Energy security, air pollution, and climate change: an integrated cost-benefit approach

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Abstract

Energy security, air pollution, and climate change: an integrated cost-benefit approach

This report presents the findings of an integrated cost-benefit analysis of options to increase energy security, reduce local air pollution, and mitigate global climate change. Although energy security is commonly recognised as an important issue, it is less clear how damaging a lack of energy security is to the economy. Moreover, it is unclear how to successfully improve on energy security in a world with scarce resources. The analysis aims to stimulate the process of the development of clear, policy targets for energy security in relation to other policy objectives to avoid air pollution and impacts of climate change.

This report explores the consequences of introducing an analytical supply-of-security expression in the integrated energy-economy model MERGE. First the abstract notion of energy security is quantified, followed by the implementation of the quantified energy security function in MERGE. A set of simulations is then conducted to explore the impact of the application of this function. These simulations tentatively indicate that concerns for energy security cause a delay in the global demand for oil, in scenarios without explicit climate change and air pollution policy. Even so, in this case oil resources will eventually be completely depleted. With additional climate change policy, the oil resources will not be depleted, and when complemented by air pollution policy, reserves of oil will ultimately remain larger. In these environmental policy scenarios, energy security policy is shown to reduce the cumulative demand (over the next 150 years) of oil in by 20%, compared to the baseline without any policies. Between 2020-2030, substantial CO_2 emission reductions will be achieved in Europe. This is induced by energy exporters, expanding on the combustion of their own abundant (and cheaper) gas and oil resources. In turn, this implies that energy importing regions will increase their CO_2 emission reductions, thus minimizing the damages, caused by climate change.

Keywords: energy security, air pollution, climate change, damage costs, cost–benefit analysis

Rapport in het kort

Integrale kosten-baten analyse klimaat, energievoorzieningszekerheid en luchtkwaliteit

Dit rapport presenteert de analyse van een mondiale geïntegreerde kosten-baten analyse van opties om de energievoorzieningszekerheid te verhogen, en de nadelige gevolgen van luchtvervuiling en klimaatverandering tegen te gaan. Weliswaar wordt het probleem van een beperkte energievoorzieningszekerheid in het algemeen erkend, maar het is onduidelijk wat de schade hiervan is aan de economie. De analyse probeert de ontwikkeling van het definiëren van heldere doelen voor de energievoorzieningszekerheid een stap verder te brengen, en deze te plaatsen in de bredere afweging van doelen voor beleid om klimaatverandering en luchtvervuiling tegen te gaan.

Dit rapport onderzoekt de gevolgen van een introductie van een analytische functie voor energievoorzieningszekerheid in het geïntegreerde energie-economie model genaamd MERGE. Eerst wordt the begrip voorzieningszekerheid gekwantificeerd, gevolgd door een mathematische formulering over dit onderwerp zoals te gebruiken in MERGE. Modelsimulaties worden gepresenteerd die rekening houden met de modelvergelijkingen over voorzieningszekerheid. Deze modelexperimenten laten zien dat wanneer er geen milieubeleid wordt gevoerd, de schade door een verminderde energievoorzieningszekerheid verlaagd kan worden door de vraag naar olie en gas uit te stellen naar de toekomst. De reden is dat in de toekomst de energie-intensiteit lager zal zijn dan nu, en daarom zullen economieën minder gevoelig zijn voor prijsschommelingen van energie of een te lage voorzieningszekerheid. In de varianten zonder milieubeleid maar met beleid om de voorzieningszekerheid van energie te verhogen, zullen de voorraden van gas en olie dus uiteindelijk toch uitgeput worden. Maar in varianten met klimaatbeleid zullen de bekende olievoorraden niet volledig aangesproken worden, zeker wanneer er ook nog beleid gevoerd gaat worden om de luchtvervuiling tegen te gaan. In een toekomst met beleid tegen klimaatverandering en luchtvervuiling en voor een hogere voorzieningszekerheid zal de vraag naar olie, gecumuleerd over een periode tot aan 2150, met 20% lager uitvallen (ten opzichte van het basispad waarin geen beleid wordt gevoerd). In dat geval zullen er tussen 2020 en 2030 in Europa substantiële CO_2 emissiereducties doorgevoerd worden. De modelsimulaties laten zien dat dit mogelijk lijkt en aannemelijk, omdat de energie-exporteurs hun goedkopere energievoorraden zullen gebruiken (en daardoor hun CO_2 emissies vergroten). Daardoor zullen energie-importeurs (zoals Europa) hun CO_2 emissies verder moeten verlagen om de schade door klimaatverandering te beperken.

Trefwoorden: luchtvervuiling, klimaatverandering, schadekosten, kosten-baten analyse, energievoorziening

Contents

Uitgebreide samenvatting

Integrale analyse klimaat, energievoorzieningszekerheid en luchtkwaliteit

Fossiele energie is de brandstof voor onze economie. Er is behoefte aan energie voor burgers en bedrijven, maar er is ook schaarste aan fossiele energiedragers. De risico's van een te lage voorzieningszekerheid (VZZ) van bijvoorbeeld olie en gas kan veroorzaakt worden door een niet goed werkende markt, wanneer aanbieders en vragers van energie niet reageren op de prijzen. Bovendien leidt de huidige toename van het fossiele energiegebruik tot een beslag op de kwaliteit van de publieke ruimte. De verbranding van fossiele brandstoffen leidt tot de uitstoot van broeikasgassen welk weer op zijn beurt klimaatverandering tot gevolg heeft, en op de lange termijn grote schadelijke gevolgen heeft voor de wereld als geheel, en voor specifieke regio's mogelijk zelfs desastreuze gevolgen. Maar in het heden en de nabije toekomst zal op lokaal niveau de verbranding van fossiele energie ook nog eens leiden tot de vervuiling van de lucht met gevolgen voor de gezondheid van de mens.

De EU heeft een ambitieus klimaatplan neergelegd, heeft een aanpak opgesteld voor de verbetering van de luchtkwaliteit, en heeft ook ambitie om de voorzieningszekerheid van energie te vergroten. Maar een integrale visie is moeilijk te realiseren, omdat de problemen apart worden behandeld, en concrete doelen als in het geval van voorzieningszekerheid ontbreken. Bovendien heeft beleid op de verschillende terreinen ook verschillende effecten. Het MNP heeft een tentatieve mondiale analyse uitgevoerd die deze problemen op een noemer brengt door middel van een maatschappelijke kosten-baten analyse. De analyse leidt tot scenario's voor de economie, energie en bestrijdingstechnieken tegen luchtvervuiling voor Europa en andere grote regio's. Deze scenario's zijn geïntegreerde schetsen voor aanpassingen van de energie-infrastructuur, die de genoemde problemen tegelijkertijd aanpakken tegen de laagst mogelijke kosten en de welvaart maximeren.

Wat zijn de belangrijkste veronderstellingen m.b.t. energie voorzieningszekerheid?

In de gestileerde modelanalyses is verondersteld is dat regio's bereid zijn om de energievoorzieningszekerheid te verhogen door voor gas de importafhankelijkheid te verlagen, en het aandeel van olie en gas in het energiesysteem (diversificatie), en het verbruik per eenheid toegevoegde waarde te verlagen. Er zijn niet veel eenduidige voorbeelden in het verleden te vinden waarbij grootschalige programma's zijn gestart om de energievoorzieningszekerheid te verhogen. Een voorbeeld is de ombouw van het Franse elektriciteitspark, in het begin van de zeventiger jaren vooral gestoeld op olie, waterkracht en kolen en 15 jaar later voornamelijk draaiend op nucleaire energie. De directe kosten van deze expansie zijn als vuistregel en aanname gebruikt om de bereidwilligheid van regio's te ijken naar het Franse voorbeeld. De maatschappelijke kosten van aanpassingen in het energiesysteem bedroegen in het Franse voorbeeld ruwweg 0,5% van particuliere consumptie.[1] Per regio verschillen de maatschappelijke kosten door de heterogeniteit van het energiesysteem.

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1) Het BNP is gelijk aan particuliere consumptie plus investeringen plus overdrachten naar het buitenland. In Europa zal in de komende 50 jaar het niveau van particuliere consumptie 75-80% van het BNP bedragen.

Tabel S1: OECD-Europa in 2030 van variant Milieu + VZZ ten opzichte van het basispad [1,2]

		Klimaatbeleid		Klimaatbeperking + luchtbeleid + VZZ		Klimaat- en luchtbeleid + VZZ	
CO_2 emissies (Gton C)		-0.22 (-5% t.o.v. 1990)		-0.22 (-5% t.o.v. 1990)		-0.49 (-33% t.o.v. 1990)	
PM_{10} emissies (mton PM_{10})		-0,04		-0,24		-0,41	
Vroegtijdige sterfte (%)		-6		-34		-60	
Gas	Importafhankelijkheid (%, import / totale vraag)	-79		-98		-100	
	Aandeel (%, aandeel van totaal primair energiegebruik)	-16		-39		-35	
	Intensiteit (%, EJ/2000$)	-20		-38		-40	
Olie	Aandeel (%, aandeel van vraag naar warmte)	-10		-21		-40	
	Intensiteit (%, EJ/2000$)	-13		-23		-45	
Totale Baten (%, aandeel in particuliere consumptie)		1,0		1,3		1,5	
	Baten voorzieningszekerheid (%, aandeel in part. consumptie)		1,0		1,1		1,2
	Baten lucht (%, aandeel in particuliere consumptie)		0,0		0,2		0,3
Particuliere Consumptie (%)		-0,2		-0,7		-0,9	
Welvaart = particulier consumptie + totale baten (%)		0,8		0,6		0,6	

1) In 2030 is er nog geen verschil in klimaatschade tussen varianten (allemaal 0,1%); deze liggen verder in de toekomst.
2) Discontovoet 4% in 2020, 2% in 2100

De gevolgen voor Europa in 2030

Tabel S1 is een illustratie van de gevolgen voor Europa in 2030 van drie varianten: [1] optimaal klimaatbeleid zonder rekening te houden met de energievoorzieningszekerheid en luchtvervuiling, [2] optimaal beleid ter verhoging van de energievoorzieningszekerheid en verlaging van de luchtvervuiling, en nadelige gevolgen van klimaatverandering tegen te gaan. Echter, de CO_2 emissiereducties van Europa zijn gelijk aan het niveau van variant 1, en [3] volledig optimaal beleid, dus net als variant 2, maar dan zonder de beperking op CO_2 emissiereducties in Europa.

Het streven naar gelijktijdig realiseren van verschillende doelen (derde variant) kan de uitworp van CO_2 in 2030 met 33% verlagen ten opzichte van het niveau van 1990. Ook de fijn stof emissies zullen substantieel dalen (0,41 mton PM_{10} is ongeveer 50%) Als er alleen klimaat- en luchtbeleid gevoerd zou worden dan zal de emissiereductie lager uitvallen (-5% ten opzichte van 1990). Het combineren van beleid om de milieukwaliteit te verbeteren en de voorzieningszekerheid te verhogen levert meer emissiereducties op voor CO_2 en PM_{10} dan varianten waar alleen klimaat -en luchtbeleid of alleen maar VZZ beleid wordt gevoerd (in het laatste geval is er zelfs een stijging van de CO_2 emissies door een stijging van het gebruik van kolen). De tweede variant - met een beperking op de CO_2 emissiereductie gelijk aan de klimaatvariant – leidt via de elektriciteitssector tot luchtkwaliteitsverbeteringen en een verhoogde VZZ door een stijging van nieuwe duurder kolencentrales (wel CO_2 emissies maar geen fijn stof) die het mogelijk maken om de vraag naar olie te verdringen buiten de elektriciteitssector.

Kosten van energiebeleid in de EU kleiner dan de baten

De kosten van beleid (verlies van consumptie ten opzichte van het basispad zonder beleid) zullen in Europa kleiner zijn dan de baten (=verminderde schade door beleid). De welvaart in 2030 kan 0,6-0,8% hoger uitkomen, mits er rekening gehouden wordt met het internaliseren van de externe schade door klimaatverandering, luchtvervuiling en een lage energievoorzieningszekerheid in de energieprijzen van Europa. De extra kosten van CO_2 emissiereductie van de tweede ten opzicht van de derde variant zijn klein (0,9% versus 0,7%), omdat de kostprijsstijgingen van deze verdergaande emissiereductie worden gecompenseerd door de dalende energiekosten en de langere termijn klimaatbaten (beperkt zich niet tot alleen Europa maar de hele wereld). De lagere kosten in Europa worden geïnitieerd doordat de afstoting van minder competitieve energie-intensieve activiteiten wordt toegestaan (deze producten worden dan geïmporteerd) en er geen beperking is op de CO_2 emissiereductie die leidt tot lagere bestrijdingskosten van de luchtvervuiling.

De plannen voor een Europese gasrotonde lijken niet strijdig met een hogere energievoorzieningszekerheid

De welvaart wordt in 2030 vooral verhoogd door de voorzieningszekerheid te verbeteren (bijdrage 1,0-1,2% aan particuliere consumptie). De meeste baten worden al gehaald door de CO_2 emissiereductie van de variant die zich beperkt door klimaatbeleid (-5% ten opzichte van het niveau in 1990). De importafhankelijkheid van gas wordt verlaagd (tot 0%) door gascentrales merendeels te sluiten en te vervangen door duurdere niet-fossiele alternatieven. Daardoor wordt de schade door gasgebruik teruggebracht naar nul, en zijn argumenten als het aandeel van gas in de energievoorziening op Europees schaalniveau geen probleem meer. De daling van gas voor elektriciteitsopwekking is zelfs zo groot dat in de niet-elektriciteitssector een kleine gas expansie kan worden doorgevoerd. Dit lijkt niet strijdig te hoeven zijn met de plannen om een Europese gasrotonde (met Nederland in het centrum) te realiseren om drie redenen. Ten eerste is de daling van de gasintensiteit gemeten ten opzichte van het niveau van het basispad in 2030 zonder beleid en gelijk aan een stijging van de vraag naar gas met +15% ten opzichte van het jaar 2000. Ten tweede, de handel in gas tussen landen van Europa is ook niet uitgesloten (dit is *één* regio in de analyse). En ten derde, de import hoeft in de realiteit niet naar nul te dalen, omdat dit in deze analyse veroorzaakt wordt door de aanname dat de gasmarkt perfect georganiseerd is. De analyse houdt weliswaar rekening met huidige verstoringen op de markt en veronderstelt dat deze niet anders zullen zijn in de toekomst. Veranderingen in de investeringen van specifieke energietechnieken zijn dus voornamelijk bepaald worden door de kostenverschillen tussen die technieken. Dat de import van gas naar nul gaat en Europa zijn gasvoorraad versneld opmaakt – immers de vraag naar gas stijgt ten opzichte van 2000 – moet dus vooral als een indicatie (en zeker niet een realisatie) worden beschouwd van de marktconforme oplossing van het EU-energiesysteem.

Het aandeel van olie (als percentage van de totale warmtevraag) en de olie-intensiteit (olieverbruik gedeeld door het BBP) dalen met 35-40% in de derde variant. Als de voorzieningszekerheid niet als een probleem wordt gezien (eerste variant) of de CO_2 emissiereductie maar beperkt blijft (tweede variant staat in beperkte mate kolencentrales toe), dan zal het aandeel van olie en de olie-intensiteit ten opzichte van het basispad minder dalen vergeleken met de derde variant. Tevens moet opgemerkt worden dat de import van olie (in tegenstelling tot de import van gas) niet een factor is die bijdraagt aan de schade van de welvaart ten gevolge van een te lage VZZ. De reden hiervoor is dat de literatuur uitwijst dat de oliemarkt een geïntegreerde competitieve markt is met een min of meer homogene olieprijs.

De welvaart wordt ook verhoogd, omdat er extra luchtbaten zijn door een afname van de primaire fijn stof emissies (meer dan 0.41 mton PM_{10}). Deze wordt gedreven door een daling van de vraag naar kolen (zowel in de elektriciteit- en niet-elektriciteitssector) en dieselolie in de niet-electriciteitssector (voornamelijk voor transport). De luchtbaten zijn in Europa lager dan in de rest van de wereld, omdat in Europa al scherpere doelen zijn gesteld (de in de EU overeengekomen nationale doelen voor SO_x, NO_X, NH_3, en VOS).

In 2030 zullen er nog weinig welvaartsbaten zijn door een minder grote klimaatverandering van het tot dan gevoerde mondiale klimaatbeleid. Deze baten groeien over de tijd en liggen vooral in de verdere toekomst (zie ook OECD, 2008). Toch zijn de lange-termijn baten een argument om al eerder de CO_2 uitstoot te beperken als bedacht wordt dat investeren in duurdere energietechnieken via innovatie deze op termijn goedkoper zullen maken.

De gevolgen voor de wereld

De belangrijkste uitkomsten van de analyse staan samengevat in drie varianten in tabel S2:

1. optimaal klimaat -en luchtbeleid zonder rekening te houden met de energievoorzieningszekerheid (aangeduid met klimaat -en luchtbeleid)
2. optimaal beleid ter verhoging van de energievoorzieningszekerheid (aangeduid met VZZ)
3. Klimaat -en luchtbeleid + VZZ (zie ook tabel S1). De resultaten in deze tabel zijn geaggregeerd voor de wereld en de cijfers hebben betrekking op de periode 2000-2150.

Tabel S2 laat het verschil zien tussen een variant met beleid en zonder milieu -en VZZ-beleid.

Geïntegreerde aanpak van de energievoorziening kan de welvaart verhogen
Het streven naar gelijktijdig realiseren van verschillende doelen werkt – net als voor Europa -welvaartsverhogend voor de wereld. Bedenk dat alle regio's beleid voeren tegen luchtvervuiling (een lokaal belang), klimaatverandering (een mondiaal belang), en voor verhoging van de energievoorzieningszekerheid (een lokaal belang dat natuurlijk niet van toepassing is op de energie-exporterende landen). Het VZZ beleid verschilt per regio, en is afhankelijk van de regiospecifieke relatie tussen economische groei en kostenontwikkeling van energietechnologieën. De externe welvaartsschade door een beperkte VZZ is toegepast voor de OESO regio, maar ook de energie-exporterende landen buiten de OESO. De derde kolom laat zien dat het combineren van VZZ en milieubeleid een gunstiger effect heeft op de welvaart, dan je beperken tot de één van de twee, of de som van de twee aparte strategieën. Het verschil tussen de gecombineerde variant en de som der delen is 0.1% (3.5-0.1-3.3), dit lijkt klein, maar is wel van belang. Er zijn twee redenen. Ten eerste, moet gerealiseerd worden dat regionale verschillen groter zijn dan het mondiale uitgemiddelde getal (zie ook het grotere resultaat in 2030 voor Europa). Ten tweede, de welvaartswinst is een getal dat geldt voor voor-nu-en-altijd (de veranderingen in de toekomst wegen minder zwaar dan de effecten in het heden, hetgeen bepaald wordt door de hoogte van de discontovoet).

