SCENARIOS FOR BIOFUELS IN THE ROAD TRANSPORT SECTOR - ENVIRONMENTAL AND WELFARE ECONOMIC CONSEQUENCES

Synthesis report from the REBECa project

Scientific Report from DCE – Danish Centre for Environment and Energy No.46 2013

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Abstract: The project, Renewable energy in the transport sector using biofuel as energy carrier (REBECa), aimed to investigate the potentials for providing biofuels for the road transport sector based on domestically cultivated bioenergy crops, and to analyse the consequences for air quality, land use, GHG emission and welfare economy. Moreover, a review of international perspectives on sustainability of biofuels was carried out. Different scenarios for the introduction of biofuels were developed – one aiming at 10 % share of biofuels in 2020, and another aiming at 25 % share in 2030. A forecast of the road transport until 2030 was produced and ensuing energy demand modelled. Estimates of the resulting demand for biomass, based on wheat grain, straw and rape, were introduced in agricultural scenarios of production and land use, and the possibilities for responding to the biomass requirements were analysed. Well-to-wheel emissions to air were calculated and impacts on air quality and health hazard investigated. Welfare economic effects corresponding to the well-to-wheel analytical framework were analysed. Results show that changes in air emissions (apart from CO_2) resulting from substitution of fossil fuel with biofuel were small, due to the general reduction of air emissions owing to EU policy implementation and technological development. The provision of sufficient home-grown bioenergy crops would at some stage influence the production of fodder. The overall results for fossil fuel reductions, CO_2 emissions and the welfare economic costs using rape, wheat grain and straw as bioenergy crops, may point in opposite directions for the different fuels. While the largest gains in fossil fuel saving is related to the Rape Methyl Ester (RME) production chain, the welfare economic benefits show the largest positive results for 2nd generation biofuel. Results are highly dependent on decisions related to the analysis of co-products, and the prices of oil and wheat.

Keywords: Biofuel, renewable energy, scenarios, road transport, emissions, air quality, bioenergy crops, land use, welfare economy, LCA

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Preface

This report describes the main results from the project (Renewable Energy in the transport Sector using Biofuels as Energy carrier), which was conducted in the period from 2007 to 2011. The project investigated the potentials and environmental and welfare economic consequences of aiming for self-sufficiency in biomass production for conversion to biofuels. Two scenarios were analysed. One in which a biofuel share of 10 % in the fuel mixture are reached in 2020, and another, where the biofuel share reaches 25 % in 2030. Moreover, the scenarios were conducted based on oil prices of 65 $ and 100 € per barrel respectively.

The report includes an executive summary for decision makers, while the main body of the report summarises the different parts of the integrated analysis mainly for the expert society.

The project partners were:

ENVS-AU: Department of Environmental Science (formerly Department of Policy Analysis, and Department of Atmospheric Environment, National Environmental Research Institute), Aarhus University.

DTU-Transport: Department of Transport, Technical University of Denmark.

ESYS, DTU-Risø: Systems Analysis Division, National Laboratory for Sustainable Energy, Technical University of Denmark.

Institute of Public Health, Department of Occupational and Environmental Health, University of Copenhagen.

Danish Technological Institute.

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The project was followed by an Advisory Panel to whom the progress and results were presented yearly at a one-day seminar. Many thanks are extended to the group for valuable comments and advise. The panel members participating in one or more meetings were:

Bo R. Larsen, Joint Research Centre, ISPRA, European Commission
Charles Nielsen, Kim Winther & Helle Juncker, DONG Energy
Christian van Maarschalkerweerd & Jesper Stubkjær, Danish Environmental Protection Agency
Henrik Wenzel, Institute of Chemical Engineering, Biotechnology and Environmental Technology, University of Southern Denmark
Jørgen E. Olesen, Department of Agroecology, Aarhus University
Michael M. Jensen, Danish Petroleum Industry Association
Peder Jensen, European Environment Agency
Peter Trier & Carsten Poulsen, Danish Energy Agency

