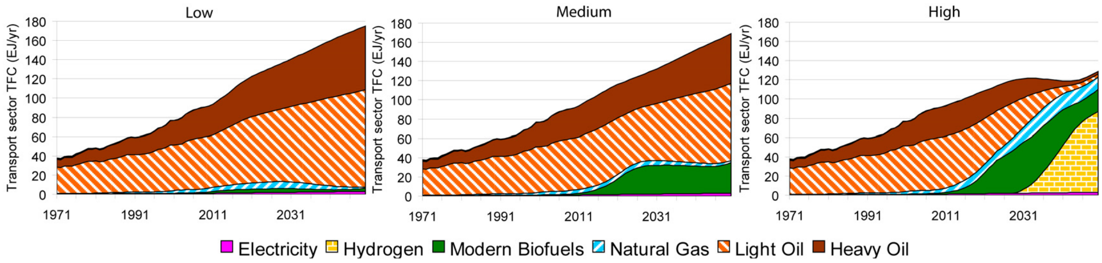

Figure 5.6 Global energy consumption in the transport sector with low, medium and high energy prices, without climate policy

Note: CTL and electric vehicles not considered

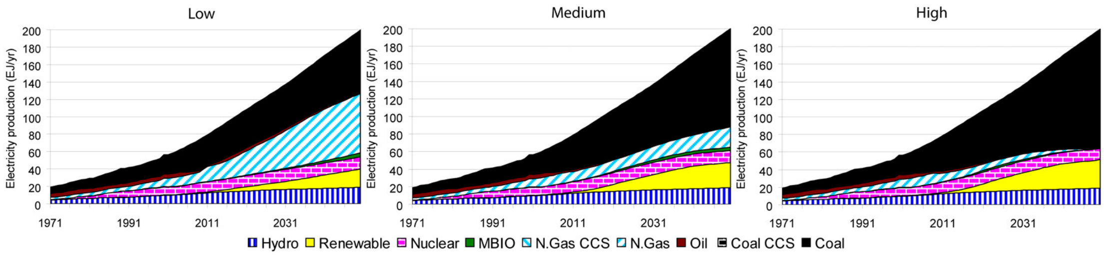

Figure 5.7 Global electricity production by primary energy carrier with low, medium and high oil and natural gas prices, without climate policy

In order to put the TIMER results into context we have included the different projections of oil prices and consumption published over the last years by the World Energy Outlook (WEO, Figure 5.8) During this period, the oil price projections for 2030 in the WEO have varied over rather wide ranges (30-120 $/bbl). Interestingly, however, the projected oil consumption volume has been adjusted much less – and there seems to be only a minor negative relationship between the projected oil price and the consumption volume. In other words, the response of consumption to oil prices (hence, the shift away from oil) is much stronger in the TIMER calculations than in the relationship that is suggested by comparing different editions of the World Energy Outlook. This issue is partly related to different modelling traditions. Econometric models (like the WEO model and CGE models) use elasticities to derive the demand for fuels as function of prices and income. Data series of the last decades indicate that oil consumption is rather inelastic to price changes and closely related to income. However, in absence of historic periods of sustaining high oil prices, it is not clear whether oil consumption is also inelastic to very high prices of 120 $/bbl. Hence, these models might project oil consumption to be too high. The system dynamics model TIMER describes the dynamics of market allocation on the basis of mutual price differences between models. Hence, if oil prices increase to very high levels, the model chooses cheaper fuels for its marginal investments. For this type of models, the values for cross-price (substitution) elasticity and the system delays are hard to obtain from historic data. Therefore, the TIMER model might be too optimistic on substitution possibilities and project a very low oil consumption.

The issue of substitution also raises the question under which circumstances high oil prices are plausible on the longer term. The answer depends both on the factors related to the oil market discussed above and to the options for substitution in energy demand (mostly in the transport sector). Different hypotheses can be assumed:

- If the substitution of oil by modern biofuels and hydrogen (but also CTL and electricity) is indeed possible (as assumed in TIMER) the demand for oil will be under strong pressure if prices increase. In that case, if high oil prices are caused by other factors than physical depletion, they are likely to fall (somewhat) because of decreased demand. Only if high oil prices are mainly driven by physical depletion the depicted TIMER scenario is likely as shown.
- If substitution to other fuels appears to be difficult, high oil prices (caused by market factors) can still coincide with high oil consumption levels as shown in the WEO scenarios (if sufficient resources are available).

The latter scenario occurs if 1) technology development for these options is much lower, 2) biofuels are much more constrained by supply side limitations (and by competition with food production), 3) the response to prices is lower than expected (i.e. a lock-in into oil-based products). Figure 5.9 shows the results for TPES, electricity production and transport energy use of such scenario. It combines the high oil price path with pessimistic technology assumptions on hydrogen and biofuels and a low rate of substitution. Still, with oil prices of around 120 $/bbl, biofuels and other alternative fuels, like natural gas and hydrogen, enter the transport sector on the longer term. Compared to the projections of the World Energy Outlook (i.e. the 2008 publication), this pessimistic scenario has still considerably lower oil consumption (compare WEO-2008 and 'TIMER high PES' in Figure 5.8). Hence, also under pessimistic assumptions for the substitution of oil, the TIMER model projects a transition to alternative options.

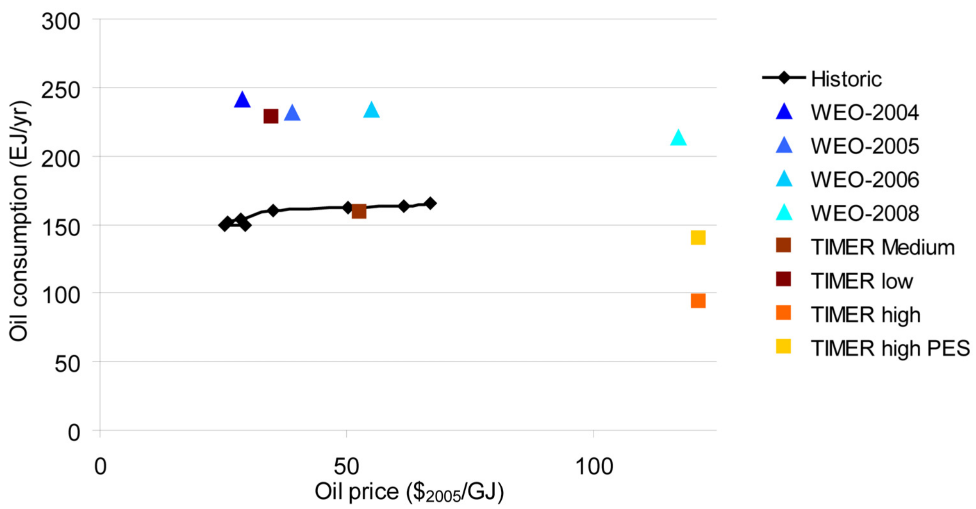

Figure 5.8 Relation between oil prices and oil consumption, historic data, projections of the World Energy Outlook (WEO) for 2030 and the TIMER model for 2030

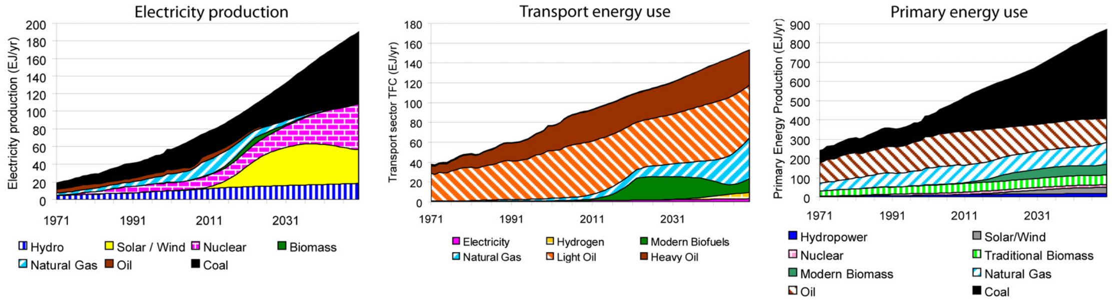

Figure 5.9 Combing high energy prices with pessimistic assumptions on hydrogen, biofuels and substitution

The consequences of high oil prices scenarios for CO_2 emissions are mixed. On the one hand, the emissions of the power sector (in the absence of climate policy) clearly increase globally with high oil and natural gas prices due to a shift from natural gas to coal. A very strong increase also occurs in the emissions of hydrogen production from coal (zero in the medium and low price scenario but substantial after 2030 in the high price scenario). The emissions from industry also increase from a shift to coal. In contrast, emissions from transport are initially lower in high price scenarios, due to the application of biofuels. Contrarily, the higher energy prices also lead to increased efficiency and lower demand for energy. The net impact of high energy prices on global emissions is a decrease on the short term, but an increase on the long-term (Figure 5.10).