Tabel S2: Mondiale effecten over de periode 2000-2150 van drie varianten t.o.v. het basispad

	Klimaat –en luchtbeleid		VZZ		Klimaat –en luchtbeleid + VZZ	
CO_2 emissies (%)	-66		32		-68	
Energie-importeurs (%)		-68		25		-70
Energie-exporteurs (%)		-60		54		-59
Vraag olie en gas (%)	-30		0		-35	
Energie-importeurs (%)		-30		-25		-45
Particuliere consumptie (%)	-0,4		-0,1		-0,5	
Baten (% van particuliere consumptie)	3,7		0,1		3,9	
Lucht (% van particuliere consumptie)		2,8		0,1		2,8
Klimaat (% van particuliere consumptie)		0,8		-0,3		0,8
SOS (% van particuliere consumptie)		0,1		0,3		0,3
Welvaart: particuliere consumptie + baten (%)	3.3		0.1		3.5	

Discontovoet 4% in 2020, 2% in 2100

De rangorde van de baten van de gecombineerde variant zijn de luchtbaten, gevolgd door klimaatvoordelen, en dan pas VZZ. De luchtbaten zijn het grootst, omdat de problemen nu al en de nabije toekomst een belangrijke rol spelen. Dit betekent dat beleidsreacties om het probleem tegen te gaan ook op korte termijn gerealiseerd worden, en daarom zwaar meewegen in de besluiten die producenten en consumenten kunnen nemen om de schade te verminderen. De klimaatbaten zijn kleiner dan de luchtbaten, maar groter dan die van VZZ. Weliswaar is het effect pas goed zichtbaar na 2100, maar is wel grootschalig. Dus mitigatiebeleid laat ook grotere verbeteringen zien die ook nu nog meewegen in de besluitvorming. Tot slot, de VZZ baten zijn relatief laag, omdat deze weliswaar nu groot zijn, maar alleen relevant tot aan 2050. Na 2050 is, volgens deze MNP-analyse, het probleem van VZZ significant lager, omdat aangenomen is dat de energie-intensiteit dan inmiddels zo laag zal zijn (groei van energie blijft achter bij die van het BBP) dat de economieën geen gevolgen zullen ondervinden van bijvoorbeeld de fluctuaties in de prijs van olie, of zelfs een uitval van aanbod van een energiedrager.

De CO_2 emissies zijn gemeten als procentuele verschillen van een variant ten op zichte van het basispad van de cumulatieve som van de emissies over de periode 2000-2150. De milieuvariant (klimaat –en luchtbeleid) laat zien dat de mondiale emissies over de hele periode van 2000-2150 met 66% omlaag gaan. Als er geen milieubeleid wordt gevoerd en wel wereldwijd beleid gericht wordt op een verbetering van de energievoorzieningszekerheid (VZZ), dan zullen de CO_2 emissies stijgen door een expansie van kolencentrales (ten koste van gascentrales) voor elektriciteit en extra kolen voor warmtevraag ten behoeve van warmte (ten koste van gas en een beetje olie dat gebruikt wordt voor elektrisch gedreven warmtebronnen). De energie-exporteurs zullen hun goedkope fossiele bronnen zelf aanwenden voor gebruik, en hun emissies zullen om die reden stijgen. De inrichting van de mondiale energiehuishouding is dus totaal verschillend in de milieuvariant van de VZZ variant, en kunnen om die reden dus ook niet bij elkaar opgeteld worden zodat de derde variant wordt geleverd. De VZZ variant pakt dus slecht uit voor het klimaat, maar is wel gunstig voor de luchtkwaliteit, omdat olie in de transport sector wordt weggedrukt.

De derde combinatievariant laat de extra CO_2 emissiereducties (68%-66%=2%) zien van de geïntegreerde variant door aanpassingen van het energiesysteem middels duurdere innovatieve niet-fossiele energietechnieken, die baten genereert door vermindering van de externe schade door een te lage VZZ en door een verlaging van de luchtvervuiling. De combinatie VZZ -en milieubeleid versterken elkaar op mondiale schaal. De CO_2 emissiereductie van de olie –en gasexporterende landen neemt af ten opzichte van de milieuvariant. Dit duidt op een weglekeffect van CO_2 emissiereducties door energie-importerende landen naar de exporterende landen. De energie-exporteurs zijn verantwoordelijk voor ongeveer 25% van de mondiale emissies, en omdat de zijn hun goedkopere energievoorraden zullen gebruiken zullen de CO_2 emissies daar stijgen. De energie-importeurs (zoals OESO-Europa) verlagen hun CO_2 emissies om de schade door klimaatverandering te beperken en tegelijkertijd een synergie-effect te realiseren met lagere bestrijdingskosten om luchtvervuiling tegen te gaan.

Tot slot, als meerdere energie-importerende regio's beleid gaan voeren om de voorzieningszekerheid te verhogen (VZZ), dan zal in combinatie met klimaat -en luchtbeleid de mondiaal beschikbare reserves dus niet volledig worden gebruikt. De mondiale gecumuleerde vraag naar olie en gas voor de komende 150 jaar zal met 30-35% lager zijn. Echter wanneer er geen milieubeleid gevoerd gaat worden, dan zullen de reserves van olie en gas toch uitgeput worden. De energie-importeurs zullen weliswaar de vraag naar olie en gas verminderen, maar deze uitval wordt deels teniet gedaan door extra vraag door de energie-exporterende landen en deels door extra vraag op de langere termijn door energie-importerende regio's (VZZ-beleid is dan minder urgent door een lagere energie-intensiteit).

1 Energy Security and Integrated Energy Policies

Recently, energy security has reappeared at the forefront of important national energy policy themes (IEA, 2007), and it also dominates the political agenda, see EU's Green Paper (2006). An increasing part of the EU's energy needs will have to be matched by imports. Particularly, for the supply of oil and natural gas, the EU is becoming more dependent on a small number of countries, some of which are threatened by political instability (see also Bollen et al, 2004). At the same time, the world energy demand is expected to boost from high economic growth in developing countries like China and India. Therefore, there will be more competing claims on the energy resources which are available in the world. Two major interrelated environmental policy problems of today, each with transboundary aspects, are global climate change (GCC) and local air pollution (LAP). Both are extensively discussed in the international political arena; the first in the United Nations Framework Convention on Climate Change (UNFCCC) and the second in, for instance, the United Nations Economic Commission for Europe's task-force on Long-Range Transboundary Air Pollution (UNECE-LRTAP).

Options to mitigate climate change consist of a number of things, such as structural shifts of economies in favour of energy-extensive services, energy conservation, switches from carbon-intensive to carbon-extensive energy technologies and carbon storage. Options to reduce air pollution consist mainly of end-of-pipe technologies, many climate mitigation options, and so-called clean coal power stations in electricity markets. There are several options to secure energy needs: reduction of demand, diversification of demand over types of energy, diversification of sources and routes of supply of imported energy, streamlining of internal energy markets, and using better equipment to cope with emergencies.

All these options are typically chosen to address each problem, exclusively. There are strategies that change the energy system, based on either a reduction of damages from GCC, or LAP, or on a low energy related Security of Supply (SOS). This report searches for integrated approaches to tackle all problems at the same time. With this purpose in mind, the MERGE model (Manne and Richels, 2004) is applied. The model has a top-down character, designed for carrying out an integrated assessment of energy-economy-environment interactions and, in particular, for performing an economic cost-benefit analysis of climate change policies. Recently, the model was expanded to also carry out a simulation and cost-benefit analysis of the environmental and economic impacts of LAP (Bollen *et al.*, 2007). This report describes how MERGE is further expanded to include issues of securing the energy supply, through the implementation of a rudimentary SOS function. The issue of energy related SOS is restricted to energy savings and diversification of energy systems, which are an integral part of the original MERGE model.

Despite the simplifying assumptions that are used in this report to integrate the global long-term problem of GCC, as well as the more immediate medium-term problems, such as lack of energy related SOS and LAP, this study is believed to contribute to the ongoing debate. A framework is provided that enables deriving economically optimal decisions in energy markets, under varying parameter values and modelling assumptions. This is done on the basis of a trade-off between costs associated with mitigation efforts and benefits obtained from avoiding medium-term air pollution, long-term climate change damages, and improving on energy related SOS. Chapter 2 gives a qualitative overview of the extended version of MERGE. Chapter 3 presents an overview of the literature of energy related SOS (section 3.1). It also designs a mathematical expression of a penalty function, reflecting the societal damage that is associated with a lack in SOS, as relevant to the structure of MERGE (section 3.2). Additionally, chapter 3 calibrates the proposed penalty function on the basis of a few historical examples (section 3.3), and it concludes with the dynamics of the penalty function in the business-as-usual (BAU) scenario (section 3.4). Chapter 4 highlights the main findings of the simulations that were carried out with the modified MERGE model. The report focuses on developments in Europe, but also sketches impacts on a global scale. Chapter 5 presents an uncertainty analysis, while chapter 6 describes the main conclusions and recommendations.

2 MERGE

The MERGE model allows for estimating global and regional effects of greenhouse gas emissions, as well as the costs of their reductions (Manne and Richels, 2004). Each region's domestic economy is represented by a Ramsey-Solow model of optimal long-term economic growth, in which inter-temporal choices are made on the basis of a utility discount rate. Response behaviour to price changes is introduced through an overall economy-wide production function, and output of the generic consumption good depends, like in other top-down models, on the inputs of capital, labour and energy. CO_2 emissions are linked to energy production in a bottom-up perspective, and separate technologies are defined for each main electric and non-electric energy option. The amount of CO_2 emitted in each simulation period is translated into an addition to the global CO_2 concentration and a matching global temperature increment. For this report, the MERGE model is used in its cost-benefit mode, in which an emissions time path is calculated that maximises the discounted utility of consumption. There are nine geopolitical regions, in which production and consumption opportunities are negatively affected by damages (or disutility), generated by GCC, LAP and energy related SOS. The cases that were analysed by MERGE and the obtained solutions assume Pareto-efficiency. Therefore, the only countries which are considered are those in which no region becomes better off while making another region worse off. Abatement can be optimally allocated with respect to the dimensions time (when), space (where) and pollutants (what).

The original MERGE model was modified, as described in Bollen *et al.* (2007), and for the purpose of this paper, a link was added between energy related SOS and energy production. This way, a model is obtained that can simulate the costs and benefits of GCC and LAP policies, as well as SOS control policies, all in a dynamic and multi-regional context.

2.1 Cost-benefit mode

All scenarios that are analysed in this paper are run in the cost-benefit (CB) mode of the model. Here we highlight the equations that are most relevant for the CB-mode. In each year and region an allocation of resources include those assigned to end-of-pipe Particulate Matter (PM) abatement costs:

$$Y_{t,r} = C_{t,r} + I_{t,r} + J_{t,r} + K_{t,r} + D_{t,r} + X_{t,r} \tag{1}$$

with Y representing output or Gross Domestic Product (GDP) aggregated in a single good or *numéraire*, C consumption of this good, I the production reserved for new capital investments, J the costs of energy, K the PM abatement costs as added with respect to the original MERGE formulation, D the output required to compensate for GCC-related damages, and X the net-exports of the numéraire good. The subscripts t and r refer to time and region, respectively. Solving the cost-benefit problem implies a control system that leads to lower temperature increases, avoided premature deaths, and increased energy related SOS.

Together they minimise the discounted present value of the sum of abatement and damage costs.[2)] There is disutility associated with the damages from GCC, LAP, and low values of energy related SOS. This is shown by the following relation expressing the objective function (maximand) of the total problem, being the Negishi-weighted discounted sum of utility:

$$\sum_r n_r \sum_t u_{t,r} \log\left(E_{t,r} F_{t,r} S_{t,r} C_{t,r}\right) \tag{2}$$

with n representing the Negishi weights, u the utility discount factor, E the disutility factor associated with GCC, F the disutility factor associated with LAP, and S the disutility factor associated with damages from a low SOS. The loss factor E is:

$$E = (1 - (\Delta T / \Delta T_{cat})^2)^h \tag{3}$$

in which ΔT is the temperature rise of its 2000 level, and $\Delta T_{\mathbf{cat}}$ the catastrophic temperature at which the entire economic production would be wiped out. The *t*-dependence is thus reflected in the temperature increase reached at a particular point in time, while the *r*-dependence is covered by the 'hockey stick' parameter *h*, which is assumed to be 1 for high-income regions, and takes values below unity for low-income regions. The GCC part of MERGE is kept unchanged in its original form, but for the part of this theory section below the focus is on the expanded MERGE model to account for (A) the chain of PM emissions increasing their ambient concentrations, (B) the increase of PM concentrations provoking premature deaths, and (C) the meaning of these deaths in terms of their monetary valuation. The following equation for the disutility *F* associated with monetised damages from LAP:

$$F_{t,r} \; = \; 1 - \frac{1.06 N_{t,r}}{C_{t,r}} \left(\frac{Y_{t,r} / P_{t,r}}{Y_{2000,weur} / P_{2000,weur}} \right) \tag{4}$$

in which *N* is the number of premature deaths from chronic exposure to PM, and *P* the exogenous number of people in a given population. For non-European regions, Value of Statistical Life (VSL) is determined by multiplying VSL of OECD Europe (WEUR) with the ratio of GDP per capita, of these respective regions. For future years, VSL is assumed to rise according to the growth rate of GDP per capita. For further reading on the modelling of *N*, is referred to Bollen *et al.* (2007). Finally, the argument *S* is added to account for disutility, associated with a low energy related SOS:

$$S_{t,r} = 1 - \sum_{f \in \{oil, gas\}} IMP_{f,t,r} \tag{5}$$

in which IMP is the penalty function for oil and gas, resembling the willingness-to-pay in order to avoid a lack in SOS (% consumption) related to one of these types of energy. Chapter 3 will provide more details on the penalty function. Here it suffices to state that a low value for oil and gas security translates into high values for IMP and lower values for *S*.

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2) Y is 'fixed'. It is equal to the sum of a production function of a new vintage and a fixed old vintage. With respect to the new vintage, there is a putty-clay CES formulation of substitution between new capital, labour, electric and non-electric energy in the production of the com-posite output good . With respect to the old vintage, it is assumed that there is no substitution between inputs. New capital is a distributed lag function of the investments of a certain year and a previous time step. K is equal to the costs of end-of-pipe abatement, and just one of the claimants of production, and therefore if K increases, then C reduces (which itself is part of the maximand).

Table 2.1 Characterisation and costs of technologies in MERGE

Technology Name (earliest possible year of introduction)	Identification/Examples	Costs in 2000	Carbon Emission Coefficients
Electric		**Mills/kWh**	**Bn tons/TWH**
HYDRO	Hydroelectric and geothermal	40	-
NUC	Remaining initial nuclear	50	-
GAS-R	Remaining initial gas fired	36	0.14
OIL-R	Remaining initial oil fired	38	0.21
COAL-R	Remaining initial coal fired	20	0.25
GAS-N (2010)	Advanced combined cycle	13	0.09
GAS-A (2020)	Gas fuel cells + capture & sequestration	30	-
COAL-N (2010)	Pulverised coal without CO_2 recovery	41	0.20
COAL-A (2050)	Fuel cells with CCS - coal fuel	56	0.01
IGCC (2030)	Integrated Gasification + CCS - coal	62	0.02
LBDE (2010)	Carbon-free: learning by doing	100 ↓ 50	-
Non-electric		**$/GJ**	**tons of C/GJ**
CLDU	Coal-direct use	2.5	0.024
OIL-1-10	Oil 1-10 cost categories	3.0-5.3	0.020
GAS-1-10	Gas 1-10 cost categories	2.0-4.3	0.014
RNEW	Renewables	6	-
LBDN	Carbon free: learning by doing	14 ↓ 6	-

2.2 Energy technologies in MERGE

Many technological options, modelled in MERGE, may generate more efficient and clean energy systems that emit less CO_2 per unit of energy. Table 2.1 provides an overview of the relevant options for the future. The current technologies can be found in Manne and Richels (2002). For each technology, Table 2.1 shows the introduction date, the costs in 2000, the floor costs (only relevant for those technologies with a learning-by-doing process), and the carbon coefficient. The electric, non fossil fuel option (LBDE) has a learning-by-doing component, and is a container of wind, solar, nuclear, and biomass options. The LBDE option can be applied from 2010 onwards, at a high cost per GJ. On the fossil fuel side are a few cheaper options: GAS-N, GAS-A, COAL-N, COAL-A, Integrated Gasification (coal-based), and Carbon Captures and storage (IGCC). All technologies are assumed to show autonomous technological progress.

A few technologies are distinguished for non-electric energy. There are two types of non-fossil fuels: ReNEWable energy (RNEW) and a more abstract technology labeled Learning-By-Doing Non-electric energy (LBDN). RNEW represents low-cost renewables, such as ethanol (available in limited supply). LBDN is available throughout the world, with an unlimited resource. In the base year, LBDN is available at a high cost price, which may decrease because of the learning-by-doing process. The remaining fossil fuel options are described in Manne and Richels (2002).

3 A Security of Supply Function

An overview of the literature of energy related SOS, enables to design a mathematical expression of a penalty function, reflecting the societal damage that is associated with a lack in SOS, and that could be relevant to the structure of MERGE. In a few historical examples, this chapter illustrates how the penalty functions are calibrated, and they are used to illustrate some of the dynamics of the behaviour of the penalty function in the business-as-usual (BAU) scenario.

3.1 Review of the literature on Security of Supply

Several projects focusing on the theme of Security of Supply, have been carried out at the Energy research Centre of the Netherlands (ECN), over the past years. These studies generally target aspects of SOS, that are related to a subset of the energy carriers available in modern society (see e.g. Scheepers et al., 2004; van Oostvoorn, 2003; van Werven et al., 2005). Two recent ECN reports frame SOS in the broader context of national energy systems of industrialised countries, and attempt to develop indicators for SOS: Jansen et al. (2004) and Scheepers et al. (2006). One of these two reports focuses on the SOS of primary energy resources, while the other mostly reviews security aspects of integral energy supply chains. Thus, the first merely addresses the supply aspects of energy systems and the long-term SOS issues, while the second presents an analysis of both supply and demand issues, and focuses on the short-term, including a more elaborate inspection of how to address and mitigate SOS concerns. Both studies attempt to quantify SOS through a bottom-up approach, in which the supply system risks are identified and impacts of supply system failures are valued. The first two sections below specify the findings of these two studies, in more detail. The third section summarises some of the major findings of two other studies by Leiby et al. (1997) and Leiby et al. (2007), which both analyse the macroeconomic costs and benefits of the USA dependency on foreign oil.

3.1.1 Designing Indicators of Long-Term Energy Supply Security

The study by Jansen *et al.* (2004) identifies the feasibility of designing a macro-indicator for the long-term security of energy supply, and proposes possible methodologies for the development of such a long-term SOS macro-indicator. In addition, it evaluates the case of possible long-term disruptions in the supply of natural gas to the European Union. This study primarily deals with measuring to which extent a particular region can ensure meeting its expected demand for energy services, at affordable prices and over long time frames, typically up to 2040. The macro-indicator focuses on long-term threats to the energy supply and delivery system of a region, notably as a result of fuel supply disruptions. Therefore, it implies the use of long-running hedging approaches. Short supply disruptions that do not pose a long-term challenge to a region's energy system, are disregarded.

An essential feature of ensuring long-term security for the energy supply is to determine an 'efficient portfolio' of primary energy sources. 'Efficiency' in this context, for a given portfolio, refers to the optimal trade-off between limiting serious threats to the sustained provision of energy services, and keeping the cost per average unit of primary energy supply as low as possible. The study recognises that incertitude plays a fundamental role in determining the efficiency of a given portfolio. Three basic states of incertitude can be identified:

- **Risk**, as a quantifiable incertitude,
- **Uncertainty**, as a known but unquantifiable incertitude,
- **Ignorance**, as an unknown, unquantifiable incertitude.

In the context of this terminology, risks allow for the application of traditional probabilistic and statistical methods. Alternatively, uncertainty may be addressed by Bayesian and scenario-based approaches, or Delphi-like methods in which expert opinions are compiled and weighted. Especially in a state of ignorance, the maintenance or creation of diversity can provide resilience to systems exposed to incertitude. Yet, the creation of diversity carries costs, since obvious and certain cost reductions, resulting from, for example, economies-of-scale or standardisation, could be forgone.