Sammenfatning

"Renewable energy in the transport sector – using biofuels as energy carrier" (REBECa) er et integreret projekt som blev udført i perioden fra 2007 til 2011. Projektet var designet på baggrund af den politiske beslutning i EU om at opnå anvendelse af 5,75 % biobrændstof i transport sektoren fra 2010. Den samfundsmæssige kontekst for denne beslutning udviklede sig imidlertid hastigt i denne periode. Oliepriserne steg voldsomt i 2008 og fluktuerede derefter med en generelt stigende tendens. Den økonomiske krise slog igennem globalt og i Europa, og knaphed på fossile energiressourcer såvel som andre ressourcer blev sat på den politiske dagsorden. EU vedtog et direktiv om vedvarende energi i 2009, som satte mål for andelen af vedvarende energi i energiforbruget i 2020, herunder et mål på 10 % for transportsektoren. På baggrund af en løbende diskussion om bæredygtigheden af biobrændstoffer, indeholdt direktivet kriterier for bæredygtigheden af disse. For projektet betød disse omstillingsdagsordener at tilpasninger i projektet blev nødvendige, og herunder blev et alternativ scenarie med højere oliepriser udarbejdet. Projektet var designet til at undersøge mulighederne for at forsyne transportsektoren med biobrændstof produceret indenlands og de nationale miljø-, sundheds- og velfærdsøkonomiske konsekvenser af en sådan produktion. I forlængelse af diskussionen af de konsekvenser der kunne opstå i andre lande af biobrændstofproduktionen blev et mindre review af international perspektiver på dette udarbejdet.

To scenarier for introduktionen af biobrændstof blev udarbejdet – et konservativt, som fulgte EU's målsætninger for andelen af vedvarende energi i transportsektoren, som var 10 % i 2020, og efterfølgende at bevare dette niveau til 2030, samt et mere ambitiøst scenarie, der øgede andelen lineært til 25 % i 2030. Bioethanol og biodiesel blev valgt som de anvendte brændstoffer og de respektive andele blev antaget at være ens. Herudover blev det antaget at væksten i bioethanol løbende blev overtaget af 2. generations bioethanol, mens andelen af 1. generations bioethanol vedvarende lå på ca. 5 %. Fremskrivninger af vejtrafikken til 2030 blev udarbejdet – først baseret på en oliepris på 65$ pr tønde og senere blev en variant med 100$ pr tønde udarbejdet. De resulterende energibehov for de fire scenarier blev beregnet og efterfølgende andelen af biobrændstof og det resulterende arealbehov, baseret på den aktuelle produktivitet i landbruget. Emissionsændringer som følge af fremskrivningerne af transporten blev analyseret og sammenlignet med en reference uden biobrændstof, og efterspørgselen på arealer blev undersøgt under forskellige scenarier for udviklingen i landbruget. En udvidet well-to-wheel-analyse og en velfærdsøkonomisk analyse af produktionen af biobrændstof relativt til produktion af fossil brændstof blev gennemført i den samme analyseramme, hvilket tillader sammenligninger af scenariernes konsekvenser for emissioner, energiforbrug og velfærdsøkonomi.

Projektets resultater viste at ændringer i emissionsfaktorer som funktion af biobrændstof til fossilt brændstof ratioen varierede, både i forhold til brændstof-, køretøjs- og emissionstype. Ændringerne i absolutte emissioner (NO_x, VOC, CO, PM) mellem reference og biobrændstofscenariet viste sig imidlertid at være små i forhold til det generelle fald i emission som kan forventes som konsekvens af de allerede vedtagene emissionsnormer i EU. Derfor viser resultaterne ingen betydelige ændringer i luftkvaliteten som konsekvens af introduktionen af biobrændstof. Supplerende målinger på forskellige typer af motorer og efterfølgende studier af farligheden af de emitterede partikler for processer i forskellige celletyper viste, at skønt forskelle mellem partikler fra biobrændstof og fossil brændstof kunne påvises til fordel for biobrændstof, synes der at være en betydeligt større effekt af anvendelsen af partikelfiltre for eksponeringen for partikelforurening.

Landbrugsscenarierne viste at landbrugsarealet må forventes at indskrænkes i perioden, på grund af by- og infrastrukturel udvikling og ændringer i arealanvendelsen med henblik på beskyttelse af natur og miljø (f.eks. gennem skovrejsning eller udtagning af landbrugsjord). Dette betyder at muligheden for at dyrke de bioenergiafgrøder som antages i scenariet (raps, hvede og halm) er begrænset under de nuværende landbrugsstrategier. Afgrøder dyrket til det globale marked kan substitueres, men konkurrence med indenlandsk producerede afgrøder til foderkoncentrat vil opstå allerede i 2012-2013 i scenariet med lav oliepris og lav indfasning – en situation, som måske nok kan udskydes nogle år gennem øget produktivitet eller lavere brændstofefterspørgsel, men som uafvendeligt vil lede til øget import af enten biobrændstof, bioenergiafgrøder til raffinering eller fodermidler. Disse muligheder vil alle øge behovet for intelligente bæredygtighedsskemaer.