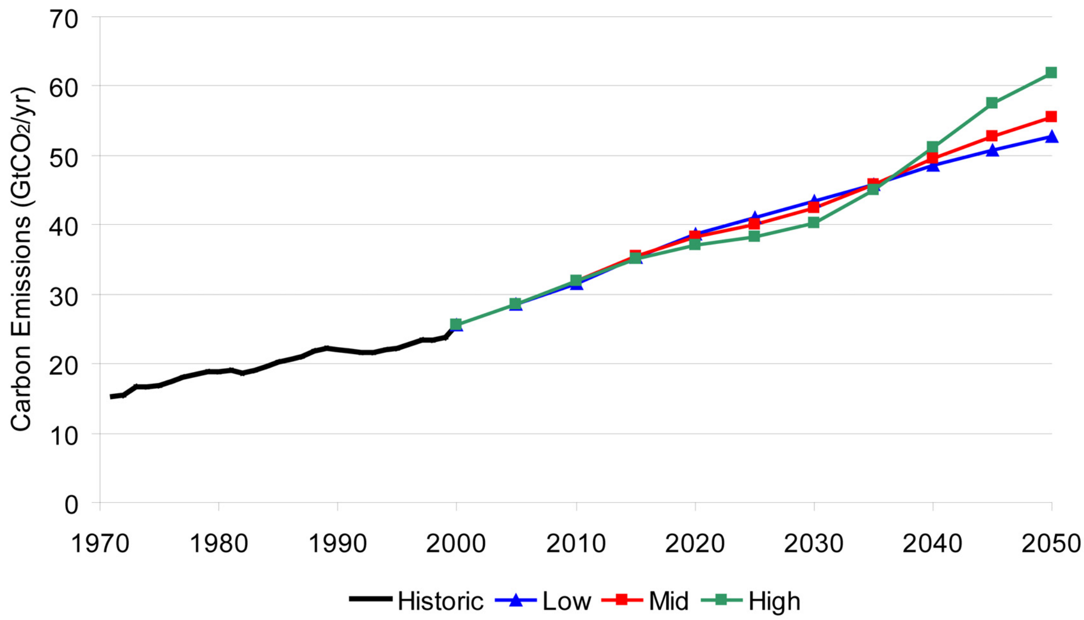

Figure 5.10 Global CO_2 emissions from energy use in the absence of climate policy for medium, low and high oil/gas prices

5.5 Influence of different price paths on climate policy scenarios

The 4th Assessment Report of the IPCC determined the abatement potentials for reducing greenhouse gas emissions for 20, 50 and 100 US$/t$CO_2$. These potentials are partly based on bottom-up calculations and also partly on the basis of top-down model runs. The latter are in fact determined by a statistical analysis of a set of scenarios from different models using very different assumptions (and thus remain more or less a black box). The oil price assumptions of these scenarios are also unknown. But given the fact that the far majority of these studies has been published between 2001 and 2006, the prices will in general confirm the medium or low price path (see Chapter 2). Here, we have explored the impact of high oil and natural gas prices on the mitigation potential of the total energy system, by running carbon tax scenarios that correspond to the high IPCC category of 100 US$/t$CO_2$, for the total period of 2010-2050.

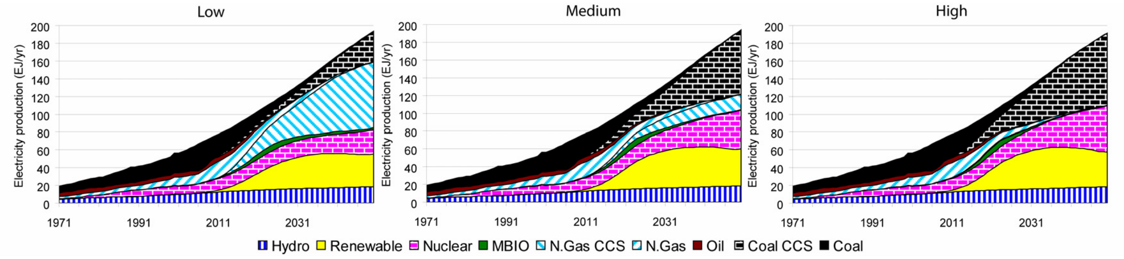

Figure 5.11 Global electricity production by primary energy carrier for medium, low and high energy price paths with carbon tax of 100 \$/CO_2 as of 2010.

Note: Coal, oil and natural gas include the option of CCS. Figures for transport energy use and TPES are comparable with and without climate policy (see Figures 5.5 and 5.6)

In comparison to the high price scenarios without carbon taxes, major changes occur in the electricity production sector (compare Figures 5.7 and 5.11). Here, high oil prices imply that fossil fuel based options become more expensive, thus decreasing the price gap between fossil fuel based options and non-fossil options like renewables and nuclear. In line with the price dynamics shown in Section 5.3 natural gas with CCS is the preferred mitigation technology in the low oil price scenario. However, in the medium and high oil price scenarios, coal with CCS, nuclear and wind are dominant and natural gas is completely phased out. The changes in relative attractiveness of the different technologies are in line with the findings in Chapter 4 (see Table 4.2). The carbon abatement costs of wind, nuclear and CCS are lower, whereas natural gas becomes more expensive.

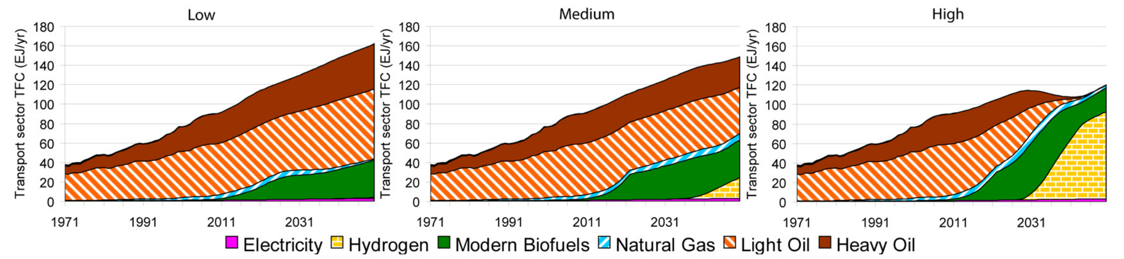

Figure 5.12 Global energy use in the transports sector in low, medium and high oil price scenarios with 100 \$/tCO_2 carbon tax for the period 2010-2050

The major change in energy use in the transport sector is the application of biofuels with climate policy (in all price scenarios), in line with the findings of Chapter 4 (Table 4.2) that biofuels become relatively more attractive. The penetration of hydrogen in the transport sector on the long-term with high oil prices opens up the possibility of CCS from this sector. Carbon emission from hydrogen production can easily be centrally captured and stored, whereas the scattered carbon emissions from oil use in vehicles cannot be captured.

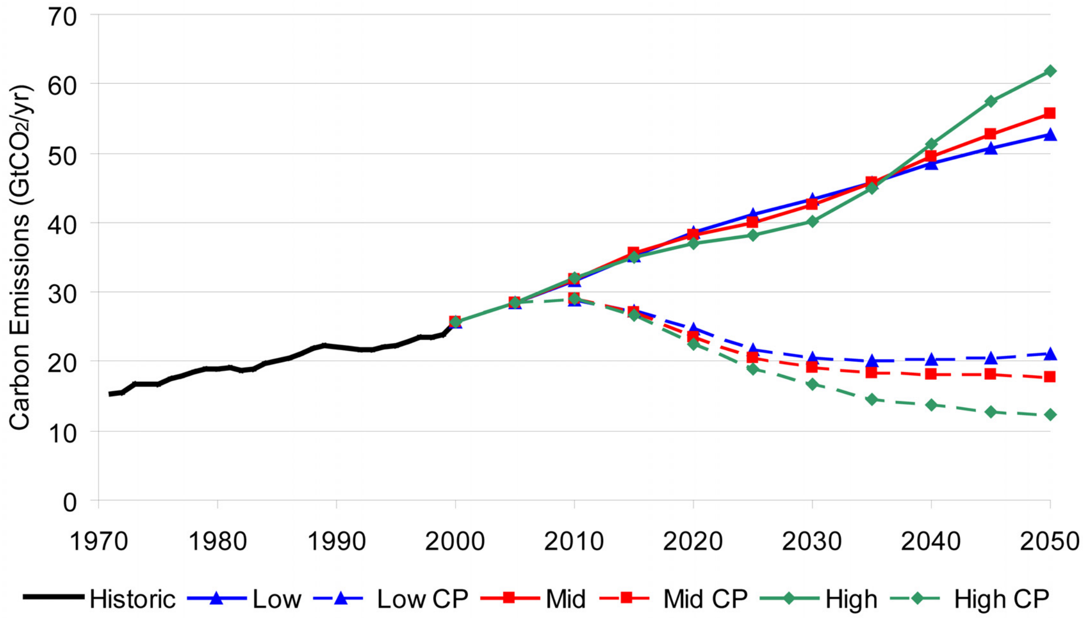

Figure 5.13 CO_2 emissions with and without climate policy for medium, low and high oil/gas prices