In order to design optimum diversity strategies, in the face of conditions of ignorance, the concept diversity needs to be characterised. Diversity can be used as an overarching concept, with three subordinate properties:

- **Variety**, referring to the number of categories into which a quantity can be partitioned. For example, the categories may denote primary energy sources or, in a more refined analysis, major energy conversion technologies. Variety is a positive integer and, all else being equal, the greater the variety of a system, the greater the diversity.
- **Balance**, referring to the pattern in the apportionment or spread of that quantity across the relevant categories, for example, expressed in terms of EJ when the categories considered are primary energy sources. Independent of the total number of categories, the more even the spread between them, the greater the diversity.
- **Disparity**, referring to the nature and degree to which the categories are mutually divergent. For example, the categories ‘oil’ and ‘natural gas’ are less disparate than ‘oil’ and ‘renewables’, not in the least given the heterogeneity of the latter. However, disparity is an intrinsic qualitative aspect of diversity.

The first two aspects of diversity are explicitly quantifiable, whereas the third is context-dependent and allows for subjective manoeuvring. The *Shannon-Wiener index* is an approach used to express diversity, reflecting both variety and balance. On the other hand, *integrated multi-criteria analysis* is a method designed to reflect all three aspects of diversity: variety, balance and disparity.

Given the time horizons involved with issues of long-term security of supply, ignorance in this context is considered to be a relevant phenomenon. Therefore, diversity is an important notion for the development of a security of supply indicator, and diversification should be a key element of any strategy mitigating security of supply risks. The *Shannon-Wiener index* and the *integrated multi-criteria analysis* both express the level of diversity and may, thus, be useful means to measure the level of security of energy supply.

In addition to recollecting this rudimentary taxonomy of incertitude, the study of Jansen et al. (2004) lists a variety of quantitative approaches by which risk, the first form of incertitude, can be expressed and/or reduced:

- Risk pooling (as with insurances),
- Value at Risk (as in banking),
- Portfolio Theory (as by Markowitz),
- Shannon-Wiener index (as by Stirling),
- Integrated multi-criteria analysis (as by Stirling).

The first three were developed in different contexts and possess limited applicability to issues of long-term security of energy supply. The last two, as developed by Stirling, allow for assessing the notion of diversity and, as such, can play key roles in long-term investment under risk decisions in the energy sector. According to Jansen et al. (2004), in the context of SOS, the Shannon-Wiener index is probably the most appropriate means of measurement, because of its dual applicability (variety and balance) and its objectively quantifiable character. It is calculated as:

$$I = -\sum_i (p_i) \ln p_i \qquad (6)$$

in which *p* refers to the share of fuel, *i* to the total supply or demand of energy.

A variety of adjustments to the Shannon-Wiener index have been proposed, to account for the diversity in suppliers of each primary fuel, as well as accounting for the limitations to each supplier's reliability, given arguments of long-term socio-political stability or resource availability. The proposed adjustments address the notion that, to determine the level of secrutity of supply, diversity may be relevant, not only in primary fuel, but also in region of supply. One can distinguish between:

- pure import diversity;
- import diversity, while accounting for the perceived political stability in regions of origin;
- import diversity, while accounting for the perceived political stability and depletion of natural energy resources in regions of origin.

The generic structure of the proposed adjustments to the Shannon-Wiener index, typically, involves an additional factor *c,* which reflects the diversity or reliability in fuel sources of the total energy supply or demand portfolio:

$$I = -\sum_i (c_i p_i) \ln p_i \qquad (7)$$

with the factor c_i reflecting the diversity of suppliers of imported fuel *i*, on the basis of a comparable Shannon-Wiener structure. Such a structure generates low values for c_i if the imported fuel would originate from a single supplier, whereas it would yield high values if the imported fuel would originate from multiple suppliers and would be well spread among them.

3.1.2 EU Standards for securing energy supply

A study by Scheepers et al. (2006) proposes an instrument that can help the EU as a whole, as well as individual EU Member States, to shape and adapt their energy policies, in view of arguments related to the security of supply. Security of supply risks refer to the probability of encountering shortages in energy supply. These can either involve a relative shortage, such as a mismatch between supply and demand that induces energy price increases, or a partial or complete disruption of the energy supply. Of course, supply shortages or disruptions affect the energy consumers. However, from the consumer's point of view, it is of little relevance what causes these shortages or disruptions.. Therefore, reviewing the security of the energy supply should include comprehending the total supply chain, and all possible causes of shortages and disruptions.

The calculation of the SOS indicator, proposed by Scheepers et al. (2006) includes variables, reflecting the levels of energy supply, demand, capacity and reliability, and of both energy conversion installations, and transmission and distribution networks. Two sub-indicators are proposed: the supply and demand index (SD) and the crisis capability index (CC). The SD index is based on the energy system of a country or region, covering the supply of primary energy sources, and the means of converting and transporting secondary energy, as well as the ultimate domestic (national or regional) energy demand levels. The index is largely based on objective information that is documented in, for example, publicly available energy balances. It also uses weighting factors and scoring rules based on existing indicators The CC index reflects the capability of a country or region to manage and mitigate short-term energy supply interruptions. It barely has any relevance on matters of long-term security of energy supply. Therefore, for this report, this index is not discussed any further.

- The SD index is calculated on the basis of four specific inputs:
- relative shares of different types of supply and demand;
- values, characterising their capacity and reliability;
- weights, determining their relative contribution;
- scoring rules, determining the value of each individual contributing factor.

In the study by Scheepers et al. (2006), the demand dependency of the SD index is based on energy efficiencies, differentiated on a sectoral basis and compared to a benchmark involving the five best-performing EU Member States. The overall demand index is weighted by the individual sectoral contributions to the total energy demand. The supply is differentiated both by fuel and by origin (whether it concerns domestic supply, imports from the EU or other imports). The result is a (somewhat arbitrary) index for each fuel-origin combination. The overall supply index is weighted by the relative shares of individual origin-fuel combinations to the total primary energy consumption. In addition, energy conversion and transportation are represented by an eightfold categorisation:

- efficiency of power generation;
- adequacy of power generation;
- reliability of power generation;
- adequacy of the electricity network;
- reliability of the electricity network;
- efficiency in heat generation;
- efficiency of refineries;
- transportation of fuel.

In the study by Scheepers et al. (2006), SD index values run from 0 to 100. As an illustration of its methodology, the SD index is determined for the current national energy systems of a number of European countries. The reported values range from around 50 (in the case of Spain, and for the EU as a whole) to around 80 (for the UK).

3.1.3 Oil imports dependency of the USA

A study by Leiby et al. (1997) and Leiby et al. (2007) provides a review of the external costs and benefits of oil imports in the USA. It assesses the changes in these costs and benefits, caused by oil import variations. This is done by analysing the marginal costs and benefits of oil dependency. The marginal benefits of oil imports are assumed to be largely created by private benefits, basically represented by prevailing oil prices. The costs associated with oil imports involve several social cost components which are, typically, not represented in oil prices. The first study (1997) identifies several types of social cost components, being long-running recoverable cartel rents, oil market disruption costs, environmental costs, and strategic insurance costs. Since the last two are hard to quantify, the study focuses on the first two components.

The first important category of social costs, associated with oil imports, are the long-running recoverable cartel rents. The study by Leiby et al. (1997) argues that most analysts assume OPEC to have some pricing power, be it not as effective as that of a text-book cartel. Cartel rents arise because international oil prices can be inflated through cartel market power. This inflationary pressure may vary around the margin of oil imports. The assumption implies that the USA has some monopsony power, depending on the elasticity of supply in other regions than the USA and OPEC. Marginal cartel rents are, therefore, said to be partly recoverable. The second category of social costs is one of oil market disruption. Sudden and unforeseen large oil price spikes confront businesses and consumers with both price and income effects. Price effects lead to an adjustment of the bundle of products purchased, possibly also going hand in hand with stranded costs, whereas income effects reduce the overall purchasing power.

The study of Leiby et al. (1997) also points out that oil price spikes lead to an increase of costs associated with import payments, as well as to macroeconomic adjustment losses. Although, arguably, oil markets offer some opportunities to hedge for private risks - for instance through stockpiling or futures market transactions - such options do not exist for social risk. Even opportunities to hedge for private risks are limited. Therefore, increased costs of oil import payments are mostly not captured in the oil price. Besides, it is also being said, that it is doubtful for any other party to do better than the futures market, let alone a national government. In other words, the oil price cost component cannot be quantified better than is done by the futures market, so that these costs are as effectively captured as possible. The macroeconomic adjustment losses relate to the lagged adaptation of wages and prices, that is to say, the delayed pass-through of a change in oil prices in all product and labour markets. Since substitution between production factors does not occur instantaneously, the economy only slowly adjusts to a new equilibrium, resulting in macroeconomic adjustment losses. Stranded costs may also slow down a flexible adjustment of production factors. Adjustment losses, resulting from oil price increases, are argued to be represented in GDP losses. Although the total effect of oil price spikes on GDP is recognised to depend mostly on the level of national oil consumption, rather than on the oil import level, the latter may still lead to significant marginal GDP adjustment losses.

3.2 Implementation of SOS Considerations in MERGE

Based on the discussion in the previous section on the various perceptions of the long-term security of energy supply, is looked at how the SOS considerations can be charactarised and implemented in an integrated assessment model, such as MERGE. Not all dimensions of SOS are relevant to, or implementable in, the structure of MERGE. MERGE simulates long-term evaluations of the global economy, up to 2100, divided into a dozen world regions (see e.g. Manne and Richels, 2004). Short-lived perturbations of the energy system are of limited relevance to MERGE, and can hardly be simulated. Only long-term SOS considerations can be represented and are, therefore, suitable to be contemplated, here.

Given the welfare optimisation structure of MERGE, with primary energy resources as basic inputs, SOS can only be considered, primarily, from the perspective of the supply of these resources. In the long-term, sub-system components, relating to the transportation, conversion and distribution of secondary energy carriers, are assumed to be aligned with the supply of primary energy resources and the end-use demand of secondary energy carriers. The long-term, main risks relating to SOS, thus, relate to the supply of primary energy sources. Hereby, the supply of oil and gas stands out most. These two fossil fuel commodities are considered the main primary energy resources, subject to potential long-term supply risks and, thus, constitute the main focus, in this case.

Energy security is interpreted as a public good. This implies that the dependency of countries on imported oil and/or gas is not directly represented in energy prices. Furthermore, for oil and gas markets we assume that:

- high *absolute values of import quotes,* of either oil or gas, lower the welfare, because countries with high import quotes are more sensitive to the availability of these fossil fuels or to peaks in the prices;
- welfare losses from high import quotes are determined by the *commodity intensity*. If the relative proportion of a commodity (oil or gas) in the fuel mix is high in some region, then so is the welfare loss associated with changes in availability or price of this commodity;.
- welfare losses from high import quotes are also determined by the *energy intensity*. If the overall energy intensity of a given region is high, the welfare loss resulting from changes in the availability or price of energy is high, too.

If the oil or gas consumption, or their relative intensity, declines through energy savings, structural changes in the economy, or fuel switches in the energy system, then the corresponding welfare loss from high import quotes decreases. One may identify two types of risk, relating to the two dimensions of a commodity market: volume and price. Volume, the first risk, relates to the probability that the region producing the fossil fuel falters in its delivery expectations. Price, the second risk, involves shifts in market prices to which the consuming region is unwillingly exposed. In competitive markets these two types of risk go hand in hand. Naturally, reduced volumes are accompanied by higher prices and vice-versa. In a fully competitive context, the impacts associated with these two risk categories need not be addressed separately. However, non-competitive markets may show divergence of these two risk variables. Several kinds of non-competitive market conditions can be distinguished:

- **market regulation** (for example price regulation). Currently, subsidised oil products in the Middle East and China yield low prices, even although crude oil prices have been on the rise. In the Middle East only opportunity costs of oil producers are involved, so no pressure is exerted on national budgets. China is a consuming nation where, through actual policy support, prices are actively subsidised and regulated;
- **market structure** (for example oligopolistic or monopolistic markets). Oligopolies effectively dominate the current international oil market, which is characterised by high oil prices. Its supply, however, does not seem to be low, since capacity can be expanded with relative ease;
- **market development** (for example infant markets or ones with low liquidity). In 1973, oil-producing countries in the Middle East declared a trade embargo against the USA, its West European allies and Japan, to exert political pressure given their positions in the Israeli conflict. In liquid markets such embargos are not effective, because products are available from various other sellers.

In these non-competitive cases, the potential impacts of volume- and price-related events or occurrences, should be regarded separately. The framework of MERGE, however, inherently assumes competitive markets, and price changes are a direct consequence of volumetric modifications in the balance of energy supply and demand, and vice-versa. From this perspective, it suffices to only consider volumetric risks as the relevant form of incertitude. This approach, thus, disregards the fact that in reality price and volume effects may diverge in some instances, which is likely to occur, particularly, in the case of oil and gas markets. This is especially true, given today's exacerbating tendencies that move towards the dominance of oligopolistic regimes, with a declining number of suppliers able to offer additional volumes. However, MERGE is considered to be insufficiently capable of grasping such phenomena and, thus, this study is restricted to the approximation of full market competitiveness.

The essence of MERGE consists of the optimisation of welfare, the integrated discounted sum of utility. In order to quantify the welfare loss associated with security of supply risks, and to include this welfare loss in the objective function of MERGE, a penalty function is proposed, that, once implemented, affects a region's welfare loss by aggregating the private consumption losses of the penalties for oil and gas (see equation 5). The welfare loss, resulting from a lack of SOS for either oil or gas, directly relates to the willingness-to-pay for avoiding this deficiency, and can be expressed as:

$$IMP_{t,r}(i_{t,r} : i_{t,r} > 0) = A_r \left(\frac{i_{t,r}}{i_{0,r}} \right)^{\alpha} \left(\frac{c_{t,r}}{c_{0,r}} \right)^{\beta} \left(\frac{E_{t,r}}{E_{0,r}} \right)^{\gamma} ; IMP_{t,r}(i_{t,r} : i_{t,r} < 0) = 0 \qquad (8)$$

in which:
IMP = willingness-to-pay to avoid a lack in SOS [in % of private consumption];
i = import ratio [in %, which applies only to gas, and not for oil];
c = the consumption ratio [in %];
E = energy intensity [in PJ per unit of GDP].

The subscripts t and r refer to these variables' respective time- and region-dependencies, while the exponents α, β and γ allow for flexible assumptions regarding the convexity or concavity of the dependency of IMP. The import ratio i is defined as the imported energy, divided by the total national energy demand, both in terms of their energy content. The consumption ratio c is defined as the consumption of a given energy commodity, divided by the consumption of energy at large, again each in terms of their energy content. The energy intensity E is defined as the consumption of energy per unit GDP. The parameter A is an overall region-dependent scaling factor. The willingness-to-pay is zero, only if a country is not dependent on foreign energy commodity imports (hence there are only commodity exports, i.e. $i < 0$). For modelling purposes, we express variables i, c and E with respect to their normalised values at $t = 0$.

This penalty function, associated with each particular energy commodity (oil and gas, in this case), expresses that there is more SOS-related welfare loss. Therefore, there is a willingness-to-pay for a lack in SOS, when there is more commodity import dependency, when there is higher commodity dependency, or when the economy as a whole is more dependent on general energy services. Each of the contributing factors is expected to affect the level of impact of the other factors, so that a multiplicative structure is proposed. For example, it is assumed that import dependency becomes more critical, if the relative commodity dependency or relative energy dependency increases, and vice-versa. This damage function is expected to show convexity with respect to each of the factors identified, which means, that the relative impact of changes in the individual factors becomes larger if the factors themselves become larger. For example, the first percent of import dependency will be less critical in terms of SOS-related welfare loss, than the last percentage. Thus the values for α, β and γ are assumed to be larger than 1 (and, by lack of further insight in this matter, typically fixed at 2).

While each of the factors, assumed to contribute to the risks relating to SOS, is normalised at $t = 0$, an additional calibration constant A_r is introduced to allow for extra appropriate modelling calibration. This permits further quantification of the willingness-to-pay, at one instant in time. The construction allows for the distinction between, on the one hand, the dynamics of the willingness-to-pay, in relation to the dynamics of the contributing factors, and, on the other hand, the willingness-to-pay at the beginning of the evaluation period. The calibration constant A_r reflects the willingness-to-pay at time $t = 0$, in some region r, and depends on the same factors that determine the SOS risks. For example, regions with a relatively high energy dependency, $E_{0,r}$ at time $t = 0$, are characterised by a relatively high calibration constant A_r. Effectively, the calibration constant is a function of the contributing factors at time $t = 0$, so that A_r: $A_r \rightarrow A_r$ $(i_{0,r}; c_{0,r}; E_{0,r})$. Formulated this way, the welfare loss function allows for less generic structures than the perceived relevance of the impact factors, as identified above. In this basic approach, however, the calibration concerns the identification of the willingness-to-pay at time $t = 0$.

This penalty function possesses a generic structure and assumes no implicit or explicit market regulation, structure or development, but rather a fully competitive market. If commodity markets are assumed to be liquid, import dependency should, in principle, not be a critical issue for countries possessing oil or gas resources, as the opportunity costs of shifting to domestic supply are identical to the costs associated with imported products. In this case, arguably, α could be assumed to be zero. However, since a vast majority of countries (and, hence, nearly all regions) do not possess domestic oil or gas resources, α is assumed to be non-zero (and in fact > 1).

Policies that successfully reduce exposure to energy system perturbations, involve sustainable strategies, typically requiring energy diversification at increasing costs. Three types of diversification can be identified, with respect to:
- the supply portfolio of a given commodity (reducing import dependency);
- the energy portfolio (reducing oil and/or gas dependency);
- the production factors (reducing energy dependency).

Each of these three dimensions of diversification are reflected in the above welfare loss equation. Diversification with respect to the supply portfolio of a given commodity may involve an increase in the number of suppliers, but could also involve shifts from high-risk to low-risk supply countries or regions.

3.3 Calibration

To calibrate the penalty function proposed in the previous section, the implied costs associated with a lack of SOS, need to be identified or estimated. Any effort, mitigating SOS risks, should come at a cost lower than the welfare loss that would result from a lack of SOS. Long-term risk mitigation options primarily involve diversification opportunities, meaning the full or partial substitution of the primary energy resource concerned. This report briefly discusses several of such diversification options, concerning oil and gas. A couple of historical instances of national policies are also inspected, which sought to mitigate long-term energy supply risks in the past. Additionally is discussed how, on the basis of such political decisions, approximations can be derived for the demonstrated willingness-to-pay to enhance the security of energy supply.

3.3.1 Substitution Options for Oil and Gas

Oil - main applications

The bulk of all oil products is used in transportation, mostly in the form of light and middle distillates. More than 99% of today's energy supply for road transport in OECD countries stems from crude oil (69% gasoline and 30% diesel), while the most important alternative fuels, currently, hold minuscule shares (LPG 0.9% and natural gas 0.05%). In developing countries the relative importance of middle distillates (automotive diesel) tends to be higher than in the OECD countries. LPG can be produced as a by-product at oil refineries and gas separation or treatment plants, near natural gas production fields. Much less significant applications of middle and, notably, heavy distillates, are those for heating in industry, in the power sector, in households and the services sector. Non-energy applications in the chemical sector are significant for, for instance, the fabrication of plastics and PVC.

Oil - substitution possibilities

LPG and Compressed Natural Gas (CNG) are short- to medium-term options to reduce the oil-share in favour of natural gas. Infrastructure requirements are fairly demanding, however, especially for the introduction of CNG. LPG can be either a by-product of oil refining (involving no oil substitution) or be produced from condensates, extracted from the cleaning of natural gas, near gas production fields (involving gas-for-oil substitution). Up to 5-10% of oil requirements for road transportation might be replaced by gas-based fuels, such as CNG and LPG, in the medium-term (2015). A long-term option to reduce up to 15% of the oil-share in the transportation fuel market, involves the use of bio-fuels (2025). These include bio-diesel (based on vegetable oil energy crops, like rape seed and sunflower, or spent cooking oil form the food industry) and ethanol (based on starchy plants, such as sugar beet, sugar cane, wheat, barley or cellulose from wood or biomass waste, like stalks). There are also methanol biofuel routes, based on woody biomass. Biofuels based on woody biomass seem to have the best long-term prospects, mostly for reasons of availability of moderately priced biomass. However, the involved conversion routes need further technological development, with prospects for significant cost reductions of the conversion process, within a ten year period. In the very long term, the use of hydrogen in fuel cells may become a substitution option. The hydrogen may be produced from the steam reforming of e.g. natural gas or renewables. This option may become cost competitive for natural gas, at a somewhat significant scale, by 2030. Renewables-based hydrogen production may not be achieved, on any significant scale, before 2040. Substitution options for oil to coal, gas and biomass tend to be readily available, for non-transport energy options. Although, sudden disruptions of the oil supply may cause short-term adjustment problems. For most non-energy oil-based products, substitutes are generally available, albeit at an appreciably higher price. Abrupt oil supply problems may cause serious transitional adjustment problems in the short-term, but less so over longer time frames.