Sammenligningen af energiforbrug, emissioner og velfærdsøkonomiske omkostninger blev kun beregnet for den aktuelle situation, og er baseret på et estimat af produktionen af et kilo biobrændstof relativt til et kilo fossil brændstof. Resultaterne vises i tabellen nedenfor.

S.1 Sammenligning af energiforbrug, emissioner og velfærdsøkonomiske omkostninger beregnet for den aktuelle situation.

	RME*	1st gen. Bioethanol	2nd gen. Bioethanol
Fossil energy consumption (MJ/MJ)	- 54 %	- 49 %	- 37 %
CO_2 equivalent emissions (kg/kg)	- 49 %	- 46 %	- 33 %
Welfare economic net-benefits (€ pr kg biofuel)	-0.35	-0.14	+ 0.16

Note: Baseret på et estimat af produktionen af et kilo biobrændstof relativt til et kilo fossil brændstof. *) RME er Raps Methyl Ester.

Tabellen viser at resultaterne for forbruget af fossil energi og drivhusgasemissionerne i forhold til de velfærdsøkonomiske konsekvenser er modsatrettede. Mens de største gevinster for reduktionen af fossil energi viser sig i Raps Methyl Ester(RME)-produktionskæden, viser de største velfærdsøkonomiske gevinster sig for 2. generations biobrændstof. Dette er afgørende relateret til antagelserne vedrørende sideprodukter og den metode der anvendes til allokering af energi til disse. På den anden side er de velfærdsøkonomiske tab forbundet med RME-produktion stærkt påvirket af den tabte hvedeproduktion. Denne værdi ville til en vis grad ændre sig hvis vi antog at det var afgrøder med en lavere værdi, der blev substitueret. Prisen på olie og halm er også afgørende for resultaterne, hvilket illustreres ved at scenariet med høj oliepris ville reducere det velfærdsøkonomske tab betydeligt for RME (til -0.06 € per kg).

Denne analyse har fokuseret på de indenlandske potentialer for produktion af biobrændstoffer og de nationale konsekvenser for miljø, sundhed og velfærdsøkonomi. Givet den høje efterspørgsel efter biodiesel og korresponderende landbrugsarealer i disse scenarier vil konkurrences om jord øges, med konsekvenser for direkte og indirekte arealanvendelsesændringer udenfor landets grænser. Uden denne produktion af raps vil import af biodiesel stadig have sådanne effekter. For at sikre bæredygtigheden af disse ændringer i arealanvendelse som følge af produktionen af bioenergi afgrøder er bæredygtighedskriterier- og skemaer blevet udviklet i EU samt i enkelte lande og organisationer. Et mindre review af international problemstillinger viste, at der stadig er behov for at videreudvikle metoder og viden med henblik på evaluering af bæredygtigheden af biobrændstoffer.

Executive summary

"Renewable energy in the transport sector – using biofuels as energy carrier" (REBECa) was an integrated research project running from 2007 to 2011. While based on the EU policy decision to introduce 5.75 % biofuels in the transport sector from 2010, changes in the societal context took place during the project period. Oil prices soared in 2008 and fluctuated afterwards, but with an upwards tendency. Economic crisis hit the global community and resource scarcity related to oil and other resources rose on the policy agenda. A policy on renewable energy targets for 2020 was adopted by EU in 2009, including a target of 10 % for the transport sector. An on-going debate on the sustainability of biofuel production and use prompted the development of sustainability criteria and schemes for biofuels, and these were implemented in the renewable energy directive. This implied that the project was carried out in a transitional context, and adaptations to this was implemented in terms of a high oil price variant in the scenarios, and a review of international approaches to sustainability schemes.

The aim of the project was to investigate the potentials for providing biofuels for the road transport sector based on domestically cultivated bioenergy crops, and to analyse the Well-to wheel (w-t-w) consequences for air quality, land use, GHG emission and welfare. Based on the international debate on sustainability, a review of international perspectives on biofuels was carried out.