As a result, the impact of high fossil energy prices on carbon emissions appears as a further reduction at the same costs (Figure 5.13). With a similar carbon tax of 100 $/t$CO_2$, carbon emissions in the high oil prices scenario are significantly lower than in the low and medium price scenarios, particularly after 2030There are three major reasons for this:

- In electricity production, there is an improved position of renewable energy sources and nuclear energy;
- Higher energy prices lead to an increase in efficiency and hence, lower final energy use
- Once hydrogen enters the transport sector, there is a large additional potential for CCS. This holds also (at least partly) for emissions from CTL or electric vehicles, technologies that are not explicitly considered.

In addition to these direct impacts from changes in the energy system, indirect effects may occur in terms of for instance technology and depletion dynamics. Two indirect effects that are not captured in the TIMER model are 1) high prices also influence the economic growth rate and 2) high energy prices can have a significant impact on the prices of other resources (like steel). In the latter case, not only the direct costs of fossil-fuel based energy would increase, but also the costs of the alternative options become higher due to, for instance, the steel dependency of wind energy and CCS.

The impact of decreased economic growth on carbon emissions may go in two directions. First of all, lower economic activity obviously reduces energy use and therefore emissions. Secondly, however, low economic growth also reduces investments and, hence, technology development. The impact of economic growth on the costs of reducing greenhouse gas emissions is therefore not clear-cut, although the volume impact of decreased energy use is likely to prevail).

6 Conclusions and recommendations

The previous chapters have used two different approaches and scopes to estimate the impact of different oil prices on:

- the abatement costs of mitigation options in Europe in 2020 (Chapter 3 and 4);
- the global energy system and CO_2 emissions until 2050 (Chapter 5).

Based on both analyses we draw the following conclusions:

- Energy prices are a key input for the calculation of abatement costs of mitigation options as well as energy and CO_2 emission scenarios. As many existing mitigation studies are based on low energy prices compared to 2008 levels, the results of these should be interpreted with care.
- In terms of CO_2 abatement costs, many mitigation options become significantly cheaper with higher oil prices. In particular the more expensive (i.e. transport) options, which are at the margin of the cost curves, become substantially cheaper at higher oil prices. Thereby carbon prices that are needed to achieve ambitious mitigation target will be lower at sustained high oil prices.
- It should however not be concluded that high oil prices will automatically lead to lower emissions, as shown in Figure 5.13. In the short term energy efficiency is likely to increase, but a switch from natural gas to coal also is more attractive. In the longer term high oil prices may lead to more hydrogen and electricity in the transport sector. Climate policy is needed to ensure that CCS is deployed, otherwise this could lead to a large increase in emissions. When assuming a \$100 CO_2 price on the other hand, a higher oil price could lead to substantially lower emissions, particularly after 2030.
- Relations between prices of oil, gas and coal are crucial in sensitivity assessment of mitigation options for different oil price levels. In this study we have assumed that gas prices are coupled to oil, but coal prices are not. If the gas-oil coupling will not continue in the future the results would change. If coal prices rises with oil price according to historic correlation the mitigation options with coal as reference will benefit to some extent.
- Oil price sensitivities for mitigation options in the power and industry can be extrapolated to other world regions, as assumptions are valid outside Europe as well. For transport options assessed (i.e. biofuels and hybrid vehicles) it is more difficult to assess to what extent the quantitative results are valid outside Europe, but it is clear that these options will also strongly benefit from higher oil prices.
- High energy prices may also influence the costs of other commodities, like steel or aluminium. Because some energy technologies are more steel-intensive than others (e.g. CCS, Wind or PV), this might change the cost differences between energy options as well. However recent research shows that this impact is likely to be small, as the cost of energy determine these commodity prices only to a limited extent.

We have shown that the costs of several essential climate mitigation options depend heavily on the oil prices, and oil prices fluctuate greatly. This could pose a significant risk for the affordability of climate policy and it is recommended that climate policy is made more oil-price resistant. A logical choice is to focus policy on measures and technologies that both reduce emissions and reduce oil dependence, such as energy efficiency. Policymakers could also consider providing more incentives in those sectors that are particularly oil-dependent and that would see deployment of climate-unfriendly technologies in the case of high oil prices. An example is CCS, which could prevent increasing emissions due to transport technologies such as CTL, hydrogen and electric vehicles, as well from a switch from gas to coal. In addition, policies that take on risks in oil price developments would give certainty to investors, but uncertainty for government budgets. Risk-sharing constructions might be preferable. The main policy recommendation is that oil (and potentially other commodity) price risks need to be made explicit in choosing policies.

The current study sheds light on the issues related oil prices impacts on mitigation technologies. However some important limitations need to be noted. These could be addressed by future research.

- Effects of volatility of energy prices has not been included in the analysis in this study due to lack of scientific methods at our disposal that could assess this properly. Volatility may however increase as fuel prices rise and are an important factor of uncertainty both for national governments as well as the private sector. Possible approaches could include applying different discount rates to technologies according to risk investor risk and a fuel risk premium for fuels with particularly high volatility. This could be a way of further exploring the impacts of externalities related to energy supply security into social cost-benefit analysis of mitigation option, an important area of research deserving further attention.
- High prices as well as climate policy may lead to lower demand for oil, and thereby reduces oil prices. A quantitative assessment of these possible 2^{nd} order effects in was outside of the scope of this study. More analysis may be needed to come up with a more consistent assessment of the interaction between oil prices and climate policy.

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Appendix A Energy prices: interaction between oil and gas

Current oil and gas price relation

The current relation between oil and gas prices can be illustrated by price data of recent years and data on actual contractual indexation found in the sector enquiry of DG Competition (DG Competition (2006).

Oil and gas price data observations

The problem is that a lot of different 'prices' exist and that the relationship observed in price statistics can be very different across continents. Which geographical region is relevant for this study? The Netherlands, the EU or the global market?

In Europe, roughly two types of gas price statistics exist. Firstly there is price data available from trading hubs across the continent (for different types of contracts such as spot, day-ahead, year-ahead, etc.) Examples of trading hubs are the Net Balancing Point (NBP) in the UK, the Title Transfer Facility (TTF) in the Netherlands, and the Zeebrugge hub in Belgium.

Secondly, there are the so-called border price estimates, which give an estimate of the value of gas at certain point on the EU border. Examples are the border prices at Bunde/Emden (for gas from Noorwegen), Baumgarten (for gas from Russia), and Zeebrugge (for gas deliveries at the LNG terminal).

Figure A.1 and A.2 present an oil price indicator, the IEA 'basket' (published on the IEA website) and two spot gas price indicators, the spot price on trading hub TTF in the Netherlands, and the spot price on trading hub NBP in the United Kingdom. Figure 1 depicts data on a daily basis whereas Figure 2 presents monthly data. The unit of measurement, Euro per MWh, might seem strange but is common in gas trade reporting.