Gas - main applications

The share of natural gas in the total primary energy supply of all European OECD countries combined, has grown, from about 10% in 1973, to some 23% in 2001. The residential sector consumes most of this natural gas, followed by industry and the electricity and commercial sectors. Especially the use of gas in power generation is, currently, still growing rapidly.

Gas - substitution possibilities

In natural gas markets, demand for gas is generally not very flexible. Most residential and commercial customers are unable to switch easily to alternative fuels, such as coal or oil, and cannot easily store natural gas, either. Industrial customers and power generators, possessing so-called bi-fuel equipment, usually, show little incentive to maintain their costly additional non-gas based equipment, because prices of natural gas are often linked to the prices of alternative fuels, such as those based on renewables. Coal is generally the most important alternative fossil fuel for natural gas multi-fuel equipment in power generation. In 14% of the net electricity generating capacity with combustible fossil fuels, coal is the preferred alternative in OECD Europe. Kerosene and oil, however, are also used as alternative fuels for natural gas combustion in power generation, but to a lesser extent than coal. In 1998, the net maximum electricity generating capacity in OECD Europe was about 622 GW, 322 GW of which, was based on combustible fossil fuels. From the generating capacity with combustible fuels, about 12% is single natural gas fired, some 8% is dual natural gas fired, i.e. is combusted in combination with solid or liquid fuels. Another 5% is multi-fired, in which the combustion of all three types of fossil fuels is combined.

3.3.2 Historical Precedents

As a means of validating the proposed approach of expressing the societal value of SOS, the general framework of portfolio management could be applied. This also applies to the appreciation of the actual costs and benefits of decisions regarding the import dependency on fossil fuels. Portfolio management has been developed in the corporate world, as a decision-making tool for investments in assets, in an environment of risk and uncertainty. In industry, risks are quantified financially, and expressed in terms of the investment costs, required for risk or potential impact reduction. As a general rule, the costs of risk reduction have to be balanced with the costs associated with risk exposure. However, there are limits to the applicability of these corporate concepts to the field of national interests, because important differences exist between industry and government:

- Governments can, in many cases, decide to shift away from energy-intensive activities, while, often, in the corporate context, little flexibility exists regarding the choice for economic activity.
- Governments are, principly, responsible for the fulfilment of primary human needs and national demand at large, the benefits of which are often valued on other than economic grounds, unlike in industry.
- Governments may be subject to substantial pressure from industrial lobbies and workers unions, advocating support for specific economic sectors, which are of limited relevance to domestic benchmarks, like GDP growth.

Quantitative validation of the willingness-to-pay, to ascertain security of energy supply, may also be derived from historical behaviour of governments, when they were facing issues of national dependency on energy resources supplied from abroad. A few representative cases are listed as follows:

- **Investment in domestic resources**. The domestic coal industry in Germany may provide clues regarding the national value of security of energy supply, in a time of, for instance, employment arguments and pressure from workers unions, and past and current subsidisation schemes. These clues can also be found in China, where current investments in coal technology, using domestic resources, are faced with explosively growing energy needs.
- **Investment in low-risk foreign resources**. The decision of France, following the oil crises of the 1970s, to invest heavily in nuclear energy, using foreign uranium reserves, may be instrumental in estimating the societal value of increasing the independency from imported energy resources. Similarly, massive nuclear investments in Japan, since that period, may give quantitative insight in the level of this value in terms of domestic welfare.
- **Investment in fundamental alternatives**. The development of Fischer-Tropp fuel production technology in South Africa, under the post-1976 economic embargo, and the corresponding investments involved, may provide a quantitative expression of the monetary value of efforts to avoid welfare losses, related to energy security. Similar to that is the nuclear embargo-induced example of India's decision to develop a domestic nuclear fuel cycle.

The use of historic precedents as a validation framework for the proposed SOS expression, may lead to undue generalisation of case-specific estimates. Often, it also seems unlikely that governments have explicitly used extensive cost-benefit analysis, to come to their decisions regarding the improvement of SOS or the reduction of fuel import dependency. Their cost-benefit analyses are not likely to have taken market-based costs of capital explicitly into account, if at all. Actual investment choices often reflect political will, or even national pride, rather than being the outcome of a detailed balancing between investment costs and the costs associated with energy supply risks. However, a short description of a few particular cases may shed light on the levels of investments, which nations are prepared to allocate to address energy supply security externalities. These observed investment levels provide information, against which the proposed SOS penalty function can be calibrated.

A first example is the investment programme in France, that was necessary to shift the power sector in the 1970s, to the large-scale use of nuclear energy. This programme was mostly financed by the government, and must have involved a total sum of about €100 billion, given the fact that each of its 60 nuclear power plants required an up-front capital investment of at least €1.6 billion France’s willingness-to-pay, to become largely independent from risky foreign fuels for power generation, must have been in the order of 0.5%.

Other examples relate to investments, made to create national strategic reserves of petroleum. The IEA recommends its members to maintain oil reserves of at least 90 days worth of consumption, in view of possible supply disruptions. The Netherlands, at present, consumes some 1 M barrels of oil per day, totalling, at some 50 euro/barrel, a daily amount of oil, worth about M€ 50 . Building a strategic reserve of 90 days of oil supply, corresponds to an investment of some G€ 4.5. Hence, with todays GDP over G€ 600 (and consumption 15% higher), the Netherlands has allocated about 0.8% of private consumption to maintain a 90-day strategic oil reserve. For the USA similar numbers apply: with a consumption of about 20 M barrels per day and total private consumption of about G€ 8,500, it has set aside an amount worth about 0.9% of private consumption to maintain a 90-day strategic oil reserve. Other examples show the efforts of some countries to replace imported fossil fuels by fuels domestically produced from, for instance, biomass. A country would have to be willing to change its oil consumption of, say, ethanol, at an additional cost of 10 euro/barrel. Brazil, for example, has achieved a sizeable transition, from oil to the use of ethanol in the transport sector. Brazil consumes some 2.5 M barrels of oil per day. Therefore, it would take an additional M€ 9 per year, to realise a full oil-to-biofuel transition. For Brazil, with a GDP of about G€ 2,000 (and private consumption of about G€ 1,750), this corresponds to approximately 0.6% of private consumption.

Similarly, one may consider the stranded costs involved in the shifting from natural gas to the widespread use of an alternative fuel in the energy sector. Such costs would probably apply to the Netherlands, in a few decades from now. The replacement of Dutch gas-fired power facilities over a period of 20 years, would easily involve an investment of about €1 billion per year. With a current GDP of approximately €600 billion, this would typically imply a share of annual GDP, dedicated to an alternative fuel based power plant construction, at the per mille level.

These examples confirm that the willingness-to-pay for large national projects, dedicated to ensure energy supply security, typically amounts to a couple per mille up to, at the most, 1% of private consumption. These estimates form the basis of the calibration of the SOS welfare loss equations, proposed in section 3.2. Figure 3.1 depicts the replacement of coal-, oil- and hydro-based power production by nuclear power production in the French power system, over the course of roughly two decades. The Figure presents the yearly evaluation of each fuel type’s relative contribution to the national production. Figure 3.2 shows how the oil import ratio, the oil-to-energy ratio and the energy intensity evolved in France, with respect to the base year 1978.

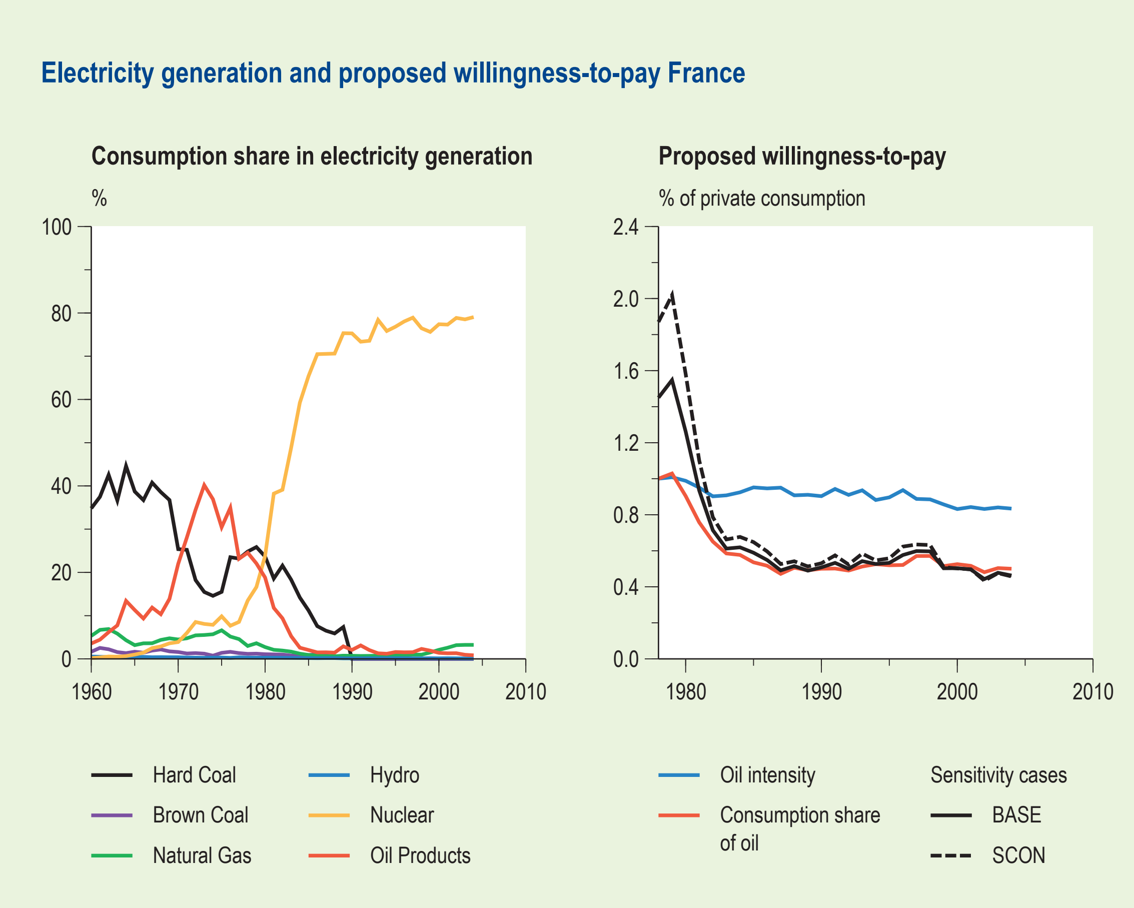


Figure 3.1 French shares of electricity generation since 1960

Figure 3.2 Proposed willingness-to-pay function for France

The depicted oil import quote appears to be fairly stable, over the full evaluation period. The oil-to-energy ratio, on the other hand, shows a strong decline in the early phase, stabilising from 1986 onward. In addition, two evaluations of the willingness-to-pay for ensuring SOS (or, alternatively, the SOS welfare penalty) for the French energy system are depicted, with regard to the base year 1978, as well. These curves have been calibrated through $A_{t,r}$, set to 1.5 and 1.9, to attain a 0.5% private consumption loss, from two different sets of assumptions, for the sum of the parameters α, β and γ. Figure 3.2 indicates that the calibration factor A should be about 1.5 in the BASE case with $\alpha+\beta+\gamma=2.5$. In the Super Convex case (SCON) A=1.9 with $\alpha+\beta+\gamma=3.5$. The observed reduction of the penalty for the French case, results from the strong reduction of oil-to-energy ratio, taking of in the early 80's, and is driven by the replacement of oil-fired power production by nuclear facilities. Accordingly, the damage resulting from a lack of SOS has been reduced by roughly 65% to 75%, depending on the parameterisation of the penalty function. This report suggests, based on the example of the nuclear program in France, to take 0.5% as central value for the willingness-to-pay for SOS, and to take a sufficiently large range of values for the corresponding sensitivity analysis, from 0.1% to 1%, thus covering an order of magnitude of spread for this variable.

3.4 The dynamics of the penalty function

The previous section proposes a penalty function, reflecting the damages incurred to consumption from a lack of SOS for some particular energy commodity. It is assumed that the penalty function is driven by the relative import dependency, the relative commodity dependency, and the relative energy dependency of every regional economy under consideration.

Since an increase in one dependency tends to aggravate the relevance of the other two dependencies, a multiplicative structure for these three factors is proposed. In addition, the penalty function is argued to be convex, in each of these three variables, given that for any economy, for example, the 'first 10% of dependency' is likely to be more damaging than the 'next additional 10% of dependency'. Appendix I explains why an increasing convexity is assumed for the penalty function, in each of the three arguments: import dependency, commodity dependency, and energy dependency (in this order).

This section presents the dynamics of these three dependencies, as well as the time-dependent behaviour of the overall penalty function in the BAU scenario (see Appendix II for an overview of the assumptions regarding this baseline scenario). As described in section 3.3, the willingness-to-pay for large national projects, to ensure energy supply security, is assumed to be in the order of 0.5% of total consumption in the year 2000 in OECD Europe, for both oil and gas. While it is recognised that this figure is debatable, several types of data have been found, supporting this assumption. For all regions, each of the three arguments is calibrated, with respect to the dependencies, as assumed for OECD Europe in the base year 2000. Therefore, in Europe all indices are one for the year 2000. Figure 3 shows the development of the two individual dependencies: consumption share (cn/cn_0), and energy intensity (ey/ey_0), as well as that of the overall penalty function for the case of oil in Europe (BAU). In the BAU scenario, all components evolve in response to international and regional economic developments, which determines the value of the penalty function (see equation 6) for each point in time. The parameters β and γ for the dependency variables behind the curves of Figure 3.3, are 1.2, and 1.3, respectively.

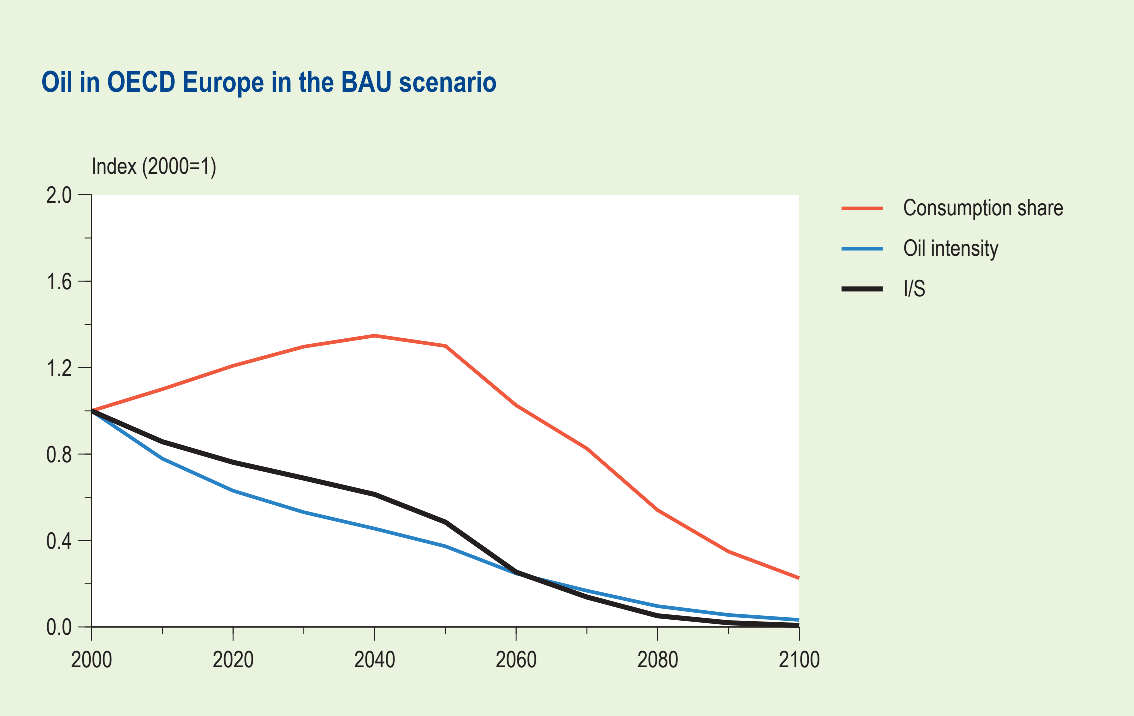


Figure 3.3 Oil in OECD Europe in the BAU scenario: time dependency of the indices for the the consumption share ($(cn/cn_0)^{1.2}$), and the energy intensity ($(ey/ey_0)^{1.3}$), as well as for the resulting overall normalised penalty *I/S*

As can be seen in Figure 3.3, the consumption share index gradually increases over the first few decades, to about 1.3 by 2040. From 2040 onward, oil consumption in OECD Europe is projected to decline in the BAU scenario, as a result of a global decline in oil production. This also explains the decrease in the consumption share index, from that year onward. The oil intensity of the European economy declines steadily, and non-stop from 2000 onward, at an average rate of 1.8%/year in the period 2000-2020, and 1.6%/year between 2020 and 2050. This is in line with the predicted 1.8%/year rate of decline of the oil intensity in OECD Europe, as reported in WEO (2006) for the coming 25 years.

The overall penalty, resulting from a lack of SOS for oil in OECD Europe, is obtained from a multiplication of the three underlying dynamic components, as indicated in Figure 3.3. The BAU scenario shows, that the normalised penalty *I/S* increases until about 2010, mostly as a result of the increasing oil import dependency. In 2010, a maximum is attained at a value of approximately 1.4, meaning that the penalty to private consumption will be 40% higher than the corresponding value in 2000. This implies that the total welfare loss, associated with the combination of the share of oil in energy consumption, and the oil intensity of the economy, amounts to about 0.7% of overall consumption, in 2020. From 2010 onward, the overall penalty steadily declines, along with the decline of the oil intensity of the OECD European economy.

Figure 3.4 presents the same four curves as depicted in Figure 3.3, but now for the case of natural gas. The gas import index in the BAU scenario in OECD Europe is assumed to be zero, between 2010 and 2020, given the ample availability of domestic natural gas. However, from 2020 onward, and especially during the first few decades, the import index steadily increases, given the depletion of many domestic West European reserves. The consumption share index in the BAU scenario increases by more than a factor of 2, until the year 2050, given the growing importance of gas in the West European economy. From 2050 onward, this trend reverses and the gas consumption share index is projected to decline, since reserves will deplete in OECD Europe, as they do elsewhere. The gas intensity remains rather stable, until about the middle of the century. During the 2nd half of the 21st century, a decline sets in, with an average rate of decrease equal to about 1.8%/year. WEO (2006) predicts a small decrease in the gas intensity, with an annual rate of some 0.2%/yr in Europe, over the coming 25 years. The MERGE simulation, however, shows a slight increase over this period, suggesting that it is inter-temporarily efficient to increase the use of gas, and first consume domestic reserves for that purpose, followed by a rapid expansion of gas imports, from about 2030 onward.