Two scenarios for biofuel introduction were developed – a conservative, following EU renewable energy targets for transport of 10 % in 2020 and keeping this level to 2030, and a more ambitious, with a biofuel share that increases to 25 % in 2030. Bioethanol and biodiesel were selected fuel types, and the respective shares of these were assumed identical. Moreover, it was assumed that the growth in bioethanol use was increasingly provided by 2nd generation bioethanol while 1st generation bioethanol was kept at a 5 % level. Forecasts of the road traffic to 2030 was developed – initially based on an oil price of 65$ per barrel and later including a variant based on 100$ per barrel. Resulting energy demands for the four different scenarios were calculated and translated into biofuel demands, and subsequently land claims. The transport forecasts were analysed for emission changes relative to a reference with no biofuel, and the land claims were investigated in different scenarios for agricultural development. An extended well-to-wheel analysis and a welfare economic analysis were conducted, based on the same analytical framework, allowing for comparisons of scenario consequences for emissions, energy consumption and welfare economic consequences.

The results from the project showed that changes to emission factors relative to the biofuel blend ratio varied according to fuel-, vehicle-, and emission type. The changes in absolute emissions (NO_x, VOC, CO, PM) between the reference and the biofuel scenarios were, however, small compared to the general decrease in emissions expected based on the presently adopted emission norms. Consequently, the results show no significant changes in air quality as a consequence of the biofuel introduction. Supplementary motor combustion and health hazard studies related to different motor technologies (Euro 2 and Euro 4) also added that while differences between biofuel and fossil fuel was detected, and some advantages related to particle emissions could be assigned to biofuel, after-treatment with particle filters seemed a more effective tool for risk reduction, in relation to the effects studied.

The agricultural scenarios showed that the overall size of agricultural land can be expected to decrease, due to urban and infrastructural development and land use changes following environmental goals (afforestation, set-aside for improvement of aquatic quality). This implies that the possibility for cultivating the bioenergy crops selected for the scenarios (rape, wheat and straw) while keeping up present agricultural strategies are limited. Globally marketed food crops can be substituted by cultivation of energy crops for a domestic market, but competition with domestically grown feed concentrates takes place already from 2012, in the low oil price, low biofuel introduction scenario – a situation which may be postponed some years by increases in crop productivity or lower fuel demand (high oil price scenario), but which will inevitably lead to increased import of either biofuel crops, feed concentrates or refined biofuel – all accentuating the need for intelligent sustainability schemes.

The comparison of energy consumption, emissions and welfare economic costs and benefits were only carried out for the present situation, and it is calculated for conversion of one kg biofuel, compared to one kg of fossil fuel, as scenarios to 2030 do not make much sense in a welfare economic context. The results are summarised in the table below.

ES 1 Comparison of energy consumption, emissions and welfare economic costs and benefits carried out for the present situation.

	RME*	1st gen. Bioethanol	2nd gen. Bioethanol
Fossil energy consumption (MJ/MJ)	- 54 %	- 49 %	- 37 %
CO_2 equivalent emissions (kg/kg)	- 49 %	- 46 %	- 33 %
Welfare economic net-benefits (€ pr kg biofuel)	-0.35	-0.14	+ 0.16

Note: calculated for conversion of one kg biofuel, compared to one kg of fossil fuel.
*) RME is Rape Methyl Ester.

The table shows that the overall results on fossil energy substitution and emissions do not follow the direction of the welfare economic costs. While the largest gains in fossil fuel saving is related to the Rape Methyl Ester (RME) production chain, the welfare economic benefits show the largest positive results for 2nd generation biofuel. This is highly dependent on the co-product values and the methods for allocation of energy. On the other hand, the welfare economic losses related to the RME production are heavily influenced by the wheat production lost. This value would to some extent change if it was assumed that rape would substitute lower value crops. Also, the prices on oil and straw are crucial for the results, which can be illustrated by the fact that the scenario with higher oil price (100$ per barrel) would reduce the welfare economic costs (e.g. to +0.06€ per kg for RME).