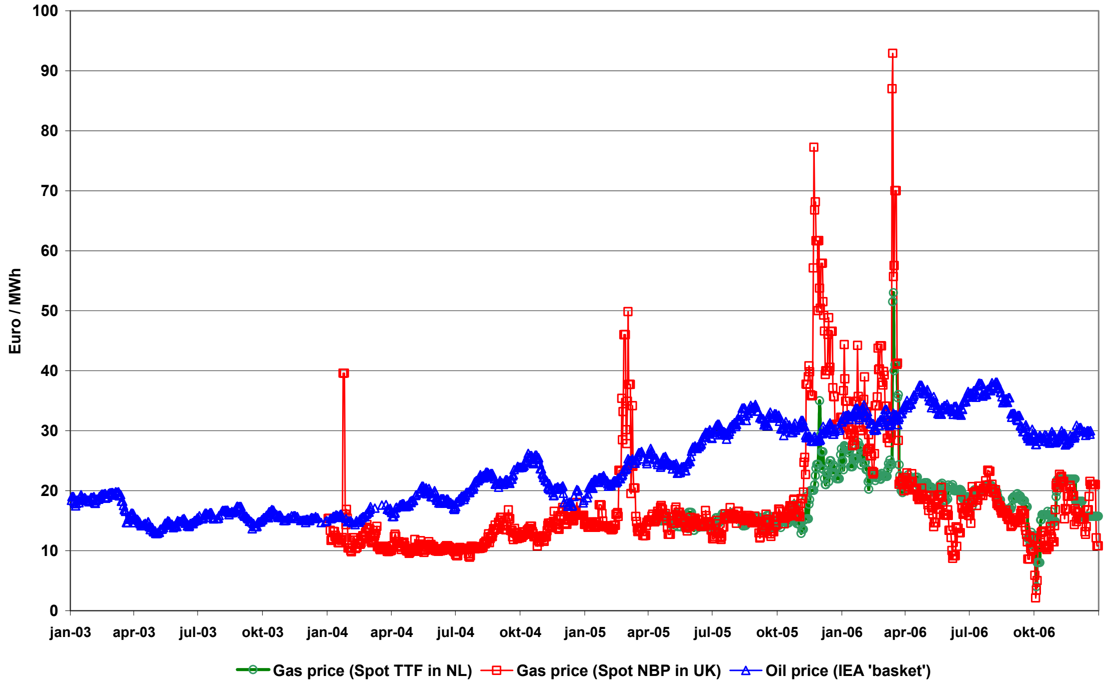

Figure A.1 Daily oil and gas prices January 2003 – December 2006

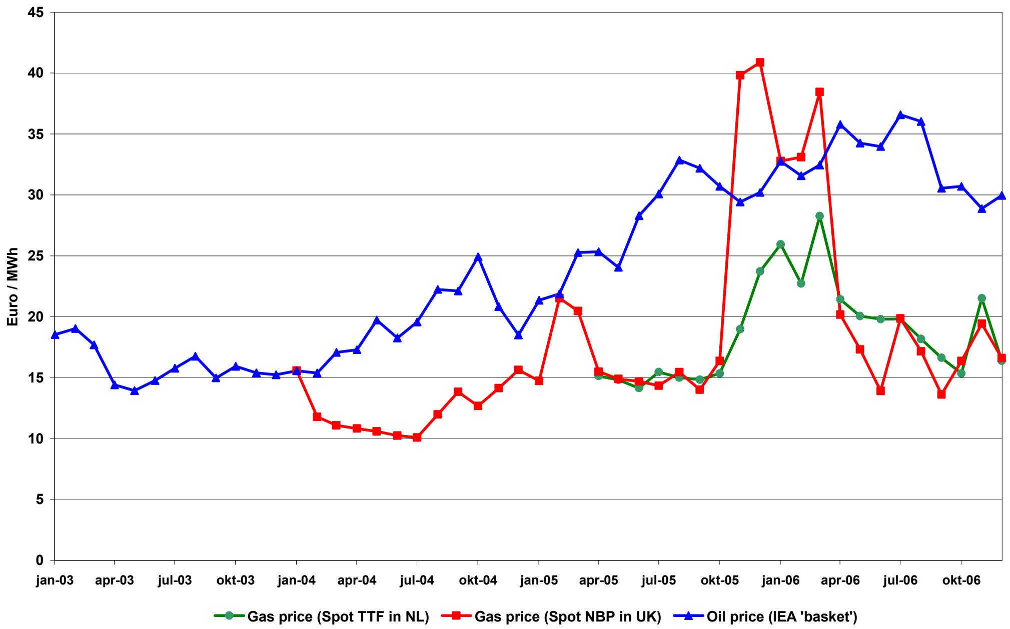

Figure A.2 Monthly oil and gas prices January 2003 – December 2006

Based on the above figures we can observe a certain co-movement of prices, but it seems obvious that gas prices definitely have their own dynamics. Especially gas spot prices show very high volatility compared with oil prices. Unfortunately we lack a good time series for gas border prices on a daily or monthly basis, which prevents us from comparing the average border prices with oil price movements. What we would expect from such a comparison is a much less volatile price path that more closely follows oil price movements.

For illustration, Figure A.3 reproduces the price data for the U.S market published in Villar and Joutz (2006).

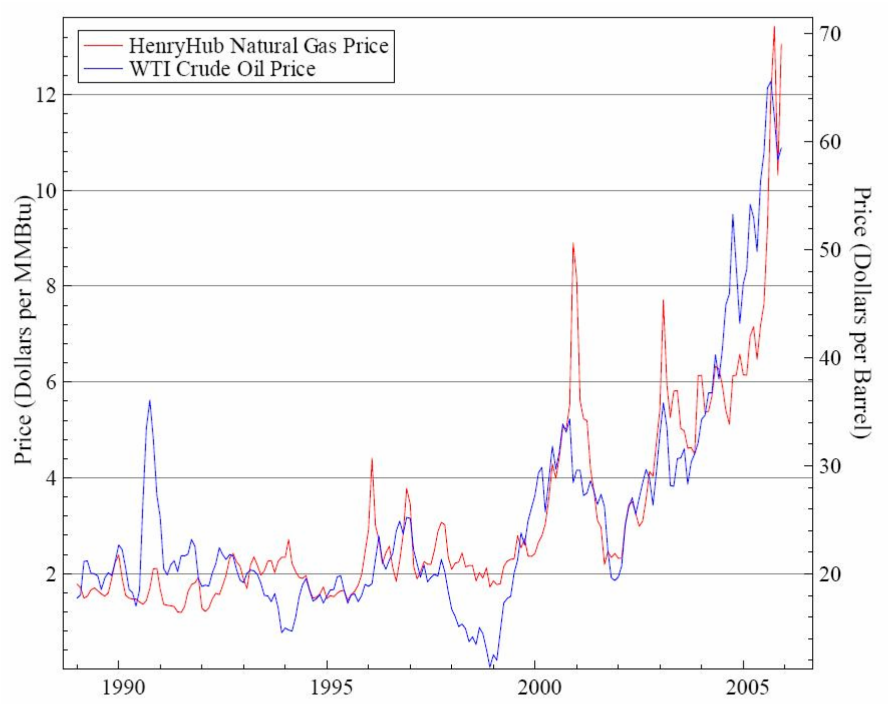

Figure A.3 Oil and gas price in the United States 1989 – 2006

Indexation data from the EU Energy Sector Enquiry
In 2005 and 2006 DG Competition undertook a thorough investigation in the functioning of the EU gas and electricity markets. Results were reported in DG Competition (2007). This energy sector enquiry also analysed available data on gas price indexation in large EU gas delivery contracts. The following figure presents indexation data the EU as a whole. Regional differences in indexation exist: gas contracts concerning gas delivery in the UK contain relatively large shares of gas price indexation (about 40%) whereas gas contracts concerning delivery of gas in Eastern Europe are dominated by oil products (about 95%).

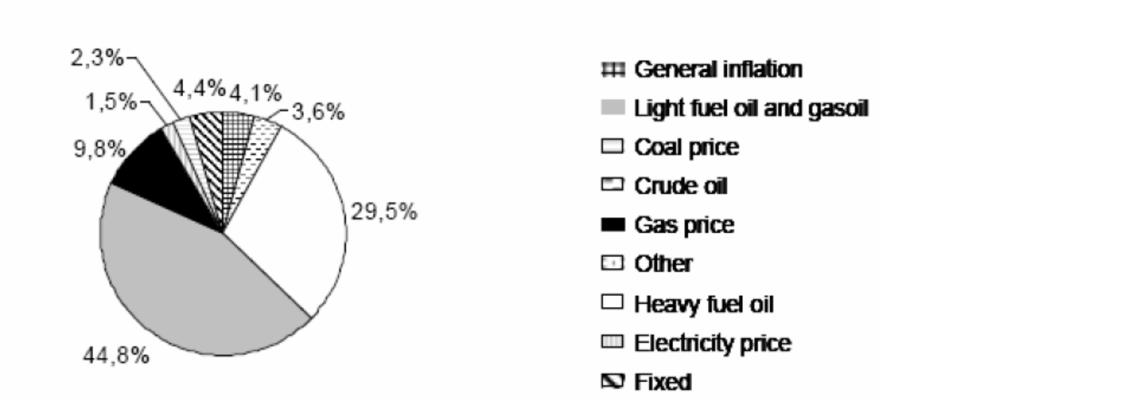

Figure A.4 Indexation in European gas contracts in 2004 (source: DG Competition 2007, p. 89)

Reasons for the relation between oil and gas price
Why should we expect there to be a relation between oil and gas market prices? There are two reasons. The first is the traditional competitiveness argument. The second is the gas market uncertainty brought about by EU gas market liberalisation.