Similar to Figure 3.3, the overall penalty, experienced for a lack of security of energy supply for natural gas in OECD Europe, is obtained by a multiplication of the three underlying dynamic components: see Figure 3.4. Naturally, given the definition of the penalty function and the confirmation in Figure 3.4, the normalised penalty *I/S* reaches a value of zero, when the gas imports are zero. Beyond 2020, when the gas import quote increases steadily (attaining the 2000 value in 2030), the gas penalty increases correspondingly. In fact, an increase in *I/S* is observed to very high levels (by more than a factor of 3 compared to 2000), given that the consumption share rises steeply, as well, until about 2050. However, from 2050 onwards, the penalty starts declining (very rapidly), because of a worldwide rapid depletion of gas.

Figure 3.5 takes a broader perspective than Figures 3.3 and 3.4, by plotting the sum of *I* (and not *I/S*) for oil and gas, in each of the nine regions considered in MERGE, again in the BAU scenario.

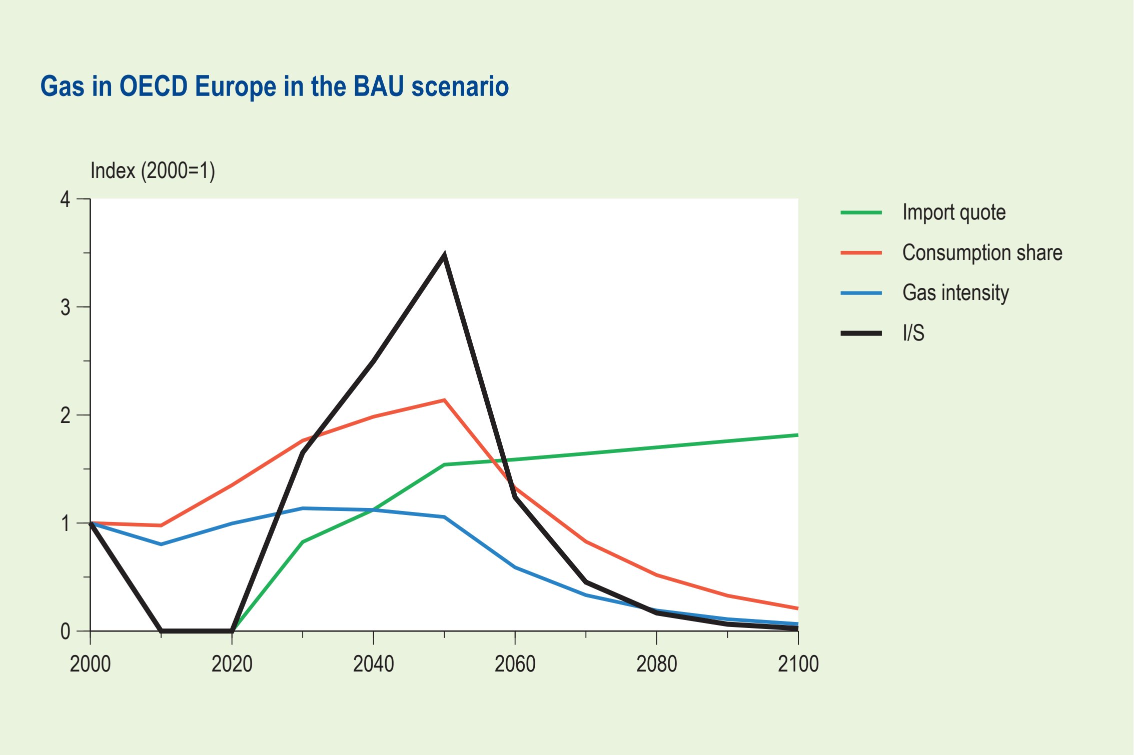


Figure 3.4 Gas in OECD Europe in the BAU scenario: time-dependency of the indices for the import quote $(iq/iq_0)^{1.1}$, consumption share $(cn/cn_0)^{1.2}$, and energy intensity $(ey/ey_0)^{1.3}$, as well as for the resulting overall normalised penalty *I/S*

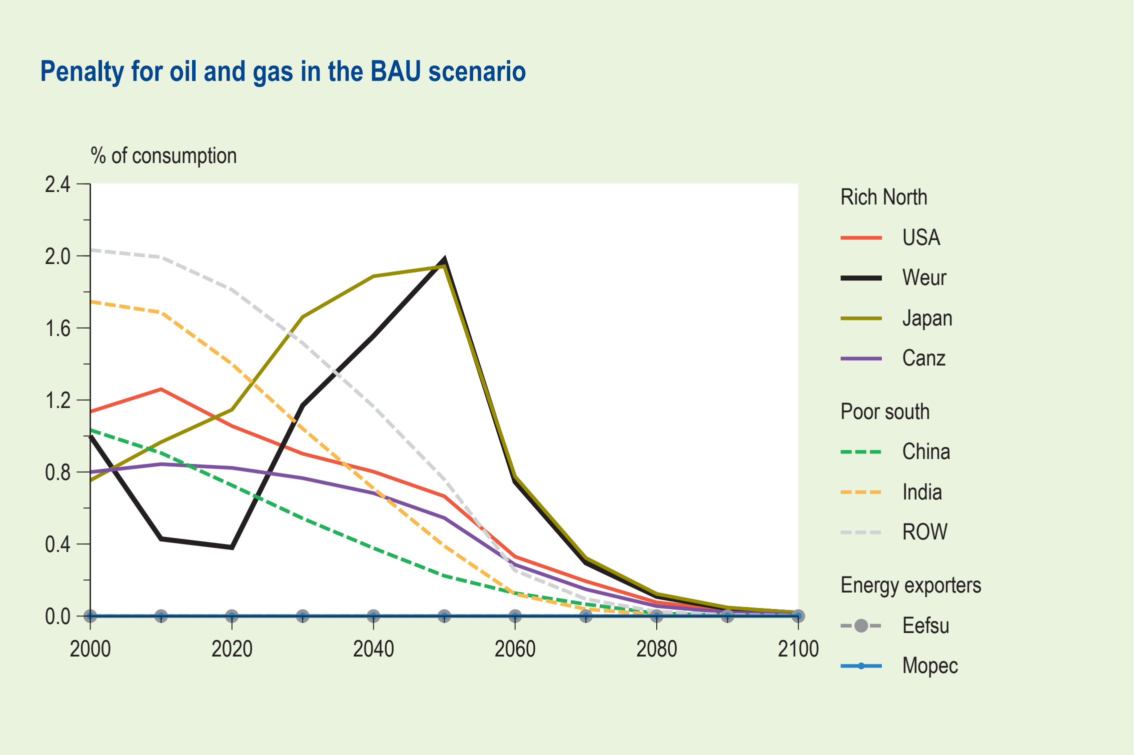


Figure 3.5 The sum of I (in % of consumption) for oil and gas in the BAU scenario for all regions as simulated in MERGE

In the BAU scenario, the aggregate penalty for oil and gas remains zero for both Eastern Europe and the Former Soviet Union (EEFSU) and Mexico and OPEC (MOPEC), throughout the course of the entire century, since these regions can be expected to remain net energy exporters during this time frame. For all other regions the aggregate penalty proves to be more dominated by the oil component, than by the gas component, given that the former is especially indispensable in the transport sector. Hence, the aggregate penalty is projected to rise with imports of oil, and to fall with a decline in oil consumption (given arguments like reserve depletion and oil intensity decline).

Although this pattern is consistent across all energy importing regions, and, especially oil imports tend to harm SOS, gas imports are also found to contribute to compromising SOS, notably in OECD Europe and Japan. The reason for this is that gas imports for OECD Europe are projected to decline to zero up to 2020, while European gas production increases. Since gas imports for OECD Europe and Japan are projected to rise rapidly, between 2020 and 2050, it affects the aggregate penalty for both these regions, and in such a way, that the maximum of the aggregate penalty is reached in that period, as well. However, the aggregate penalty for the USA and Canada Australia and New Zealand (CANZ) is mainly determined by the oil penalty, which rises with the oil import dependency, but declines with the energy intensity. Figure 3.5 shows particularly high values for the aggregated penalty in India and Rest-Of-the-World, up to 3% of their total consumption opportunities. This is mostly driven by the relatively high oil intensities of their respective economies. The oil intensity also explains the overall trend of the penalty in these regions, with a peak during the coming twenty years, followed by a decline from a sustained reduction in the oil intensity. China’s penalty is significant and increases as well, but its oil intensity is significantly lower than that of the rest of the developed world. Therefore, the regional penalty of China is lower than that of, for instance, India..

4 Simulation Results

To analyse the effects of GCC, LAP, and SOS control, eight different scenarios are defined, each of which by running the expanded MERGE model. Externalities are internalised in these policy scenarios, that is to say, that in these variants the external costs (or dual prices of either the environment or energy security) are included in the prices for energy services and consumer goods. This section zooms in on the results for OECD Europe, since for this specific region the parameters of the penalty functions were validated. First, OECD Europe's reductions of the penalty for oil will be shown, under various policy scenarios, to get a better understanding of the potential gains for this region to improve on their energy-related SOS. Following that, will be shown how this response is driven by the evolution of specific technologies to meet the demand for energy, and will be illustrated how this may affect the region's CO_2 emission profile. This section will, then, zoom out of these regional impact descriptions, and highlight the main global results. Since energy-related SOS is the topic of this paper, the impacts of SOS control policies on the global demand for oil, will be summarised. This section concludes with the global monetary costs and benefits of policy interventions.

For simulating the business-as-usual (BAU) scenario, the GCC loss factor E, the LAP loss factor F, and the energy damages factor S, are exogenously set to 1. For example, for the GCC scenario, the E variable is 'switched on', after which the model calculates the equation's relating temperature to climate related non-market damages. The endogenously generated variable E attains values <1, and, hence, climate change damages are internalised, as they may affect decision variables in different regions to mitigate climate change. Similarly, the LAP loss factor can be 'switched on' and have the model generate the variable E endogenously (values <1). In this way, the model internalises LAP damages into the decisions in different regions, to reduce the impacts of LAP. Finally, a similar procedure applies to the damage factor S. Policy interventions internalise externalities of GCC, LAP, or SOS, a combination of pairs, or of all three issues. The abbreviations of the scenarios corresponding with the specific, internalised externalities, are listed in Table 4.1.

Table 4.1 Externalities internalised in all scenarios

Abbreviation Scenarios	Externalities		
	LAP	GCC	SOS
BAU			
GCC		X	
LAP	X		
LAG	X	X	
BOS			X
LOS		X	X
GOS	X		X
LGS	X	X	X

If cell entry equals X then specific externality switched on.

4.1 Regional Impacts: OECD Europe

SOS control policies can be shown to increase consumption, provided that the penalty function as described in Chapter 3 actually exists, by reducing the value of the penalty function. A lower value can be achieved through a decrease of either the import dependency, the commodity dependency, or the energy dependency, or of a combination of the three. Figure 4.1 depicts these consumption gains (% consumption) in OECD Europe. related to oil, for the coming 40 years. The welfare gains are derived for different cases. For example, the line indicated with 'BAU-BOS' equals the gains of internalising the SOS externality only, that is to say, when no other two externalities (LAP and GCC) are internalised. The line indicated with 'LAG-LGS' equals the gains of SOS control policies, assuming both other externalities of LAP and GCC are also internalised in the regional decisions. Results for OECD Europe are shown, because this constitutes an average well-documented reference case (which is also why the oil damage functions for other regions are based on data of OECD Europe)..

From Figure 4.1 the following can be observed. Firstly, lowering the value of the penalty function of oil without SOS control policies can be substantial, that is to say, they approximate up to 80% in the medium-term. This may not be surprising, as the penalty value is based on multiplicative dependencies, that is also convex in each of these dependencies. If the import dependency is lowered - for example the import of oil being partly replaced by the region's own gas resources - then the consumption share dependency is likely to decrease, also. Therefore, *I* will likely reduce more strongly than the distinct dependencies. However, the benefits cannot immediately accrue to the full 100 % without excessive adjustment costs, because of inertia in the energy system (the existing capital stock is long-lived). Secondly, the benefits to improve on the value of the penalty function of oil will decline to 60%, in the long run.

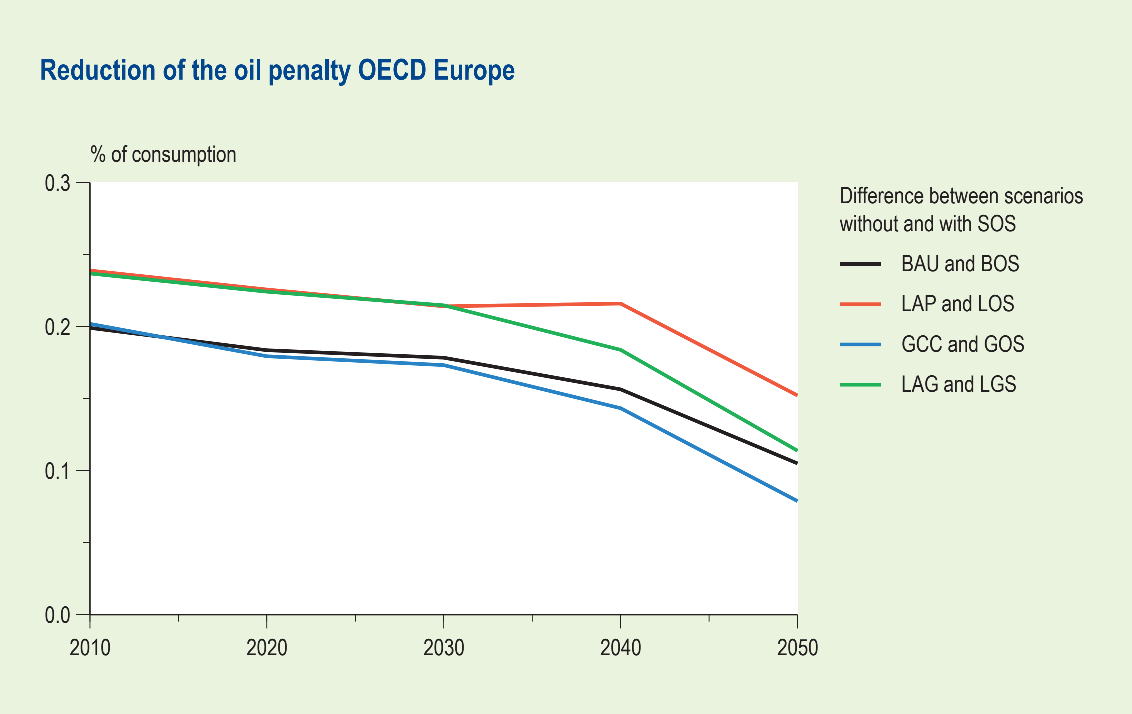


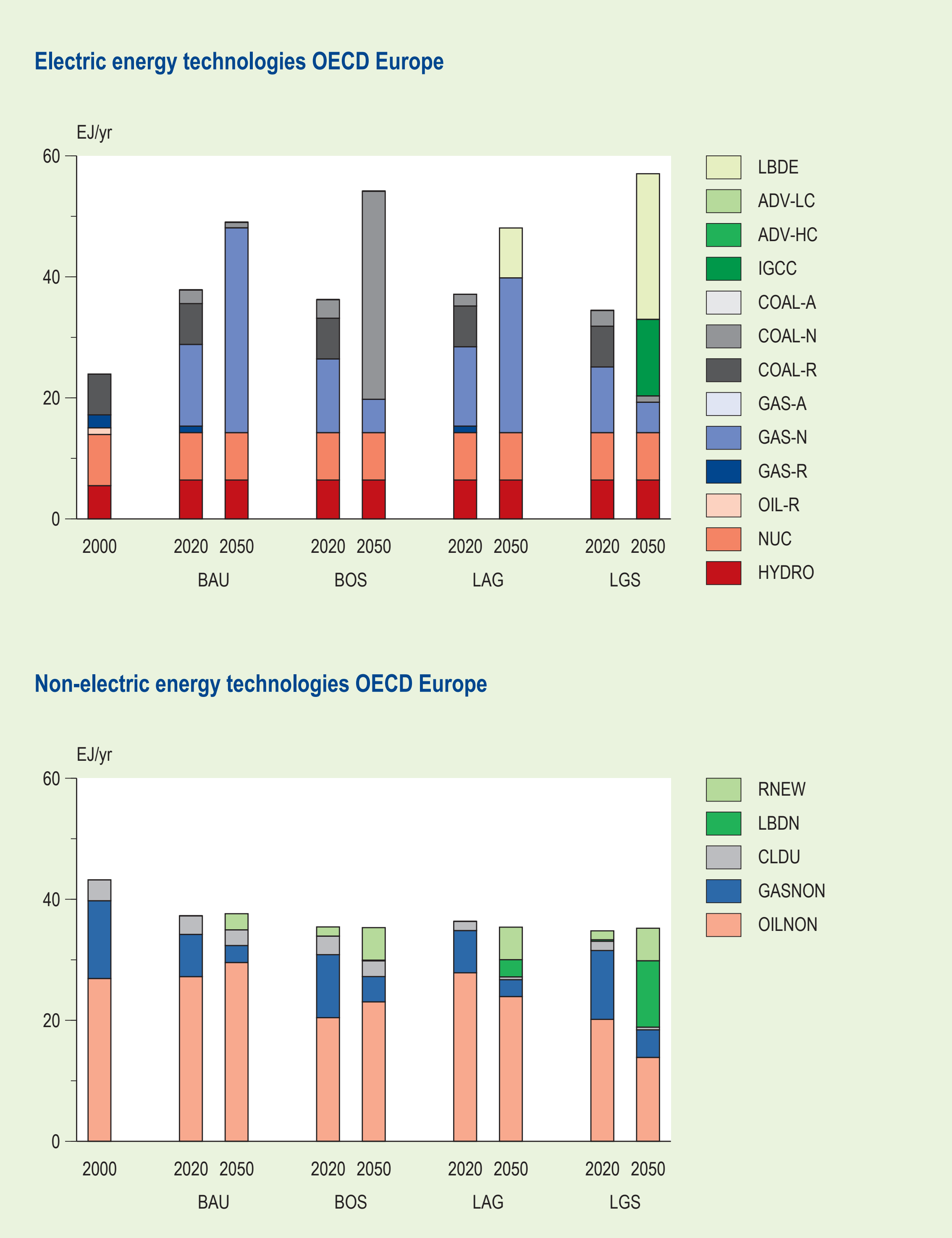
Figure 4.1 Reduction of the oil penalty *I* (% consumption) from SOS control policies in OECD Europe, as simulated in MERGE

Although, at such a time, there will be less inertia in the energy system, and beyond 2020 the penalty of gas also requires resources, not necessarily improving the value of the oil penalty. Thirdly, if SOS control policies are combined with LAP policies, the medium-term benefits will be higher. The reason being, that tackling LAP externalities throughout the world, will reduce the global demand for oil and, consequently, its supply prices. Therefore, some regions, such as OECD Europe, can lower their oil bill (lower prices but higher demand) and increase their expenditures on EOP measures by a smaller amount (without significantly deteriorating the level of LAP). In the LAP scenario, the penalty of oil will increase compared to the BAU scenario. Hence, the reduction of the penalty (welfare gain) in OECD Europe will be larger, when addressing both externalities of LAP and energy-related SOS, simultaneously. Fourthly, in the long run, the reduction rate of the benefits of oil-related SOS control policies, will be the highest in the LGS case. The main reason for this is that, in the long-term, in the LAG scenario the demand for oil will decline faster, to also obtain the benefits of mitigating GCC, that is to say, a "lock-out" from oil also triggered from medium-term reduced expenditures on EOP-measures.