This analysis has focused on the potentials for domestic production of biofuels and on national consequences of such a production for environment and welfare economic cost and benefits. It is clear that given the high demand for biodiesel in these scenarios, and the corresponding land claim for rape production, this would increase the competition for land, with consequences outside the Danish territory, in terms of direct and indirect land use changes. Without such production, import of biofuels will still have such effects. Ensuring the sustainability of such changes has prompted sustainability schemes to be developed by EU, but also in different national versions. The short review of international issues related to biofuels concludes that the assessments of the sustainability of biofuels are still to some extent based on non-scientific assumptions and political trade-offs, and that both methodology and evidence need to be improved.

1 Introduction to the REBECa project

Senior researcher and project co-ordinator Pia Frederiksen, Department of Environmental Science, Aarhus University.

The research project REBECa – Renewable Energy in the transport sector using Biofuel as Energy Carrier - kicked-off in April 2007, as a collaborative study between Danish research partners. At that time a policy aim to reach 5.75 % of biofuel in the transport energy consumption in 2010 had been agreed at EU level (CEC 2003, CEC 2005). It was followed by suggestions for a 10 % biofuel target for 2020 (CEC 2006), but in the meantime the sustainability of using biofuel for transport was increasingly contested, among other due to arguments on related CO_2 reductions and global perspectives on potential indirect land use changes (e.g. Searchinger 2008; Wang & Haq 2008). Eventually the Renewable Energy Directive was adopted (CEC 2009), containing the aims of EU to derive 20 % of its energy consumption in 2020 from renewable resources. For the transport sector this implied that a target of 10 % for the renewable energy share of the transport energy consumed in 2020 was set, but without specifications to the energy carrier types. The directive stated, however, that biomass for biofuel had to fulfil certain sustainability criteria to be calculated as a contribution to the 10 % target.

In Denmark, political reluctance to develop the biofuel solution prevailed in the early phase, due to the already high share of biomass used in combined heat and power plants, which were again efficient energy producers. This, however, did not solve the transport energy problem, and the Danish Government stroke a broad agreement on energy in 2008, in which targets for biofuels *and other renewable fuel sources* for transport were set to 5.75 % in 2010 and 10 % in 2020, following the EU policy at that time. It was specifically mentioned that supporting measures would be adapted when EU had decided which fuels could be included. The National Action Plan for Renewable Energy in Denmark confirms the 10 % target for the share of renewable energy in the transport sector 2020, based on as well electric vehicles and an expansion of the use of biofuels (Ministry of Climate and Energy, 2010).

In a European context studies of the potential for production of bioenergy in Europe under different criteria for environmental protection had been carried out by the European Environmental Agency (EEA 2006, 2007). The debate on possible negative aspects of biofuel use fuelled by articles and debates in Science on aspects of forest clearance and following possible carbon debt (Fargione, 2008), actualised these concerns and set forth several large EU scenario studies, as well as the development of sustainability certification schemes and criteria.

As a nationally oriented study, REBECa investigated the potentials and environmental and welfare economic Well-to-wheel (w-t-w) consequences of aiming for self-sufficiency in biomass production for conversion to biofuels. The project adopted the Danish policy targets as discussed at the time of project kick-off, and a 10 % share of biofuels reached in 2020 and kept at this level until 2030 were used in the main policy scenario. In an alternative scenario higher targets were set (25 % in 2030), for studying impacts of more ambitious use of biofuels.

Based on forecasts of development in the road transport these targets were translated into energy demand and resulting demand for biofuel, and the possibility and consequences of self-sufficiency in supply were investigated by analysing different agricultural scenarios. Impacts of the main scenarios on land use and emissions to air and soil were analysed, and a combined method for well-to-wheel assessment and welfare economic assessment was developed and used for integrating the results from the sub-analyses. The main results of this integrated chain of analyses are presented in the following chapters. Moreover, different aspects of biofuel production and use, which did not have a direct input to the integrated scenario analyses were studied and are presented in separate boxes.

Looking back, and reflecting on the changes in the policy priorities and the economic and societal context which took place during the project period, it has been a challenge to adapt to changing external economic conditions and political discourses.

The oil price used, for instance, was initially set to 65$ per barrel, using the newly finalised traffic forecast produced for the Danish Infrastructure Commission. Initially set high (the oil price was in 2007 around 55$ per barrel) the basis for the traffic forecast was increasingly discussed among the project partners, and it was decided that a variant of the main scenario should be produced, building on an “extreme” oil price of 100$ per barrel. Reality showed that this extreme quickly became reality. From 2004 to 2010 the oil prices more than doubled from around 40$ per barrel to around 90$, with a peak in 2008 of 140$, and returning again to 65$ with an upwards movement. In 2011 the price was around 115$.