Historically, the rationale for an oil-gas price linkage was the competition between these fuels in final energy consumption in certain market segments, most notably the industrial and electricity sector. In order to maintain competitiveness, gas delivery contracts typically contained price clauses containing an oil price indicator. This resulted in gas prices closely following oil prices, with some delay due to typical ‘six months average’ oil price indexes in gas contracts. The principle applied by gas producers was the so-called ‘netback market value’ principle (Stern 2007).

Another reason for a continuing oil price indexation is the relatively undeveloped spot market for gas in the EU. Since the beginning of EU gas market liberalisation, several trading hubs have emerged across the EU where gas could be traded spot. However, most of these hubs still show insignificant liquidity. Most notable exceptions are the hubs in North-West Europe: the NBP in the UK, TTF in the Netherlands, and Zeebrugge in Belgium. Although all trading hubs report daily prices indicating the value of gas at the moment, gas traders and producers delivering gas in the EU are still reluctant to fully rely on these price indicators when it concerns the hedging of investment risks associated with investments in assets. Indexation of gas delivery contracts to these, often still volatile, hub prices is generally seen as to risky. In addition, gas hub prices are, given low trading levels, vulnerable to manipulation of dominant market parties. In order to ‘lock-in’ future profit margins traders and producers rather seek the liquidity of other commodity markets: the oil and coal market. Given the general poor state of gas trading markets, Indexation of contracts to oil and coal prices is perceived to give more certainty on future profit margins than indexation to gas prices.

Finally we should note especially in the electricity sector, a ‘new’ type of indexation of gas contracts has taken place. Based on the same ‘competition’ argument that was used for oil price indexation, coal price indexation is becoming more and more relevant in gas delivery contracts. This should keep gas competitive vis-à-vis coal in especially the electricity sector. In addition, throughout recent years, gas delivery contracts are also reported to contain, next to oil or coal price indexation, a partial indexation to gas prices at for example the UK NBP. Some experts also anticipate a move towards electricity price or CO_2 price indexation in the future.

Could the coupling continue until 2040?
In answering this question it makes sense to look at the rationale for oil price indexation and see whether old arguments still hold.

With the competitiveness argument being one of the rationales for oil price indexation of gas price contracts, the relevant question regarding the future viability of the linkage is: are there still fuel switching options for gas consumers in the short and long run?
In the short run (days or weeks), fuel switching capabilities of gas consumers seem to be very limited. Electricity producers could switch back to some old oil-fuelled electricity generating units when gas prices spike vis-à-vis oil prices. In the transport sector, some oil products and gas can be substituted. Empirical data on fuel-switching capacities are not available unfortunately.

In the long run, the justification for a continuing oil price indexation of gas delivery contracts could be based on the proposition that electricity producers in the future will build power plants that can run on both oil and gas. In reality however, we observe that no new oil-fired plants are being built in Europe. Hence, long run relationship between oil and gas prices based on physical switching capabilities is not credible.

Regarding the other argument of gas market uncertainty brought about by relatively undeveloped EU gas markets we would need to assess the chances of the development of a very well-functioning and liquid EU gas market. The recently published proposed EC legislative package for the energy sector (which will ultimately culminate in the third Gas Directive) is aiming to address the problems at the root of slow gas market integration and development. However, it still seems optimistic to suggest that the measures in the package will succeed in fostering liquid gas market places across the EU and a level playing field in gas wholesale market competition within the next decade.

In the very long run, it seems inevitable that gas prices will be less related to oil prices. On the one hand switching capabilities between gas and oil are decreasing and on the other hand eventual effective (global and EU) competition on gas markets are the conditions for this projection.

However, we should note that based on econometrics this projection seems radical. Econometric studies on the oil-gas price linkage conclude that gas and oil prices have historically had a stable relationship, even in periods where they appeared to decouple (Villar and Joutz 2006). Of course this study analyses a period where the ‘old rules of the game’ still applied and where a transition towards a possible new system with different indexation schemes could not yet be traced.

Which factors influence the relation until 2040?
Some factors have already been mentioned above. Below list of factors is provided.

- Switching capabilities gas-oil: *trend towards less switching capabilities*
- Gas market developments
  - Development of gas trade liquidity: *improvements would stimulate gas price indexation*
  - Development of market concentration (market domination): *reducing concentration would stimulate gas price indexation*
  - Market integration (developing gas market interconnections): *stimulates gas price indexation*
- Coal market developments
  - Gas vs. coal competitiveness (in electricity sector): *stimulates move from oil price to coal price indexation*

What are likely gas price trajectories?

Given gas price indexation trends (less to oil and possibly more to coal) and the progress in the development of well-functioning gas markets constructing gas price trajectories until 2040 is difficult; even more so than in the past.

It is reasonable to assume that the future gas price will at least move within a band between a floor and ceiling, where the total production and transport cost functions as a floor, and the price of alternative fuels in the power sector (where largest incremental demand is expected) acts as a ceiling. Within this band, price movements are likely to be influenced by gas price and coal price indexation. Important in this respect is the price level of gas at which gas is competitive with coal. Obviously, the level of CO_2 prices in the future plays a role here as well. When oil price linkage results in gas prices becoming uncompetitive with coal (in the power sector) gas producers will be reluctant to continue oil price linkage.

For the purpose of this study, a construction of two scenarios regarding gas price development seems reasonable. One scenario, a minimum gas price scenario, could relate to the ‘floor’ in gas prices, including a certain mark-up for the compensation of gas asset investments. A coal price bound scenario could relate to the ‘ceiling’ in gas prices, with the gas price a certain margin below the coal price (in terms of Euro per MWh). At this point we believe that no such price scenario’s for the period until 2040 are constructed. However, the IEA reference price assumptions are usually interpreted as being quite optimistic, and to a large extent share based on a well-functioning gas market. The latest IEA reference price trajectory could therefore be used a relatively optimistic trajectory. A maximum gas price scenario could be based on coal price projections (which generally are perceived to involve less uncertainties) for the period until 2040, based on competitiveness in the electricity sector.

Appendix B Energy prices: interaction between oil and coal

An indication for any oil-coal price relationship could be derived from historical data sets. In principle the question which prices to relate to each other is as valid here as it was in the discussion on oil-to-gas price linkages. Prices can be different geographically and vary due to the particular quality of coal. However, whereas the gas market is not yet a truly global commodity market, both the oil and coal markets are. Below we present two figures containing oil and coal price data. The first figure is taken from an US study on the co-integration of energy prices undertaken by Yucel and Guo (1994). The second figure presents data published by the US Energy Information Agency (EIA) in the 2008 International Energy Outlook (DOE/EIA 2008b) and actually complements the first figure concerning time span. For our purposes, i.e. obtaining an indication for the development of the long-term oil-coal price relationship, these figures are sufficient.

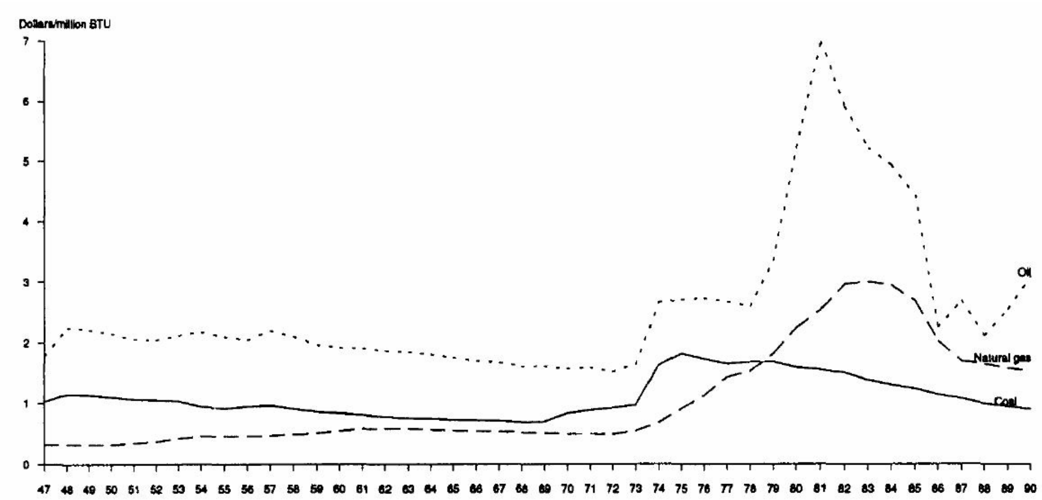

Figure B.1 Oil, natural gas and coal prices from 1947-1990 (Yucel and Guo 1994)