Figure 4.2 illustrates impacts on technologies in the energy sector, for both electric and non-electric energy demand in OECD Europe, for the years 2000, 2020, and 2050 for four scenarios. The impacts of reducing the energy penalties for oil and gas, can be traced from comparing two pairs of scenarios – BOS versus BAU, and LGS versus LAG. Accounting for the externalities of a low energy-related SOS, restricts to these two extremes: either having no environmental controls at all, or addressing both externalities of LAP and GCC, to be able to illustrate the full range of potential changes of all energy technologies modelled in MERGE (see also Table 2.1). The responses that change the energy system, balance the discounted marginal costs and welfare improvements, obtained from reducing LAP, GCC, or energy penalties. In the medium-term, the irreversibility of the energy system leads to high costs of abatement, but in the long-term the energy system changes will be more flexible. The potential welfare gains, in the medium-term, are dominated by air quality improvements, followed by lower energy penalties. In the long-term, the welfare gains associated with lower impacts of GCC, will become more pronounced.

Figure 4.2 shows that the total energy demand (the sum of electric and non-electric demand) will be slightly lowered in the medium-term, and increased in the long-term. Energy savings itself, play only a modest role in trying to lower the penalties for oil and gas. This is not surprising, as this option affects not only the demand for oil and gas, but also that for all fuels for electric and non-electric purposes. The vintage structure of MERGE, with its CES production function for new capital, limits the possibilities to tackle a low energy related SOS through energy savings. Moreover, in the long-term, the demand for electric energy will even increase, because of a forced lock-in of high conversion efficiency electric power stations, especially in the LGS scenario. In Figure 4.2, reductions in the demand for non-electric energy, from SOS policies, can be seen to occur when there are no environmental policies, as the marginal cost to reduce non-electric energy use is lower, at the higher unaffected level of demand in the BAU scenario.

However, underneath these aggregates, non-electric energy can also be substituted by electric energy, or vice-versa. For example, gas-fired furnaces can substitute electric-driven heat pumps. Also, gas can be switched from being used as fuel input in electric power stations, to being used in transport. Figure 4.2 shows, that the reductions in the demand for gas in electric markets, will be partly offset by an increase of gas in non-electric markets. The reduction is brought about by removing almost all gas imports, thus, slightly accelerating the depletion of gas reserves, but at the same time yielding welfare benefits by bringing down the gas penalty to zero, in the BOS, LOS, GOS, and LGS scenarios.


Electric energy technologies OECD Europe

Non-electric energy technologies OECD Europe

Figure 4.2 Technologies for electricity and non-electricity generation in OECD Europe in BAU, BOS, LAG and LGS for the 2000-2050 period

However, underneath these aggregates, non-electric energy can also be substituted by electric energy, or vice-versa. For example, gas-fired furnaces can substitute electric-driven heat pumps. Also, gas can be switched from being used as fuel input in electric power stations, to being used in transport. Figure 7 shows, that the reductions in the demand for gas in electric markets, will be partly offset by an increase of gas in non-electric markets. The reduction is brought about by removing almost all gas imports, thus, slightly accelerating the depletion of gas reserves, but at the same time yielding welfare benefits by bringing down the gas penalty to zero, in the BOS, LOS, GOS, and LGS scenarios.

In electric markets, gas fired power stations are replaced by more expensive options of LBDE or IGCC, when LAP and GCC externalities are internalised in regional decisions, and they are replaced by COAL-N, when there are no environmental policies. These options are currently more expensive than gas but, in the long-term, they will become cheaper through rapidly increasing conversion efficiencies. This may even lead to an increase in the demand for electric energy, in the long-term (compare the 2050 bars LGS and BOS with LAG and BAU).

In non-electric markets, the demand for oil will drop, to generate a welfare gain by lowering the oil penalty. In 2020, the reduction in the demand for oil will be equal to 30% (compared to the oil demand in BAU), in all cases. In the long-term, the reduction of oil will accrue to 35% in the BOS scenario (compared to BAU), and 50% in the LGS scenario (compared to LAG). The medium-term result is robust, as there is inertia in the energy system, which restricts the changes in the energy system to changing the demand for gas in electric to non-electric markets and also some energy savings. The long-term result is mixed. In the LGS scenario, the LBDN technology will significantly penetrate the non-electric energy market. Avoiding EOP abatement costs – that aims to lower LAP - enables the costly switch away from oil to LBDN, and sufficient air quality improvements can be sustained. Moreover, this technology strengthens CO_2 abatement in OECD Europe and other energy importing economies, to suffice the global CO_2 abatement effort. This will be necessary, as a reduced demand for oil by energy importing countries, will partly leak to energy exporting economies, which will increase their CO_2 emissions. In the BOS scenario, there will be no rationale for the LBDN technology to enter the market, as there is no incentive to act on the problems of LAP and GCC. Finally, RNEW expands, but does so in the same limited way, as in the variants with and without environmental policies. The key distinction between RNEW and LBDN is that the former technology is assumed to be available in limited supply, at considerably lower marginal cost than the latter, which is available in unlimited quantities.

In addition, Figure 4.3 depicts the CO_2 emissions in the next hundred years for all scenarios. The results for OECD Europe are highlighted, because this region was also used in the other analysis. The order of scenarios without SOS controls, with respect to the cumulated CO_2 emissions over the next 100 years, is: LAP, BAU, GCC, and LGS. The LAP scenario lies above the BAU, while also attaining low PM_{10} emission levels through EOP abatement technologies. The CO_2 emissions will be higher, because emissions from electric energy use will increase, despite that there will be emission reductions from non-electric energy use. In electric markets, COAL-N (zero emissions of PM_{10}) serves as a substitute for gas fired power plants, and in non-electric energy markets, gas is a substitute for oil. However, the CO_2 emissions in the LGS scenario are much lower than in the GCC scenario (also aiming to mitigate the adverse effects of GCC). The reason for this is that extra CO_2 abatement costs will be a substitute for EOP abatement measures, lowering LAP.

The impacts of reducing the penalties for oil and gas on CO_2 emissions, can be analysed by focussing, in Figure 4.3, on the difference between lines with open markers and closed versions of the same type. The SOS control policies will yield CO_2 emission reductions in 2020, but beyond that year the impact is ambiguous. This is caused by the fact that, in 2020, the oil penalty dominates over the other externalities. The oil penalty will be lowered by the demand for oil. Gas is a substitute for oil in non-electric markets, brought forward by a switch of gas from electric to non-electric energy purposes, which, in turn, leads to a faster depletion of gas reserves.

However, there is more flexibility to adapt the energy system, in the long-term, and the changes in CO_2 emissions are different across scenarios. Without any environmental policies, there will be an increase in CO_2 emissions, of almost 20% in 2050, compared to the BAU level, although this increase will slowly fade away during the second half of this century. The results in 2050 come from an expansion of COAL-N (see Figure 4.2), because there are no incentives for producers to mitigate CO_2 emissions or reduce the adverse effects of LAP. The increasing CO_2 emissions in electric markets are partly offset by lower CO_2 emissions of non-electric energy switches, from oil to gas. Beyond 2050, the autonomous energy intensity improvements depress the values of the penalty functions, and, thus, lower the potential welfare gains from favourably altering the energy system. Therefore, CO_2 emissions slowly return to the levels of the BAU scenario. Clearly, there is no lock-in of alternative energy technologies, other than what will occur anyway. However, if the assumptions of LAP apply instead, then lowering the penalty functions for oil and gas will lead to an increase in CO_2 emissions by a small amount, up to 2050, and lower emissions in the long-term. The main reason for the increasing CO_2 emissions in 2050 (LOS compared to the LAP scenario), is extra COAL-N in electric markets, but this increase is almost compensated by lower CO_2 emissions of switching non-electric energy use from oil to gas (and to some extent) LBDN. In the long-term, there will be a further expansion of LBDN, which will lower the CO_2 emissions from non-electric purposes, and that will more than compensates the CO_2 emission increases from electric energy use. The fuel switch to LBDN will be costly, but is compensated by welfare gains, through lowering both penalties and economic gains from avoided resources, to be spent on EOP abatement of PM_{10} emissions.

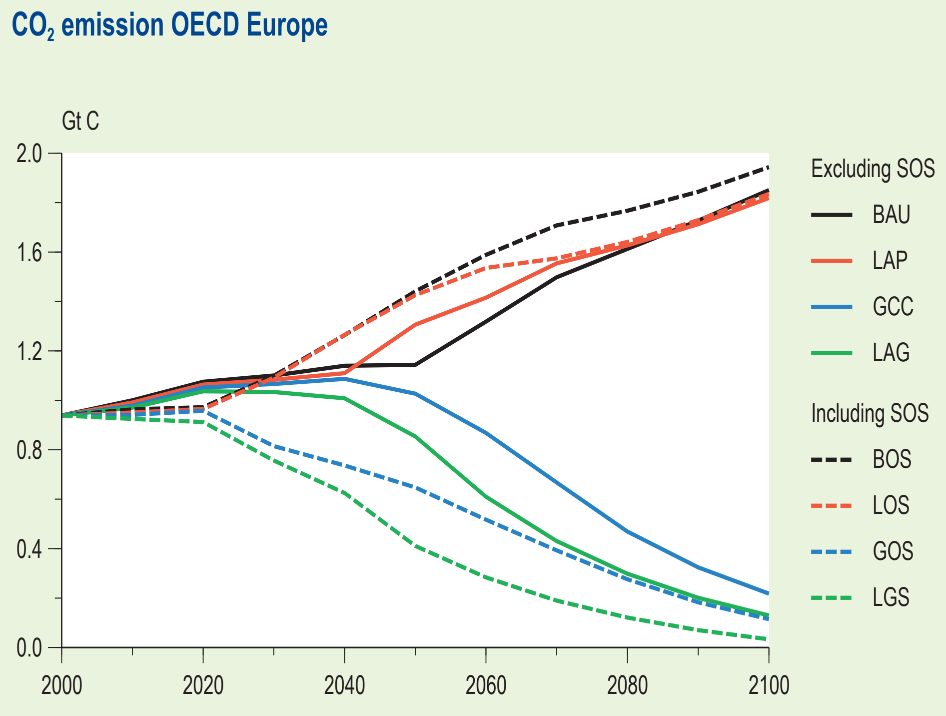


Figure 4.3 CO_2 emissions in Europe (Gt C)

However, if the penalty functions for oil and gas are allowed to be reduced, combined with climate policies (GCC scenario), this will already lead to lower CO_2 emission levels. The costs involved in switching to non-carbon fuels will be more than offset by welfare gains, and by CO_2 emission reductions from lowering the penalties for oil (and, to a lesser extent, for gas). Substantial CO_2 emission reductions by energy importing countries will be costly but necessary, as the decreasing demand for oil and gas in these countries will lead to an increase in CO_2 emissions of energy exporting economies. In the LGS case, the added possibility to avoid costs of PM_{10} abatement further magnifies this result, and creates a stronger incentive for reducing CO_2 emissions.

This implies that, in the climate debate, OECD Europe can indeed argue for strong CO_2 emission reductions within its borders - based on arguments from CBA, and on sufficiently high penalties for oil and gas (as is the case in the BAU scenario). This extra CO_2 emission reduction extends to other energy importers, as well, as these reductions will be offset by energy exporting countries expanding their oil consumption (gas is less important).

4.2 Global Impacts: The World

The global perspective is next. The impacts of SOS control policies will be shown, for oil and gas in all energy importing regions, on the global demand for oil. The costs and benefits of all SOS control policies will also be highlighted. Below, Figure 4.4 shows the global pattern of the demand for oil. The focus is on oil, because this tradable resource will deplete at a much lower rate than gas. Additionally, oil is of more immediate importance, as it has a larger share in total primary demand for energy, on a global level.

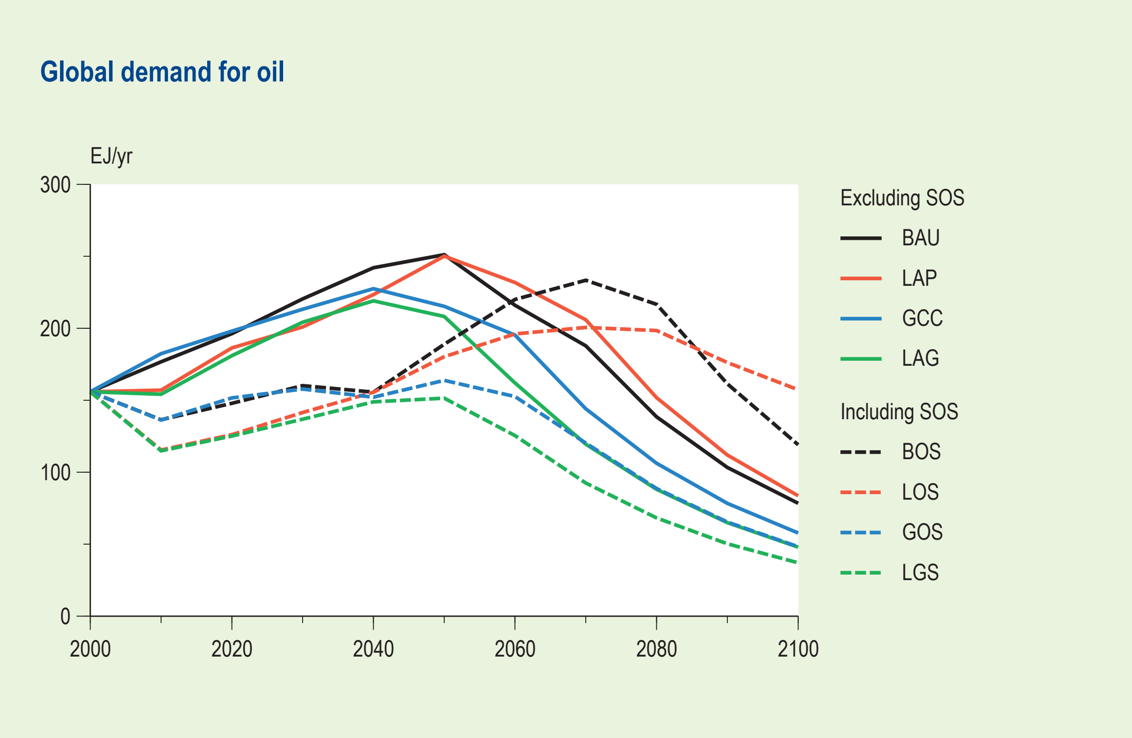
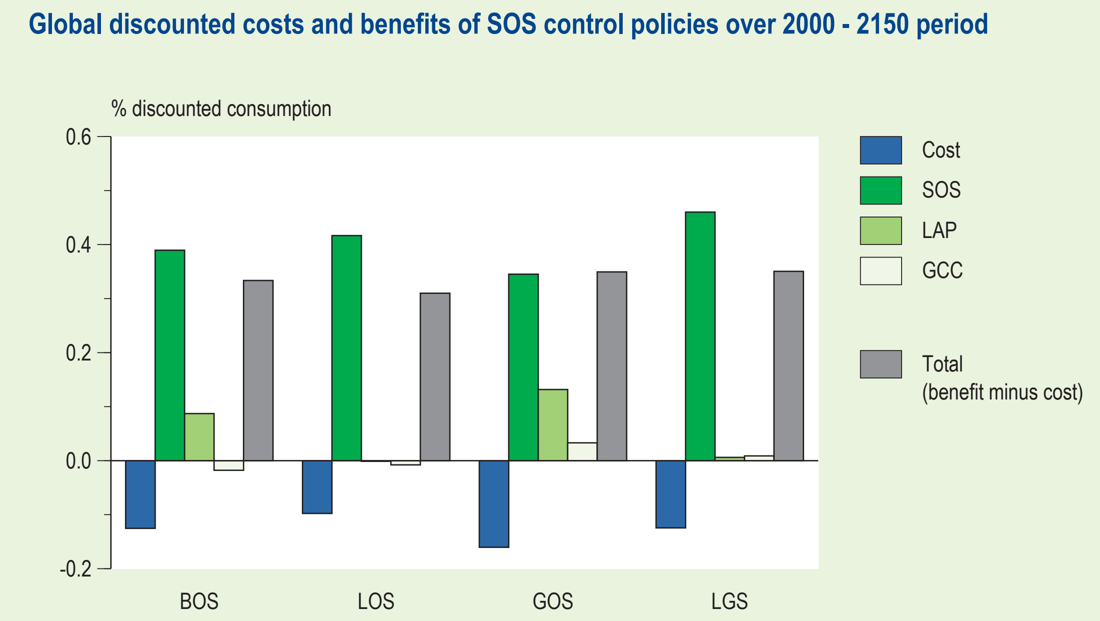


Figure 4.4 Demand for oil in the world (EJ)

Figure 4.4 reveals that, in the BAU scenario, the demand for oil will peak around 2050, and will subsequently decline to 25% of the current value. The LAP policy depresses the demand for oil in the medium-term, and the difference with the baseline diminishes by 2050. The reduction in the medium-term is mainly driven by the oil importing countries. These countries reduce their demand for oil in non-electric markets, through a gas expansion. The increasing demand for gas is due to several substitution. One substitution is that of electrically driven heat pumps by gas-fired furnaces. Another substitution, in the transport sector, is that of both gas and more expensive alternatives, such as RNEW (2nd generation biofuels) and LBDN. In the long-term, these effectively avoid EOP abatement costs, and aim to lower LAP. At the global level, the reduction in the demand for oil is limited by oil exporters expanding the demand for their cheap oil resources. In the long run, oil-importers will apply PM-filters in the transport sector, which also reduce PM_{10} emissions, because the VSL attains higher values and, although currently a more expensive option, it provides an incentive to lower LAP. Together with increasing oil reserves, it depresses the asking price at international markets. Moreover, in the long-term, the declining oil penalty causes the initial reduction at the global level to evaporate. The LAP profile shows, that there will be a delay in the demand for oil and it will exceed the BAU scenario in the second half of this century. This delay also occurs in the scenarios with SOS control policies. Not until beyond 2090 will the demand for oil in LOS exceed BOS, as the penalty will be lower due to low oil intensities.

The environmental policy scenarios (either GCC or LAG), although without SOS control policies, all aim to reduce the accumulation of CO_2 emissions in the atmosphere. Under these scenarios, the demand for oil will already peak around 2040. The oil peak will, subsequently, lower and attains a lower maximum, than if no climate policies would be applied. The LGS scenario remains below GOS due to stronger CO_2 mitigation efforts from adding LAP policy goals, but this does not hold witout any climate policies (variant LOS, compared to the BOS scenario). The reason for this is that substantial oil reductions provide welfare gains at the global level, from lowering the oil penalty as it directly lowers LAP, or reduces the EOP abatement costs to lower LAP. Lastly, the demand for oil is not only delayed in GOS and LGS, compared to the scenarios without SOS controls (GCC and LAG, respectively), but oil reserves will also not be depleted. The main reason for this is that reductions in oil serve to lower the damages arising from GCC. Over 150 years the accumulated oil demand remains 10-15% below the scenarios without SOS control policies.

Figure 4.5 shows the net impact on global welfare, resulting from both the incurred costs and the obtained benefits. It expresses this impact in the percentage of change (with respect to the baseline) of the total discounted sum of consumption up to 2150, for each of the four SOS control scenarios. A comparison of the total discounted consumption stream, corrected for values of E, F, and S as differences between the baseline, and of the respective variants, together generate the benefits of policies that lower GCC, and/or LAP, and/or a low energy SOS, as reported in Figure 4.5. The first bar represents the scenario, in which the external costs of a low energy SOS is separately internalised in the prices of energy services and consumer goods, in the BAU scenario. The second bar denotes the scenario in which SOS control policies are added to a scenario, in which also LAP-related external costs are already internalised in the regional decisions. The third bar denotes the scenario in which SOS control policies are combined with the internalisation of the GCC externality in regional decisions. The incurred costs are depicted below the X-axis, and the avoided monetary damages (the benefits) above the X-axis. These benefits are the result of avoiding damages associated with a low energy related SOS, GCC and/or LAP.