According to the traffic forecast model used, increase in oil prices would to some extent be reflected in a decrease in traffic growth. As will be illustrated in the chapters below, the high oil price variant predicted road traffic around 44000 km in 2010, while the low oil price variant resulted in just below 50000 km in 2010. Statistics from the Danish Road Directorate show a level in 2009 of 46000 km – not far from the high oil price forecast.

The biofuel demand is divided into biodiesel and bioethanol. The share of fuel is assumed the same for the two types, but as diesel based cars are assumed to increase relative to petrol driven cars, this is reflected in increasing share of biodiesel in the biofuel demand, which has consequences for the land use scenarios. Statistics from 2010 show that half of the new cars registered are diesel driven, and while the first target of substituting 5.75 % of the fossil based fuel with biofuel was by Danish law extended from 2010 to 2012, the scenario assumptions on biofuel demand does not seem to be basically challenged by the present development.

2 Biofuel scenario description

Senior researcher Henrik Gudmundsson, DTU Transport, Department of Transport, Technical University of Denmark and Senior researcher Pia Frederiksen, Department of Environmental Science, Aarhus University.

2.1 Purpose

The purpose of the scenario part of the project (Work Package 1) was to form the basis for calculating future needs for biomass based energy and associated land use, and for assessing the environmental and economic consequences, assuming various future levels of biofuel use in the road transport sector.

By using a scenario approach the magnitude of future resource needs and consequences can be investigated and compared for different assumptions about factors such as overall demand for transport fuel, fuel mix in the vehicle fleet, crop feedstock types, biomass conversion technologies, and policy ambitions for the level of biofuel introduction. A main purpose of the scenario work was to identify the key variables, to specify reasonable assumptions for them, and to zoom in on a limited set of plausible scenario alternatives among the many possible ones.

Two overall biofuel scenarios (in addition to a fossil fuel baseline) were defined (HS1 and HS2), differing mainly in the assumed level and profile of biofuel phase-in to replace fossil fuels (gasoline and diesel) in the road transport sector. In addition a limited number of scenario 'variants' were studied, in order to illuminate the significance of assumptions regarding various other variables. The scenario work was to inform and underpin the work to analyse the environmental and economic consequences in detail in subsequent work packages of the project. In the land use study, specific agricultural scenarios were defined for analysis of agricultural consequences of land claims for biomass to biofuel production.

2.2 Methods

Many ways exist for looking at the interactions between biomass and society, and the resources themselves can be considered in terms of units such as weight, volume, energy content, nutrient content, land use requirements, economic value etc., The perspective depends on the purpose and scope of the assessment. Several of these units are required for comprehensive analysis. The biofuel scenario construction adopted a physical approach deriving subsequent steps from the specified share of biofuel in the fuel consumption of road vehicles.

A range of methods were combined to define and produce the scenarios. Key elements in the scenario definition were the following:

- To identify the key variables and connections between them in a systems perspective.
- To define scope and delimitations for the system under consideration (e.g. time horizon for scenarios; alternatives to consider for each variable; adoption of 'well-to-wheel' approach to compare fuels etc.).

- To propose and coordinate assumptions about key characteristics of alternatives for each variable.

The assumptions made were based on literature reviews, studies of historical trends, review of policies, and existing international databases with key figures for well-to-wheel[1] energy use of various fuel types adapted to the situation in Denmark. The emphasis of the scenario construction process was to enable calculations of the consequences of the specified biofuel profiles, not to construct 'optimal' scenarios or similar.

The following scenario factors were identified as potentially significant for the demand for biomass resources and environmental impacts. Resulting delimitations and assumptions for each of them is given below.

- The overall share of biofuel assumed in the fuel system for road transport (see below).
- The future demand for road transport, split into four main vehicle categories and two fuels (see below).
- The distribution and time profile for phasing-in biofuels replacing fossils in the vehicle fleet.
- The types of biofuels assumed to replace fossil fuels (Rape Methyl Ester (RME) for diesel; ethanol for gasoline; 1st and 2nd generation).
- The type of crops used to produce biofuels, as cultivated in Denmark (see below).
- The type and efficiency of technologies assumed to convert harvested crops into biofuel (see below).
- The costs associated with each type of technology and production chain.