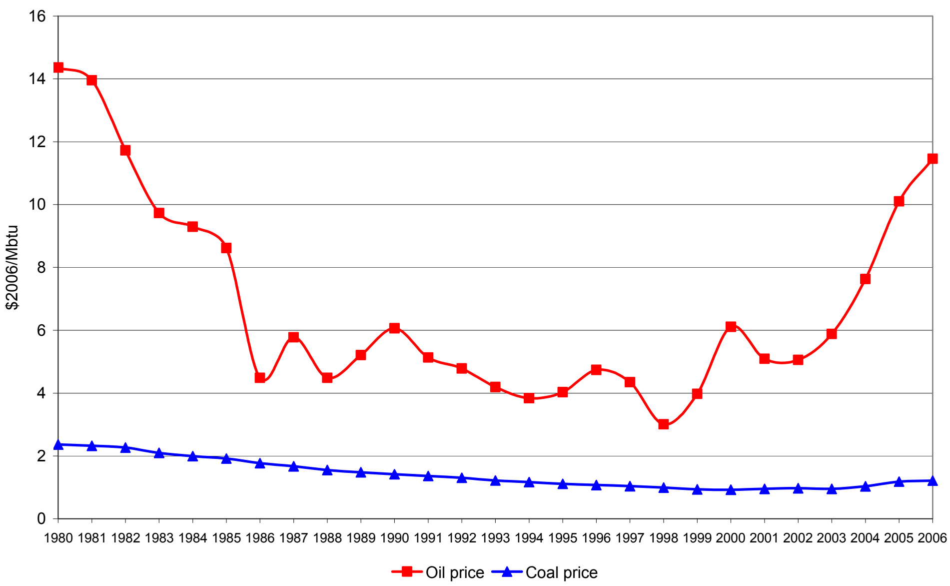

Figure B.2 Oil and coal price from 1980-2006 (DOE/EIA 2008)

Based on the figures we observe that until the 1970s coal prices showed a similar development as oil prices, albeit at a lower level. From the 1970s onwards the oil price has become more and more volatile whereas the coal price has remained relatively flat. One exception is the strong increase in coal prices in the 1970-1976 period. Whereas both natural gas and oil have seen numerous large price hikes this has not been the case for coal. The general explanation for this phenomenon rests on the idea that, unlike natural gas and oil, coal consumers are less capable of short-term switching to other fuels.

Whether oil and coal prices move together in the long-term depends on the degree to which both energy carriers serve as substitutes on various consumer markets. In the industrial sector coal was at first the dominant energy input but both oil and natural gas have surpassed coal since then. In the electricity sector however, coal has for long been the dominant energy input vis-à-vis gas.

Based on the fact that the different energy carriers can in the long-run serve as substitutes Yucel and Guo (1994), through co-integration tests, find that a permanent 1% increase in oil prices brings about a 0.63% increase in coal prices in the period until 1974. As an explanation they point to the fact that coal prices are generally less responsive for energy price increases of competing energy carriers since a relative high share of coal is sold under long/term contracts (30 years or more). Another explanation is the large increase in coal sector productivity over the whole time period (as compared to oil). Lastly, the ´dirtiness´ of coal causes a relatively larger move to natural gas then to coal when confronted with oil price increases. In the period after 1974 co-integration analysis produces similar results albeit that the responsiveness of coal to oil price increases has decreased compared to the period before 1975. This could indicate that coal and oil are starting to serve more different markets (i.e. less direct competition). This is obviously the case for the electricity sector where the role of oil has been decreasing for years.

The major question now is how the relationship between oil and coal prices will evolve in the future. This is largely determined at the markets on which both energy carriers compete: the electricity market, the industrial sector and the transport sector. On the electricity market competition between these energy carriers will become less and less since oil is largely leaving the electricity generation stage. Although not certain about the real competition between oil and coal in the industrial sector and the actual switching capabilities between the two, no large developments are foreseen that will change these competition and switching dynamics in the future. Finally, the transportation sector is potentially a sector where competition between oil and coal is can increase. This development is off course based on the increasing penetration of coal-to-liquids technology. According to the International Energy Outlook (DOE/EIA 2008b) the total production of coal-to-liquids is projected to increase from about 0.1 million barrels of oil equivalent in 2005 to 1.0 in 2030, on a total projected demand for 'liquids' in 2030 of 112.50. In itself this may seem insignificant but it is important to reflect on the impact of this liquid demand for the coal market. According to the DOE office of petroleum reserves[11] a 32,000 barrels per day coal to liquids plant using bituminous coal would consume approximately 16,000 tons of coal, which is equivalent to 6 million tons of coal per year. The same size plant using lignite would require twice that volume. A production of 1 million barrels per day in 2030 could therefore, based on these indicative figures, require 187.5 million ton of bituminous coal or 375 million ton of lignite. This represents about 3 to 6% of total coal production in 2008.

Undoubtedly this 'new' competition with oil will have implications for coal price dynamics and the coal to oil price linkage. Although the total remaining coal reserves will not warrant a sudden leap in coal prices – additional demand can potentially be met by increasing production – the short-run switching capability for transport fuel consumers may increase short-term price volatility on the coal market.

Although we do not know of specific studies analysing the coal price impact of increasing demand for coal to liquids, available future price projections give a hint on what experts expect. Below we present future price projections of the International Energy Outlook (DOE/EIA 2008b).

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11 http://www.fossil.energy.gov/programs/reserves/npr/Coal_to_FT_Liquids_Fact_Sheet.pdf.

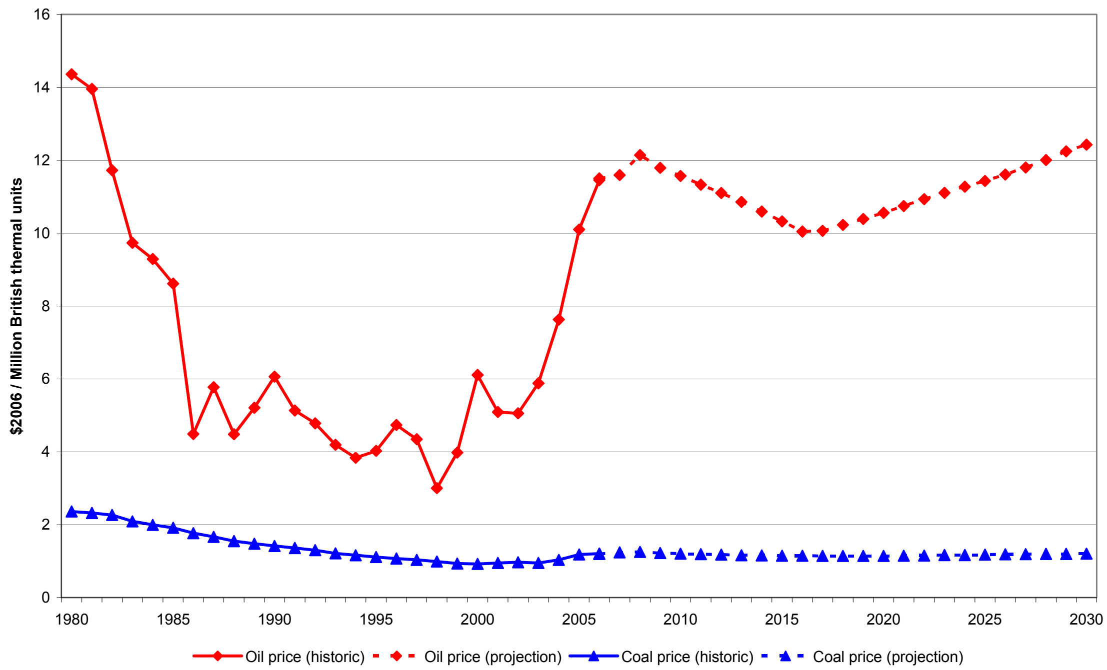

Figure B.3 Oil and coal price projections until 2030 (DOE/EIA 2008b)

The presented figure does not give insights into expected short-term fluctuations in coal price (possibly caused by oil price volatility) but implicitly does give an indication on how the EIA estimates the impact of increased coal to liquids production on coal price. Apparently, the EIA reckons that the additional demand for coal for use in transportation will not have a long-term impact on coal prices.