	BOS	LOS	GOS	LGS	
$PM_{2,5}$ deaths	990	70	790	70	millions
Temperature increase	4.8	4.7	3.1	2.9	Compared to pre-industrial level (°C)
Demand for oil and gas	100	100	88	78	Index (without SOS policies=100)

In the BAU scenario there are 1024 mn premature deaths from PM2.5 exposure, the temperature increase equals 4.80C, and the accumu-lated demand for oil and gas will be equal to 41816 EJ over the period 2000-2150

Figure 4.5 Global costs and benefits of SOS control policies in BOS, LOS, GOS, and LGS scenarios, compared to BAU, LAP, GCC, and LAG scenarios, respectively.

The benefits are differentiated between those of climate change mitigation (GCC, higher part), PM emission reduction (LAP, middle part), and improvements in securing the energy supply (SOS, lower part). Also indicated for each scenario, is the cumulative number of premature deaths due to $PM_{2.5}$ emissions, the long-term (2150) equilibrium temperature change with respect to its pre-industrial level as a result of GHG emissions, and the global cumulative demand for oil and gas (indexed to the BAU scenario, which is set to 100) . For the baseline scenario these observables amount to 108 million, 4.8°C, 41816 EJ, respectively, over the period 2000-2150.

Figure 4.5 illustrates that SOS control policies generate benefits which are mainly related to avoided damages of a low SOS of 0.6-0.7% of discounted consumption, with costs equal to 0.1-0.2%. However, these benefits only accrue to the energy importers; energy exporters will increase their own demand for oil and gas. In addition, the sense of urgency of a low energy SOS will decline as energy intensities steadily reduce. Therefore, the GCC co-benefits will be only small. However, SOS control policies will generate some LAP benefits of about 0.1% of discounted consumption, in cases where no appropriate policies are in effect. This is due to the substitution of oil by gas, in non-electric markets, and of gas by renewables and LBDE, in electric markets. However, when LAP policies are active, then the marginal benefits of additional switches away from oil are small, or even very little, This happens, because most of the damages are dealt with by a switch to non-oil fuels or EOP measures, such as dust-filters in cars. SOS policies with GCC policies, but without LAP (GOS), produce an extra benefit of avoided GCC damages, because of a forced lock-in of LBDN technologies (lower CO_2 emissions from reductions in oil). However, in cases with both GCC and LAP policies (LGS), there are few benefits in terms of avoided damages from either GCC or LAP, but there are also no extra losses, keeping in mind that coal is an option to reduce the penalty of high (import) dependencies on oil and gas. Although, the costs decline in that scenario, too.

5 Sensitivity analysis

The modified model of MERGE allows for calculating and comparing the optimal decisions on region-specific and time-dependent emissions of GHG's and PM_{10}. The model was extended with penalty functions for oil and gas of energy importing countries. These penalty functions create incentives for regions to lower the import dependency, the energy share, and energy intensity, as a means to increase welfare. The modified MERGE model allows for analysing impacts under different assumptions, for GHG's, PM_{10} and for a low energy related SOS on welfare. In its cost-benefit mode, MERGE can generate monetary values for the corresponding environmental benefits of climate change mitigation, air pollution reduction, and energy related SOS control policies. The results, however, are subject to a range of specific parameter assumptions. Figure 5.1 presents the results of a detailed uncertainty analysis, for the most relevant of these assumptions in terms of the average CO_2 emission reduction between 2020 and 2030, and for the cumulated global demand between 2000 and 2150. The CO_2 emission reductions are averaged over the period 2020-2030, because some individual years show a significant reduction acceleration, compared to others in that period. The percentage of CO_2 emission reduction is expressed by the additional percentage to the -20% (compared to the 1990 level). The demand for oil and gas is accumulated over all regions and over the 2000-2150 period, and indexed to 100 of the results of the LAG scenario. For example, the cumulated demand for oil and gas in the LGS scenario (LAG scenario plus SOS control policies) declines with 10%, compared to the demand in the LAG scenario (similar to the result in Figure 4.5) . The average CO_2 emission reduction between 2020 and 2030, can be seen to be equal to 20% (see also LGS line in Figure 4.3). All respective sensitivity variations are clarified in more detail, under the headings I-VIII below.

I Damages SOS weakly convex (WCON) /super-convex (SCON)

The damages, associated with a low energy related SOS, are based on a parameterisation of the equation 8. As pointed out, it is unclear what the values are of α, β, and γ, beforehand. The values of α, β, and γ in the base case, are fixed at 1.1 (0 for oil), 1.2, and 1.3, respectively. Therefore, to analyse the importance of the issue of energy related SOS, the parameters of α, β, and γ are also fixed to 0.5 (and 0 for oil), 0.6, and 0.7, respectively, which is 50% of the benchmark case. The former parameterisation transforms the penalty function to a weakly convex function, compared to the parameterisation of the benchmark case. However, the latter creates a more (super-)convex behaviour of the penalty functions, because lowering the imports of oil also reduces the oil share of energy in non-electric energy use, and the oil-intensity of the economy. The weakly convex parameterisation increases the demand for oil and gas, as the global penalty will be lower in future years, and improvements will, therefore, be less effective, in terms of welfare gains. This is not the case in Europe, where the damage of a low energy related SOS is relatively low, compared to other regions. This implies that switching away from oil is still relatively beneficial, in terms of an improvement in energy related SOS and a reduction of LAP. Even so, the global increase in the demand for oil and gas will rise, although the CO_2 emission reductions in OECD Europe remain the same. The SCON assumptions imply significant benefits, against relatively small efforts, for OECD Europe. However, the larger regions will be experiencing larger damages, without SOS controls, and will, therefore, significantly reduce their demand for oil and gas. At the same time, the CO_2 emissions in Europe will rise in the SOS control policy case (SCON), as the demand for oil will increase, compared to the base case (LAG).

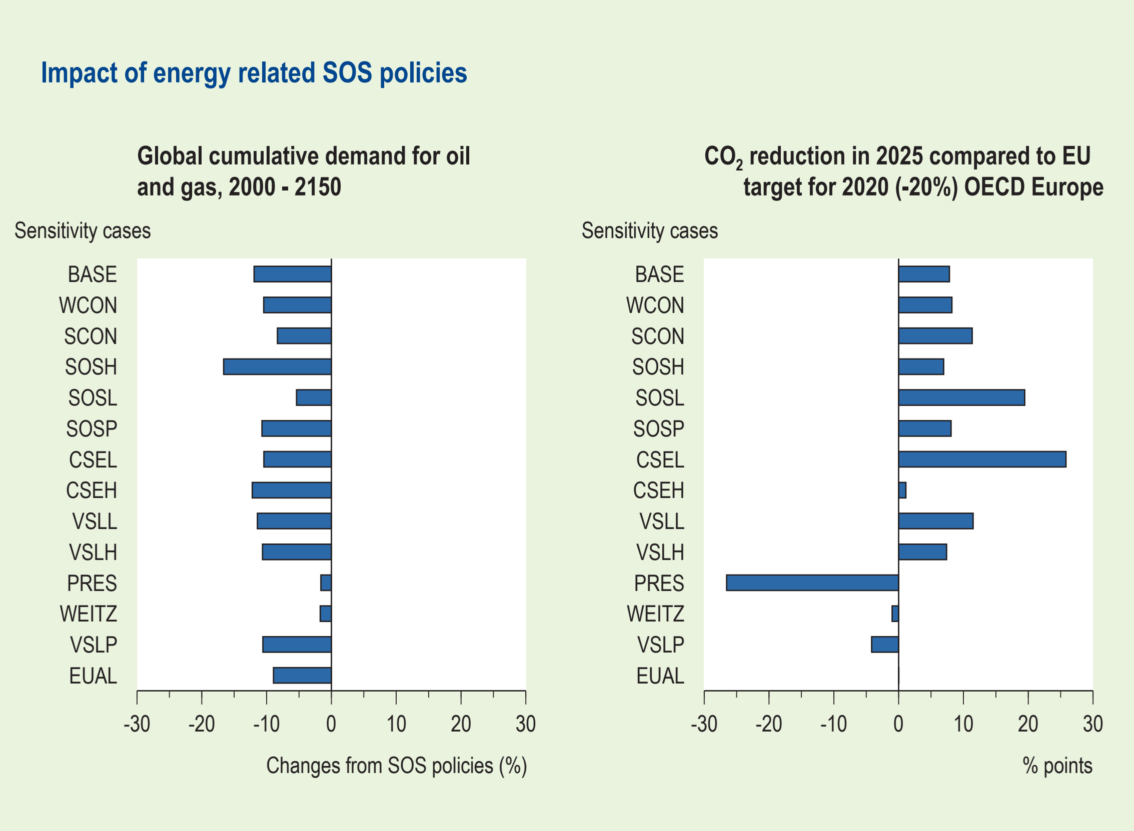


Figure 5.1 Average annual CO_2 emission reduction in OECD Europe between 2020-2030 (% in addition to the 20% emission reduction of the 1990 level) and the global demand reduction for oil and gas, compared to the scenario without SOS control policy (%)

II Damages SOS 3 times (SOSH)or 1/3 times (SOSL) the base case

The damages, associated with a low energy related SOS, are calibrated to 0.5% consumption loss in 2000, for both oil and gas. As pointed out, it is not clear if these damages are correct, and, therefore, we de- and increased the scale parameter of the penalty fuction, to sketch the full range of possible impacts. The scale parameters of the penalty functions (oil and gas, and 9 regions) are set to higher levels (*A* is increased with a factor of 3, labelled SOSH) and lower levels (*A* is reduced with a factor of 3, labelled SOSL). The results are straightforward. SOSH urges all regions to reduce the demand for oil and gas, and, hence, the result is a 18% reduction of the cumulated demand for oil and gas for the next 150 years, compared to the case without SOS control policies (10% reduction in the base case). The opposite occurs in SOSL, with a reduction equalling 7%. However, it seems that the reduction of oil and gas behaves non-linear, compared to the changes of the parameter *A,* mainly driven by the convexity of the penalty function, with respect to the other arguments. In OECD Europe the CO_2 emission reductions in both cases are lowered, compared to the base case. In SOSH it is coal that drives this result, and in SOSL it is mainly oil. The latter case gives a straightforward result; when the damages are lowered, the reductions in the demand for oil (which also lowers the CO_2 emissions) become less urgent. Therefore, without these oil reductions, the CO_2 emissions will increase again. In the former case, with high damages, the gas fired powerplants will have to be replaced, in the next 20 years. At first, the only relevant option for electric markets is COAL-N, with relatively high emission coefficients, and only in the long-term can it be IGCC, with very low emission coefficients. Hence, CO_2 emissions will increase between 2020 and 2030, and reduce beyond 2040.

III Damages SOS based on PPP (SOSP)

The damages of energy security are region-specific, as import dependencies, energy shares, and either oil or gas intensities differ per region. The GDPs in the energy intensity are measured in Market Exchange Rates (MER). Normalising GDP for Purchasing Power Parity (PPP) metrics, implies a lower energy intensity for developing regions, and, thus, a lower incentive to mitigate the damages of a low energy related SOS, for example, in China and India. To explore the relevance of the impact of this assumption, the base case MER relations were transformed into ones expressed in PPP, using the relation (as in Manne and Richels, 2003):

$$PPP_{t,r} / Y_{t,r} = 1 + 1.25 \left(\frac{P_{t,r}}{Y_{t,r}} \right) \tag{9}$$

This equation implies that the oil and gas intensity will be considerably lower for all developing regions, and, therefore, the oil control options will remain to be dominated by the rich northern countries. The poor southern energy importing countries will act on control policies at higher income levels, but, in that case, the problem of oil-dependency would be less prevalent, as energy intensities will reduce over time, anyhow. This explains why the alternative does not create any significant changes in the simulations.

IV Climate sensitivity, high (CSEH) or low (CSEL)

One of the most speculative parameters in analysing GCC is climate sensitivity. It refers to the long-term global average temperature increase, corresponding to a doubling in the atmospheric concentration of CO_2, with respect to pre-industrial levels. Under a given climate change control target, this parameter is among the main determinants for widespread CO_2 emission reduction levels (see, for example, van der Zwaan and Gerlagh, 2006). In the base case, the climate sensitivity is fixed at a 2.5°C. If the climate sensitivity is lowered (or raised), so will the damages incurred by CO_2 emissions. This, in turn, will call for less (or more) climate mitigation efforts, and, correspondingly, achieve less (or more) reductions in the demand for oil and gas, at the global level, and CO_2 emission reductions, in OECD Europe. Moreover, more (or less) urgency of the GCC problem, caused by a higher (or lower) climate sensitivity, will also generate a larger (or smaller) reduction in the demand for oil and gas.

V VSL high (VSLH) or low (VSLL)

Assumptions, with regard to VSL, are key to cost-benefit analyses. In CAFE, a VSL of US$ 1.06 mln is assumed as a base case (Holland et al., 2005). This source reports a VOLY of US$ 57,300, which is multiplied by the presumed value of 10 for YOLL, as a result of chronic exposure to $PM_{2.5}$ in Europe (Pope et al., 2002). For the VSL sensitivity exercise, the resulting VOLY-based figure is adopted, as lower bound. The upper bound is US$ 2.1 mln, corresponding with the estimate for VSL in the USA (US-EPA, 1999). With these lower (or higher) values for VSL, there is reason to spend less (or more) on PM emissions abatement, so that more (or less) can be spent on energy related SOS damages. This entails more (or less) resources at the global level for CO_2 emission reduction, and correspondingly there will be more (or less) demand for fossil resources. OECD Europe's CO_2 emissions will hardly be affected, because most of the PM emission abatement already occurs in the base case.

VI Prescriptive discounting (PRES)

In all the sensitivity scenarios, the avoided damages (or benefits) from GCC policy are found to be significantly smaller than those from LAP and/or energy related SOS policy. This is due to the fact that GCC is intrinsically a long-term problem: both climate damages and the effects of climate change mitigation manifest themselves only in the long-term. Therefore, they are discounted accordingly, at a rate that determines the present-day valuation of these impacts. The consequences of two opposing views were explored, with respect to the subject of discounting. The utility discount factor *u* in equation (2), equals the difference between the Marginal Productivity of Capital (MPC), and the per capita growth rate of GDP. In the base case, a descriptive view of discounting is adopted, with an MPC of 5 % in 2000, that declines linearly to 3.5 % in 2150 (see Manne, 1995). For the prescriptive case, a value of 0 for MPC is assumed, throughout the entire modelling horizon. Switching to this prescriptive approach, enhances the importance of long-term GCC damages, and, thus, magnifies climate change mitigation, which is confirmed by the PRES-bar in Figure 5.1. OECD Europe will almost halve its emissions, compared to the 1990 emission level. At the global level, the reduction of the cumulative demand for oil and gas, over the entire time horizon, is reduced by a low percentage, compared to the benchmark case. The reason for this is that the prescriptive base case (with policies reducing LAP and lowering GCC) already entails a high reduction of fossil energy. Switching away from the remaining (low) demand for oil and gas will turn out to be rather costly, and will, therefore, occur only to a limited extent.

VII Weitzmann discounting (WEITZ)

Just like the previous sensitivity case, an alternative discounting method can be assessed on its'consequences. The utility discount factor *u* in equation (2), equals the difference between the Marginal Productivity of Capital (MPC), and the per capita growth rate of GDP. In the base case, a descriptive view of discounting is adopted, with an MPC of 5 % in 2000, that declines linearly to 3.5 % in 2150 (see Manne, 1995). For the prescriptive case, a value of 0 for MPC is assumed, and for the WEITZ case a declining discount rate is assumed, i.e. 4% in 2000, linearly declining to 2% in 2100, and 1% beyond 2100. This case is less extreme than the previous case. Switching to this WEITZ case, also enhances the importance of long-term GCC damages, and, thus, magnifies climate change mitigation, which is confirmed by the WEITZ-bar in Figure 5.1. OECD Europe will reduce its emissions by 21%, compared to the 1990 emission level. At the global level, the reduction of the cumulative demand for oil and gas, over the entire time horizon, is increased to zero, compared to the benchmark case. The reason for this is that the WEITZ case (with policies reducing LAP and lowering GCC) already entails a moderate reduction of fossil energy.

VIII VSL dependence on GDP expressed in PPP (VSLP)

The value of VSL is region-specific, because premature deaths are valued less in low-income countries than in wealthier countries. For the year 2000, all regional VSL values are obtained through normalisation on the basis of GDP per capita, relative to that in OECD Europe, which, in turn, is measured in Market Exchange Rates (MER). Normalising instead with GDP per capita values, expressed in terms of Purchasing Power Parity (PPP), would imply a higher VSL for developing regions, and, thus, a larger incentive to mitigate LAP in, for instance, China and India. To explore the relevance of these VSL assumptions, the base case MER relations were transformed into ones expressed in PPP, then applied to equation 4, using the relation (as in Manne and Richels, 2003):

$$PPP_{t,r} / Y_{t,r} = 1 + 1.25 \left(\frac{P_{t,r}}{Y_{t,r}} \right) \tag{10}$$

This equation implies that, for all developing regions, VSL is increased considerably, therefore, energy importing countries will drop their demand for oil. Energy exporters will increase their use of fossil energy. Consequently, energy importing countries will reduce more CO2 emissions, to attain the same reduction in damages of GCC, as reported for the benchmark case.

IX Penalty functions restricted to EU

The penalty functions of all other regions are calibrated to the situation in OECD Europe. Figure 5.1 shows, that there are considerable regional penalty values, especially in India and Rest-Of-the-World (ROW). If, alternatively, it is assumed that only OECD Europe will implement measures to reduce the potential adverse effects of a low energy related SOS, then the impact on global oil markets will be smaller, although still surprisingly large, as prices at the global level are unaffected, compared to the shock in the base case. Moreover, the CO_2 emission reduction will increase, as international prices for gas and oil decrease. In Europe, there will be a larger incentive to switch away from these energy carriers, which are the major source of energy in Europe, and to lower the CO_2 mitigation cost.

6 Conclusions

This report presents a cost–benefit analysis that combines the damages, resulting from global climate change, local air pollution, and the perceived problem of a lack of energy related security of supply. It is demonstrated that MERGE, originally a global welfare optimisation model of the energy-economy-environment system - only capable of investigating climate change policies - can be extended with an analytical expression for the supply-of-energy security. The adapted version of MERGE is used to perform an integrated assessment of the long-term issue of climate change mitigation, the short-term challenges of reducing local air pollution, and a lack of energy security, including the associated costs and benefits, for each. As these problems are driven by present energy production and consumption patterns, they constitute an inseparable trio that should, ideally, be studied together, as this report has tried to argue.

In Europe, in the case of oil, the consumption share (as % of total energy) will rise from 60% in 2000 to 75% in 2020, while the oil intensity in the same period will decline with 1.8%/year. This increasing consumption share and decreasing intensity can be shown to be associated with a disutility equal to 0.1-0.3% of consumption. Other regions may also consider mitigating the potential problems of a low energy security. Especially developing regions, with high energy intensities, are likely to be even more affected by, for example, sudden oil price increases. One of the means of tackling a low energy security, is to shift the applied fuel mix, thereby lowering, for example, the demand for oil. The position of oil exporters is completely different from that of oil importers. Energy exporting countries will be faced with a decline in oil demand, and be left with their ‘cheap’ resource. The oil exporters will, probably, exploit oil themselves, thus partly offsetting the decline in demand by oil importers aiming to increase their energy security. If the energy intensity level of energy-importing economies really is a driving force of energy security policies, then taking a global and long-term perspective, leads to the notion that these policies imply the oil resources to be consumed by the traditional exporters and, probably, also later in time. A delay in the depletion of oil may be expected. However, with a successful climate and air pollution policy, the cumulative demand for oil over the next 150 years, could decline by almost 20% (hence no depletion), due to energy SOS policies. SOS policies magnify the lock-in to non-fossil fuel technologies. Simulations also show, that - in the climate debate - OECD Europe can indeed, to some extent, defend the position of stringent CO_2 emission reductions within its borders, based on arguments by CBA, and if they perceive a sense of urgency of a low energy related SOS.

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Appendix I Properties of the penalty function

In this appendix is evaluated how the penalty function, derived in chapter 3, behaves for various possible settings of the elasticity parameters. For any energy commodity, such as oil or natural gas, the function was proposed to be structured as follows:

$$IMP_{t,r}(i_{t,r} : i_{t,r} > 0) = A_r \left(\frac{i_{t,r}}{i_{0,r}}\right)^{\alpha} \left(\frac{c_{t,r}}{c_{0,r}}\right)^{\beta} \left(\frac{E_{t,r}}{E_{0,r}}\right)^{\gamma} ; IMP_{t,r}(i_{t,r} : i_{t,r} < 0) = 0 \qquad (11)$$

in which:
IMP = willingness-to-pay to avoid a lack in SOS [in % of private consumption],
i = import ratio [in %],
c = he consumption ratio [in %],
E = energy intensity [in PJ per unit of GDP].
In a first approach, one may consider to apply equivalent parameter settings to all contributing factors:
If $\alpha = \beta = \gamma$:
With these settings, and taking oil as an example, the penalty function results in;

$$IMP_{t,r}(i_{t,r} : i_{t,r} > 0) = A_r \left(\frac{oil\ import_{t,r} / GDP_{t,r}}{oil\ import_{0,r} / GDP_{0,r}}\right)^{\alpha} ; IMP_{t,r}(i_{t,r} : i_{t,r} < 0) = 0 \qquad (12)$$

In this set up, several of the contributing factors are no longer relevant to the penalty function. The penalty function merely reflects the evolution of the ratio of oil imports and GDP. The dynamic behaviour of such a set up tends to track the levels of oil imports in early stages, while it predominantly reflects the development of private consumption at later stages. In addition, oil consumption and energy consumption are no longer represented in the penalty function, so that oil conservation and energy conservation are not rendered as an effective strategy to mitigate threads to security of supply.
Accordingly, selecting only the parameters of the import ratio and commodity consumption ratio to have identical parameters, renders oil consumption to be irrelevant. If $\alpha = \beta \neq \gamma$, then the penalty function becomes:

$$IMP_{t,r}(i_{t,r} : i_{t,r} > 0) = A_r \left(\frac{oil\ import_{t,r} / energy\ cons_{t,r}}{oil\ import_{0,r} / energy\ cons_{0,r}}\right)^{\alpha} \left(\frac{E_{t,r}}{E_{0,r}}\right)^{\gamma} ; IMP_{t,r}(i_{t,r} : i_{t,r} < 0) = 0 \qquad (13)$$

and oil consumption is no longer a contributing factor to the penalty function. Of course, oil conservation is, therefore, no longer an effective strategy to mitigate the damage exerted by a lack of security of supply. Finally, comparable reasoning applies, in case the parameterisation of the consumption ratio and the energy intensity is leveled. The parameters would then be restricted to $\alpha \neq \beta = \gamma$, and the penalty function will read as;

$$IMP_{t,r}(i_{t,r} : i_{t,r} > 0) = A_r \left(\frac{i_{t,r}}{i_{0,r}}\right)^{\alpha} \left(\frac{oil\ cons_{t,r} / GDP_{t,r}}{oil\ cons_{0,r} / GDP_{0,r}}\right)^{\beta} ; IMP_{t,r}(i_{t,r} : i_{t,r} < 0) = 0 \qquad (14)$$

In this case, energy consumption is no longer relevant to the penalty function, and mitigation of damages, resulting from lack of SOS, cannot be achieved through energy conservation. Concluding, the parameters of the penalty function should not be equal, because this would render one

or more of the postulated comprising factors of the penalty function as irrelevant. In addition, it is proposed to impose convexity of the penalty in relative commodity imports, commodity consumption and energy consumption, respectively. In other words, the first 10% of imports are assumed to be of less relevance than the last. In other words, $\alpha, \beta, \gamma > 1$
Furthermore is proposed to impose that the penalty increases with commodity imports, commodity consumption and energy consumption. In order to show how this imposition shapes the parameterisation of the penalty function, one may rewrite the penalty function as follows:

$$\begin{aligned}
&\frac{IMP_{t,r}(i_{t,r}, c_{t,r}, E_{t,r})}{A_r (i_{0,r})^{-\alpha} (c_{0,r})^{-\beta} (E_{0,r})^{-\gamma}} = (i_{t,r})^{\alpha} (c_{t,r})^{\beta} (E_{t,r})^{\gamma} \\
&= \left(\left. \frac{oil\ import}{oil\ cons} \right|_{t,r} \right)^{\alpha} \left(\left. \frac{oil\ cons}{energy\ cons} \right|_{t,r} \right)^{\beta} \left(\left. \frac{energy\ cons}{GDP} \right|_{t,r} \right)^{\gamma} \\
&= (oil\ import_{t,r})^{\alpha} (oil\ cons_{t,r})^{\beta-\alpha} (energy\ cons_{t,r})^{\gamma-\beta} (GDP_{t,r})^{-\gamma}
\end{aligned} \tag{15}$$

The imposition of convexity in each of these components, except GDP, suggests $\alpha < \beta < \gamma$. Finally, one should note that private consumption and the penalty function form a recursive loop, so that instabilities may arise. For example, an increase of imports causes a penalty increase, while this reduces consumption, which causes penalty increase, et cetera. Therefore, the dependency of the penalty on private consumption should not be 'too' large, in relation to the average rate of growth of private consumption.

Appendix II Overview of the BAU scenario

Nine world regions are modelled in MERGE: ROW, MOPEC, INDIA, CHINA, EEFSU, CANZ, JAPAN, WEUR, and the USA. ROW (rest of the world) includes all remaining countries, that are excluded from the other eight categories, mostly consist of Africa and South and Central America. The baseline scenario follows Manne and Richels (2004), which has also been used by Energy Modeling Forum 21, see Van Vuuren et al (2006), and Weyant et al (2006). World population is expected to grow from about 6 billion in 2000, to over 9 billion in 2100. Virtually all population growth is assumed to take place in four regions only: China, India, MOPEC, and ROW, while the population in other regions remains roughly stable. Relative population growth is strongest in MOPEC and ROW, which will roughly double their inhabitants during this century.

During the 21st century, GDP cumulated over all regions, that is, gross world product (GWP), will experience a ten-fold increase from the current approximate US$ 40 trillion (2000). By 2100, about two thirds of GWP will be generated by the same four regions, in which most of this century's population growth will take place (China, India, MOPEC, and ROW). The currently developed part of world, today representing some 90% of GWP, will represent about US$ 130 trillion (2000) of the total world economy in 2100.

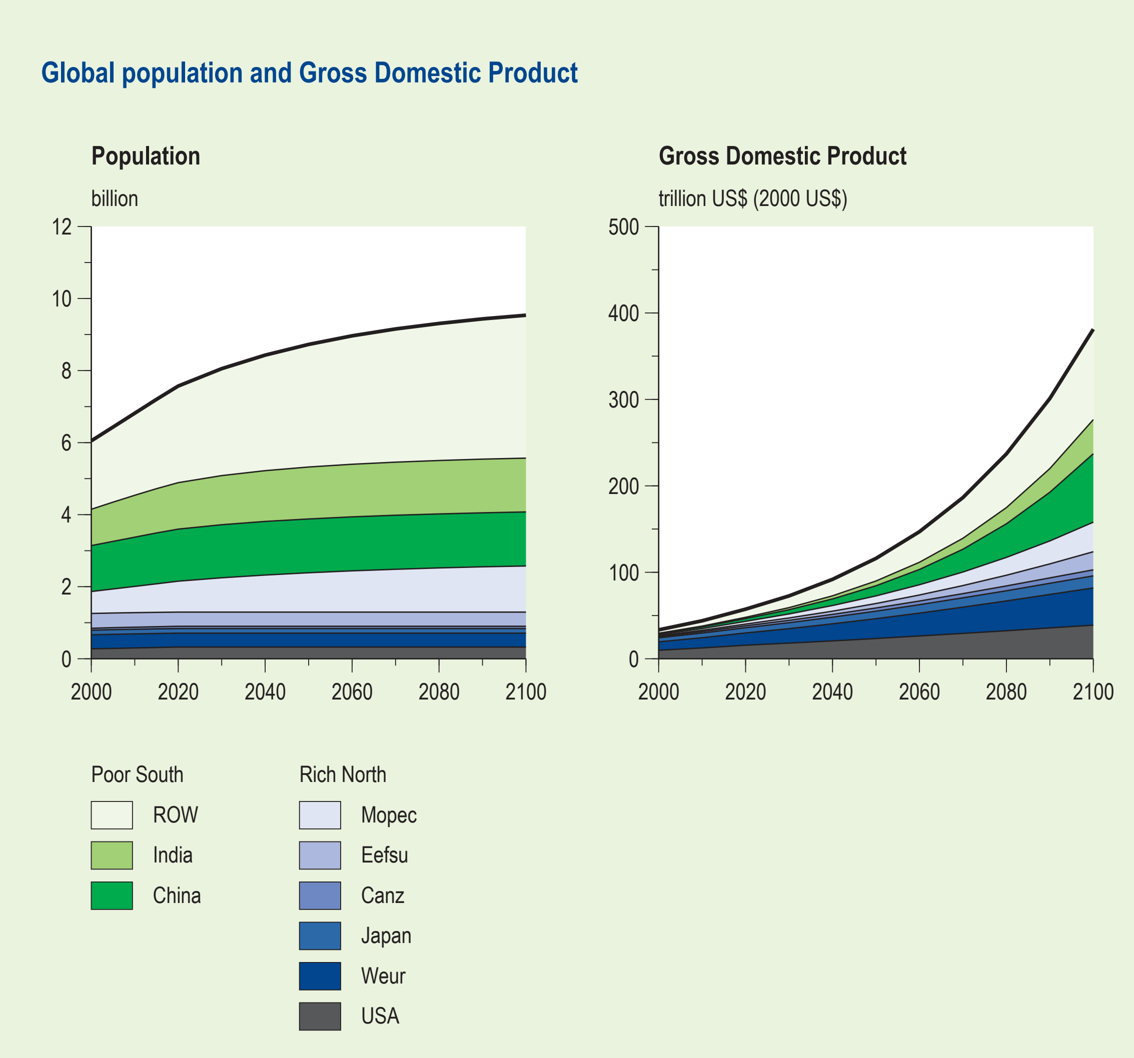

Figure AII.1 Population and GDP in the baseline scenario (billions)

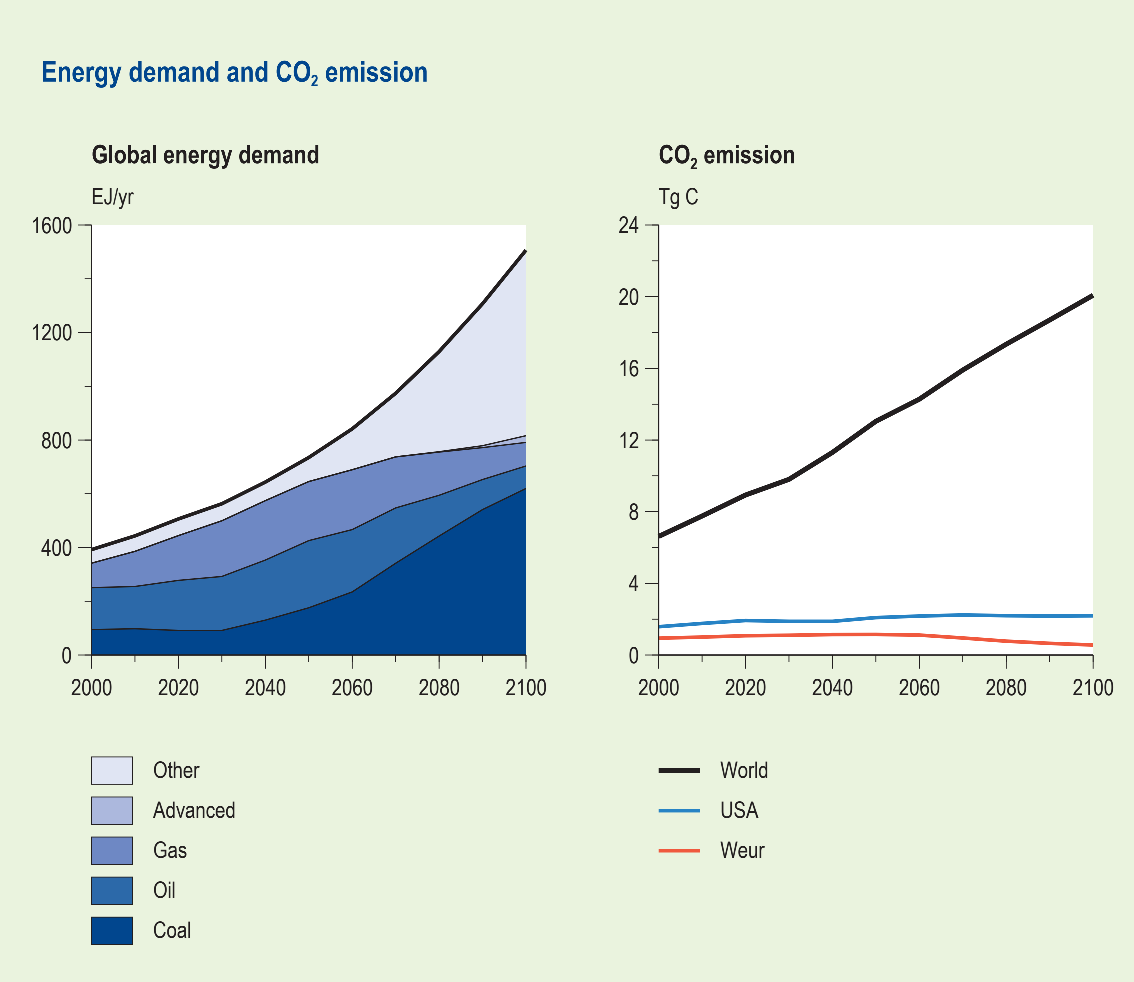

Figure AII.2 Energy mix in the baseline scenario (EJ) and CO$_2$ Emissions in the baseline scenario (Pg C)

In the BAU scenario, it is assumed that global energy consumption more than quadruples, from the present 400 EJ, to close to 1700 EJ per year in 2100. In 2100, more than half of the global energy supply will be provided by non-carbon emitting sources (predominantly renewables and nuclear energy), which, today, only represent 10% of the total primary energy mix. Coal will regain interest from about the middle of the century onwards, accounting for close to 40% of the energy production worldwide in 2100. The remaining 10% of the energy supply will be provided by natural gas and oil, by the end of the century. The baseline scenario is characterised by a steady monotonous increase of carbon dioxide emissions, from about 7 GtC in 2000, to 20 GtC in 2100. The USA will increase its emissions, from about 1.5 GtC in 2000, to 2.2 GtC in 2100, while it is assumed that WEUR manages to set in motion a decrease in emissions, from about 1.0 GtC, down to 0.6 GtC, during this time frame. The global average temperature increase, today, with respect to pre-industrialisation, amounts to about 0.8 C. The carbon dioxide emissions increase, expected over the 21st century, will lead to this 0.8 C increase augmenting to over 3 C, by the year 2100.

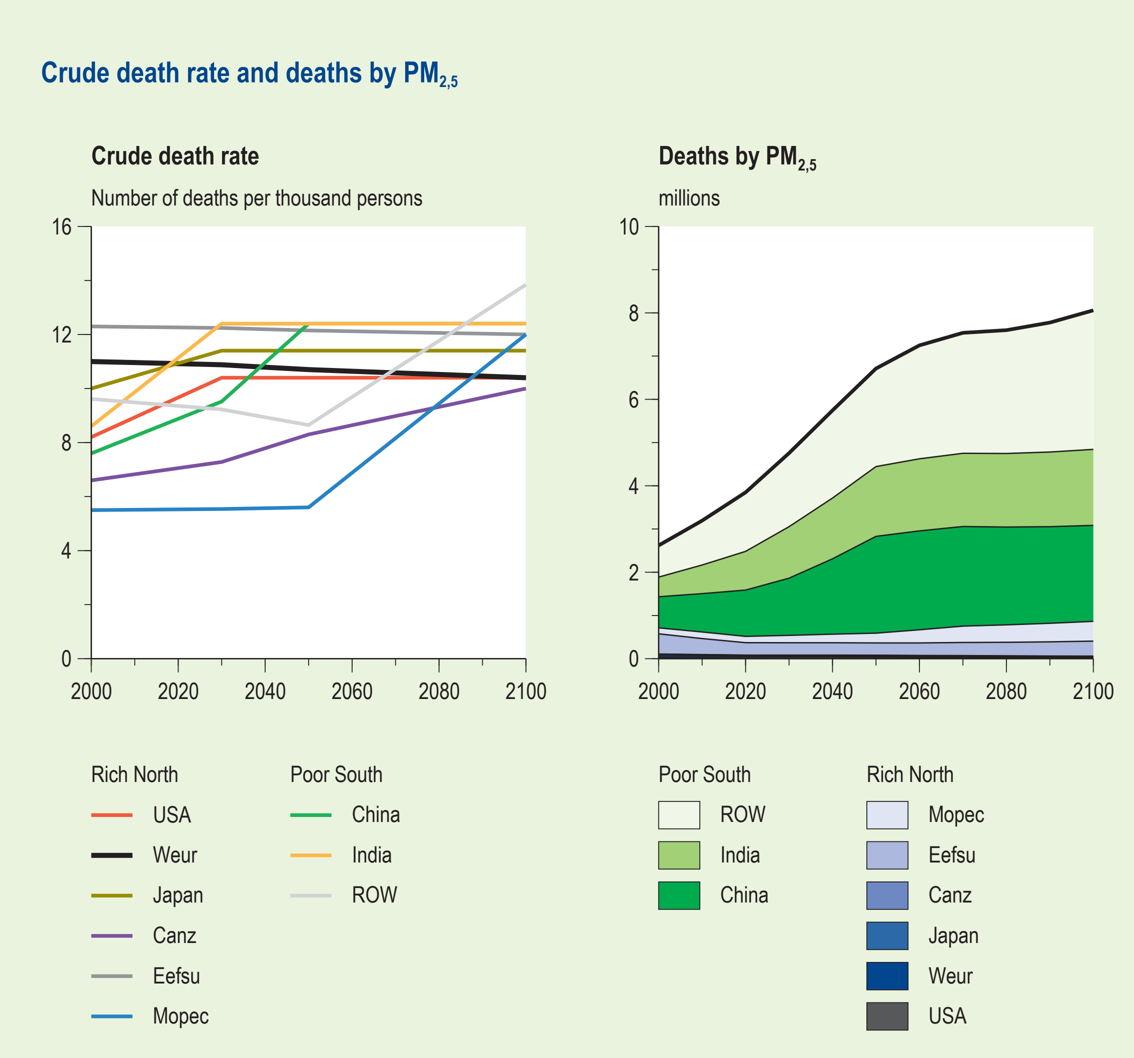

Figure AII.3 Crude death rates (# per thousand of people) and number of deaths from long-term exposure to $PM_{2.5}$ in the baseline scenario

As a result of PM_{10} emissions, the number of deaths, currently expected from long-term exposure to energy related particulate matter, amounts to some 2 million worldwide. This number is likely to increase to over 5 million, by 2100. $PM_{2.5}$-related deaths in the developed world (USA, WEUR, CANZ, and EEFSU) are assumed to slowly decrease, during the century. The vast majority of the total absolute number of $PM_{2.5}$-induced deaths in 2100, are incurred in China and India, and, to a lesser extent (given their lower populations), in ROW and MOPEC. The crude expected death rate for China and India, as a result of PM10 emissions, is around 12 (per thousand people), during essentially all of the 21st century. Initially, MOPEC and ROW will have substantially lower death rates, but by the end of the century they will have increased to a similar level as that of China and India. For much of the developed world the $PM_{2.5}$ death rate hovers, typically, between 10 and 11.