Little other literature is available on the possible future developments in coal prices in relation to oil prices. But with the increasing use of coal for liquids production the (research) interest for this issue is bound to increase in the medium term.

Appendix C Valuation of costs and benefits methodology

The methodology for valuing costs and benefits of different abatement of CO_2 emissions is distinguished into three different categories of type of costs:
a) National economic perspective
b) Private end user perspective
c) Social perspective

Brief descriptions of different perspectives, their main assumptions and differences between their cost calculations are discussed below:

Economic perspective
Calculation of costs and benefits from a national economic perspective refers to costs and benefits that an option involves for a country as a whole. The costs of energy and the benefits of energy savings are calculated based on international trading prices of the energy sources involved. Taxes, subsidies and levies are not included to the calculations as they perceived as money flows within the country and not costs or benefits. Implementation costs of certain policies are governmental costs and thus they considered as a part of the national costs. Carbon prices not taken into account, as we are calculating CO_2 abatement costs of options. Also these are considered as taxes, as the ETS has been imposed by the EU government and thus will not be taken into account for the calculations from a national point of view. In addition the CO_2 costs (i.e. damage cost due to climate change) reflect global environmental costs and thus they are out of the spatial boundaries of the study and consequently cannot be taken into account from a national and social point of view. The discount rate usually assumed for national investments is about 3- 5%.

Private perspective
Financial costs and benefits refer to the costs (and benefits) that individuals, investors and sectors would realise during the investment decision making process. To estimate the private costs, there are some assumptions that differ from the assumptions made for the calculation of national costs. Normally the discount rate that is assumed from an investor's financial perspective is higher and depends on the average cost of capital at different sectors. A value in the range of 6-10% discount rate is assumed in private investments. Another main difference in comparison to the assumptions taken from a national point of view is the fact that all fiscal incentives (e.g. subsidies, tax reductions, soft loans, taxes, feed in tariffs) are taken into consideration as they have direct impact to the end user prices. CO_2 prices resulting from the EU ETS are excluded, as we are calculating CO_2 abatement cost of options.

Social perspective
The impact of a project to the society as a whole should be considered when calculations of costs and benefits of a project are estimated from a social point of view. The main difference between calculation of social costs and economic costs are the so called "external" costs. External costs (and benefits) or "externalities" – which can be positive or negative - are the impacts that arising from an activity or project and affect members of society but are not accounted for in the economic or private analysis (mainly because those costs caused are not adequately internalised into market prices). While performing social costs assessment of GHG abatement technologies, external costs should be included in the calculations. Important relevant externalities are health damage due to air pollution, energy supply security (Egenhofer et al, 2006) Regarding carbon costs, as was mentioned before, they express global environmental external costs and as the geographical scale of the analysis is at the EU level, global externalities and thus climate change external costs will not taken into account. The social discount rate used can be similar to those applied in the economic analysis (3 - 5 %).

Box C.1: Discount rate

The selection of discount rate is essential when calculating costs and benefits of climate policies since the long time horizon involved. Normally in public policy appraisal there are standard discount rates adopted but the selection of the appropriate discount rate in projects related to climate policies has been subject of debate. The selection of discount rate (or rate for time preference) for climate policy measures and projects has a serious impact on the calculation of economic costs of climate change and furthermore on the estimation of costs of GHGs abatement options. The main climate change negative impacts will be occurred in the future and the benefits of combating climate change will be therefore realised for future generation and thus a selection of a higher discount rate leads to lower economic costs of climate change and consequently leads to lower benefits of climate measures and mitigation options.
Many studies adopt a social rate of time preference for discounting (as used in public policy by governments) rather than a private discount rate that used in the private sector and investments. Recently the idea of using a declining discount rate has been supported by some authors where it has been recognised that the discount rate should not be unchanged over time.
The discount rate used in public policy evaluation is a social rate of time preference (SRTP). The SRTP is thee value that society attaches to present consumption than in future consumption and is based on comparisons of utility between different time points or different generations. The SRTP consists of two elements: a) The so called pure rate of time preference (PRTP), the rate that individuals discount future consumption in relation to present consumption, while assuming a constant level of consumption per capita and b) the growth of the per capita consumption over time $\mu * g$, where μ is the elasticity of the marginal utility of consumption and g is the annual growth in per capita consumption. In conclusion the STRP is the sum of these two elements:

$STRP = PTRP + \mu * g$. In Europe the resulting social discount rate that normally governments are adopting for no-risk public works, projects, and investments is 3.5 % - 4 %.
Sources: EEA, 2007; Eigenraam et al, 2008.

Appendix D Cost calculation methodology

In the ECN Abatement Cost model, an annuity-based method was used, in which the lifetime of each technology is respected (amortisation over the whole lifetime at a constant interest rate). Fuel prices have been kept constant. The following sections elaborate on these choices.

Calculation method

For evaluating the mitigation costs of technologies, the choice of the calculation method can be decisive on the trade-off between to competing mitigation options. *However, it is important to realise that the uncertainty of the input parameters is a very relevant factor, which in most cases will be overruling the deviations due to the calculation method applied.* This section discusses the pros and cons of two methods: the annuity method and the cash flow method.

In the *annuity method* the annual costs are evaluated: costs due to amortization of the investment, fuel costs and fix and variable operation and maintenance costs. Alternatively and dependent on the perspective of the cost calculation, external costs and heat credits can be considered. The investment costs are annualised, assuming constant payments, a constant interest rate and a lifetime. The annuity method obviously is a relatively simple approach.

In the *cash flow analysis*, each consecutive year of a project is considered, which makes the method much more flexible for different assumptions, such as non-linear depreciation, variable values for fuel costs and time-dependent fix and variable operation and maintenance costs. It allows detailed analysis of a project, but at the same time requires more inputs.

Comparing projects with different lifetimes

Another methodological problem is how to comparing projects with different lifetimes. For example, compare wind power (average lifetime 20 years) with a pulverised coal plant (PCC, average lifetime 20 years). The comparison can be performed using three different approaches:
1. Use different lifetimes for each technology (example: evaluate wind over 20 years and PCC over 40 years);
2. Use an equal lifetime for the amortisation (i.e. the shortest of all options, example: evaluate wind over 20 years and PCC over 20 years as well including a residual value in year 20);
3. Include a second investment decision and make sure that the projects end in the same year (example: evaluate two wind parks over 40 years and evaluate PCC over 40 years).

Starting with the third approach, the implicit assumption is that the second investment decision is already taken at the beginning of the 40-year period. This does not correspond with reality, in which at the end of the lifetime other business opportunities might seem more attractive. Alternatively, also the PCC plant can be decommissioned at an earlier stage. On the other hand, the approach makes it possible to take into account future cost decrease for wind power as a result of technology learning. All in all, approach 3 seems to introduce more problems than it solves, although the idea is elegant in itself.

Approach 1 and 2 only result in different outcomes in case costs are calculated using a cash flow analysis. As in the current approach it is opted for the annuity-method, the first approach (1) is most logic to implement. In a future project the second approach can be implemented.

Dealing with constant versus increasing fuel prices

For the fuel price scenarios two options exist:
A. Use constant prices for the fuel prices and other costs during the whole period under study
B. Use real price escalators for the fuel prices and other costs

Approach A is a straightforward way of representation, which does not mix different effects. Policy makers might be primarily interested in the influence of energy prices on the costs associated with decisions taken at a specific point in time, say 2020. Focusing on rising prices (approach B) however is understandable, but it still is a bias. It complicates evaluation of the results and leads to less transparent outcomes. Also, calculations based on rising prices do not allow to determine at which price exactly the one technology becomes more attractive than the other. An additional option in case of rising prices is the possibility of postponement as opposed to investing now, i.e. explicitly address the option value of waiting. In other cases, technologies may be cost-effective now, but rising prices may result in operational losses later during their lifetime. In such a case, calculations based on fixed lifetimes give unfair negative results: premature closure of a plant would result in better cost-effectiveness. The maximum NPV (and lowest average production costs) will in this case be achieved at a shorter lifetime than the technical lifetime.

In conclusion, using rising prices during the lifetime of a technology leads to less transparent results. Therefore, initially the scenarios are built around constant fuel prices over time (approach A). In combination with the calculation approach of the annuity method (see previous section) it is opted here for constant prices. Nevertheless, the ECN Abatement Cost model is set up in such a way that variable fuels prices (approach B) can be evaluated as well, namely by applying the approach of levelising (see next section) in order to reduce the price series to a value in one year.

Levelised cost approach

The concept of levelised costs allows to value a time-series of costs / prices at a certain interest rate, and to create a single mean value of that series. For example: a series of variable fuel prices for the period 2020 to 2040 needs to be characterised by one value because the annuity method for calculating cost of electricity allows only one entry[12]. The interest rate is a measure for the risk-aversion: the higher the rate, the less importance is paid to future costs or prices. A zero interest rate simply results in the average value of the series.

The aim is to find a mean and constant value $\bar{c}$ which, considering discounting at a rate i, yields the same outcome as the discounted series of varying values c_n:

Present value of c_n during N years at interest rate i	=	present value of $\bar{c}$ during N years at interest rate i

In mathematical terms this reduces to:

$$\sum_{n=1}^{N} \frac{c_n}{(1+i)^n} = \sum_{n=1}^{N} \frac{\bar{c}}{(1+i)^n}$$

As $\bar{c}$ is a constant, it can be moved out of the summation:

$$\sum_{n=1}^{N} \frac{c_n}{(1+i)^n} = \bar{c} \cdot \sum_{n=1}^{N} \frac{1}{(1+i)^n}$$

[12] The choice of the calculation method here requires a single value for the fuel price. More advanced methods, such as a cash-flow analysis, allow variable fuel price series as input.

The mean value $\overline{c}$ can now be found as follows:

$$\overline{c} = \frac{\sum_{n=1}^{N} \frac{c_n}{(1+i)^n}}{\sum_{n=1}^{N} \frac{1}{(1+i)^n}}$$

In the current analysis, each technology considered has its own lifetime, so the levelised fuel price is to be determined over a period which is not equal for all technologies. This is a serious drawback and complicates the use of different lifetimes when non-contant fuel prices are assumed. For the exercise as presented in the current report, fuel [prices are constant and therefore the above mentioned levelised cost approach will not be used.

Appendix E Electricity sector assumptions

The basic formula used for the CO_2 abatement cost calculation for options in the electricity sector:

$$Cost(Mx) = \frac{Cost(Tx) - Cost(Rx)}{CEF(Rx) - CEF(Tx)}$$

Where:
Cost(Tx) : Costs of Technology x in €/MWh
Cost(Rx) : Costs of Reference technology x in €/MWh
CEF : Carbon emission factor in t CO_2/MWh
Cost(Mx) : Costs of Mitigation option x in €/t CO_2

This formula is also used for the industry and transport sector (with the units changed accordingly).

The main sources of data of information for the cost assumptions and calculations for the electricity technologies are Jansen et al (2008) and the CASES (2008). The next table shows the mean values of major input parameters. In the ECN Abatement Cost model input ranges are used for each parameters, but these are not shown here.

Table E.1 Electricity sector input values.

		PCC	CCGT	Wind onshore	Wind offshore	Nuclear	Biomass co-firing	CHP (gas)	CHP (coal)	PCC + CCS	CCGT + CCS	PV
Initial investment costs	€/kW	1400	700	1250	1650	2400	1523	885	1585	2400	1050	2500
Construction period	years	4	1	1	2	6		1		5	2	
Interest rate during construction	%/year	8%	8%	8%	8%	8%	8%	8%	8%	13%	12%	8%
Discount rate during operation (social)	%/year	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%
Efficiency	%	48%	59%	100%	100%	100%	35%	46%	36%	39%	50%	100%
Discount rate during operation (private)	%/yr	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%
Fuel costs	€/GJ					0.008	6					
Fuel CO_2 emission factor	tonCO2/GJ	0.094	0.056				0.094	0.056	0.094	0.094	0.056	
Variable O&M costs	€/MWh	0.2	0.05	1	0.5	0.15		0.05	0.2	0.4	0.15	
Fixed O&M costs	€/kW	53	30	24	80	80		39.5	59	65	45	29.4
Operational (full load) hours	hours	7446	7446	2199	3679	7884	6000	5900	5900	7446	7446	1071
Lifetime	years	35	30	20	15	45	30	20	30	40	35	25
Thermal efficiency	%							33%	42%			
Reference efficiency heat generation	%							90%	90%			

Appendix F Industry sector assumptions

Table F.1 gives a summary of major input parameters (only 'mean' values) for the analysis using the ECN Abatement Cost model.

Table F.1 Industry sector mean input parameters

		Efficiency 1	Efficiency 2	CCS (EOR) ammonia	CCS (no EOR) ammonia
Investment cost	€/tCO_2/yr	834	1337		
Investment cost additional	€/tCO_2/yr			26	26
Fixed O&M costs	€/tCO_2/yr	5.7	5		
Lifetime	yr	20	20	30	30
Efficiency	%	0.9	0.9		
Energy intensity	GJ_{th}/t_prod			34	34
Discount rate social	%	4%	4%	4%	4%
Discount rate private	%	8%	8%	8%	8%
Fuel CO_2 emission factor	tCO_2/GJp	0.0561	0.0561	0.0561	0.0561
Oil recovery rate	GJoil/tCO_2 inj			7.686	
CO_2 capture efficiency	%			80%	80%
CO_2 storage cost	€/tCO_2			15	4
CO_2 transportation distance	km			400	250
CO_2 transport costs	€/tCO_2/km			0.07	0.02
Capture energy requirements	GJ_{th}/tCO_2			0.4	0.4

Appendix G Transport sector assumptions

This annex briefly discusses the input parameters used in the transport sector calculations of the AC model.

Investment Costs
The investment costs (in € per vehicle) from an investor's perspective who is buying a passenger light duty car consists of the retail price of the vehicle excluding the taxes.

Constant average mileage
Constant average mileage refers to the distance that a vehicle is covering in one year. The constant average mileage for a passenger light duty vehicle is set to 16,000 km.

Average vehicle lifetime
A lifetime of 13 years is considered for an average vehicle.

Fuel consumption
The fuel consumption of a vehicle measured in litre/100 km.

Energy Content
The energy content of motor fuels measured in MJ/litre.

Carbon emission factor
The factor that represents the CO_2 emitted by the combustion of a motor fuel, expressed in grammes of CO_2 per unit of primary energy (gCO_2/GJ).

Oil Cost Factor (OCF)
The OCF indicates the extent to which the price of a motor fuel will increase when the oil price increases, i.e. the price elasticity. This is a key factor for the sensitivity calculations.

Fuel tax
This variable is considered at the calculation of abatement costs of transport technologies from the private point of view. The fuel tax variable consists of the excise duties on fuels and the VAT on fuels (gasoline and diesel) and is expressed in €/litre of fuel.

Tax on acquisition
Taxes on acquisition are taxes paid once, by a vehicle owner, for a vehicle purchased and entered into service. This type of tax consists of the registration tax and the VAT. It is also considered from a private perspective.

Calculation of costs of Mitigation option formula for transport sector:

$$Cost(Mx) = \frac{Cost(Tx) - Cost(Rx)}{CEF(Rx) - CEF(Tx)}$$

Cost(Tx) : Costs of Technology x in €/km
Cost(Rx) : Costs of Reference technology x in €/km
CEF : Carbon emission factor in gCO_2/km
Cost(Mx) : Costs of Mitigation option x in €/tCO_2

The main references used to obtain the relevant assumptions and calculations are Uyterlinde et al. (2008) and Refuel (Londo et al, 2008) studies. Table F.1 shows the mean values of the transport sector assumptions.

Table G.1 Transport sector assumptions in the ECN AC model.

		Hybrid light duty cars	Biodiesel 1st gen	Bioethanol 1st gen	Biodiesel 2nd gen	Bioethanol 2nd en	Bas. eff. Diesel	Gasoline	Diesel
Investment Costs	€	18400	16100	15400	16100	15400	15900	15200	15900
Discount rate	%	4%	4%	4%	4%	4%	4%	4%	4%
Lifetime	years	13	13	13	13	13	13	13	13
Constant Annual Mileage	km	16000	16000	16000	16000	16000	16000	16000	16000
Energy content	MJ/l	36	33	21	33	21	36	32	36
Fuel consumption	l/100km	3.5	4.6	7.0	4.6	7.0	4.2	4.6	4.2
Fuel prices	€/GJ	13.6	22.5	25.0	21.8	22.2	13.6	13.9	13.6
Fuel CO_2 Emission Factor	gCO_2/MJ	85.4	22.1	20.3	17.08	16.56	85.4	82.8	85.4
Oil Cost Factor	-		0.1	0.1	0.1	0.1			
Fuel Tax	€/l	0.51	0.47	0.43	0.47	0.43	0.51	0.65	0.51
Tax on acquisition	%	38%	38%	38%	38%	38%	38%	38%	38%
Discount rate private	%	8%	8%	8%	8%	8%	8%	8%	8%