Other important assumptions concern the prices of oil and other marketed products, the utilization of biomass residues, the need for auxiliary energy sources; and the way emissions and costs are shared across multiple biomass output. They are described in the following chapters. It was predominantly assumed that all biofuels in the scenarios was produced domestically, in order to assess domestic potential and consequences. However, well-to-wheel energy use data were considered global.

A sequence of analyses and calculations was established connecting these various assumptions to produce the aggregate results.

2.3 Main assumptions

2.3.1 Shares of biofuel

Both biofuel scenarios start from adopting 5.75 % biofuel share for both diesel and gasoline in 2010. In scenario 1, the share gradually rises to 10 % in 2020, at which level it remains stable. In scenario 2, a continuous growth is assumed reaching 20 % in 2025 and 25 % in 2030. The shares are assumed identical for diesel and gasoline and identical across the vehicle categories. Biofuel scenario 1 (HS1) is conservative broadly following adopted European policies. Biofuel scenario 2 (HS2) is more aggressive assuming further policies near a maximum conceivable effort. Figure 2.1 shows the two scenarios.

[1] Well-to-wheel analysis is the specific type of life cycle analysis made for transport fuels.

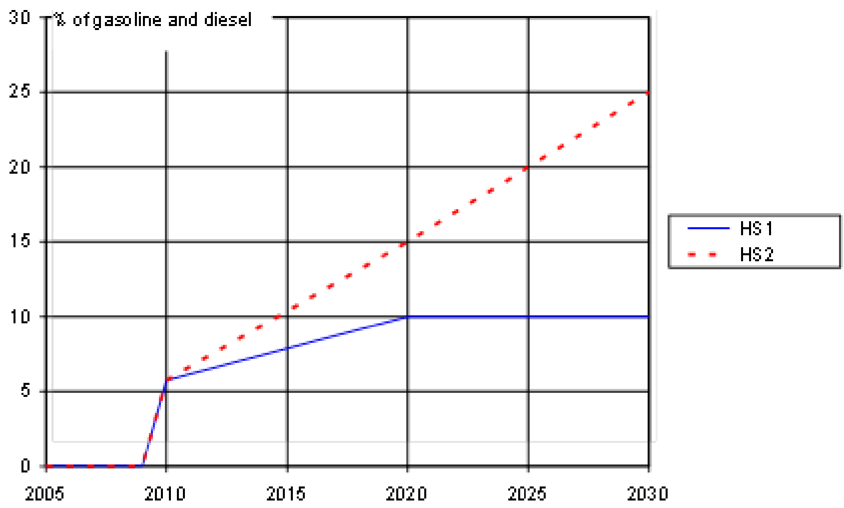


Figure 2.1 The two main scenarios (HS1 and HS2) – biofuel shares.

2.3.2 Demand for road transport

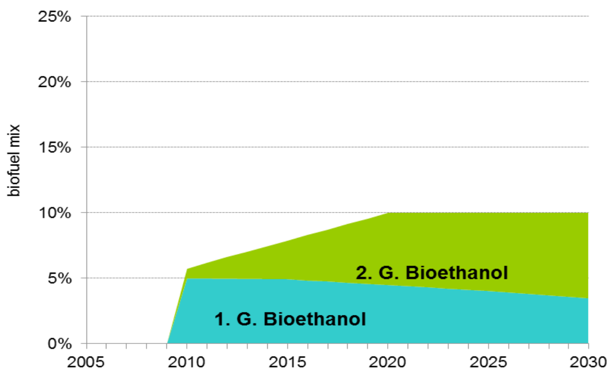
Forecasts with the Danish transport model ART were made for four vehicle categories, passenger cars, light duty trucks, heavy duty trucks and busses. Two alternatives are considered, with different assumptions about oil prices. The traffic forecast is explained in Chapter 3. The future demand for biodiesel and ethanol was rigidly projected from these forecasts. Since diesel car traffic volume is expected to grow more than for gasoline, the resulting 2030 demand for biodiesel would be 20-25 % higher than for bioethanol.

2.3.3 The distribution and time profile for phasing-in biofuels

A number of low blend/high blend/flex fuels can be considered. For biodiesel low blend can be up to 100 %, for ethanol up to 5 %. Generally an increase on high blend vehicles is assumed over time, rather than a gradual increase in the average biofuel content of fuel.

2.3.4 Types of biofuels and crops replacing fossil fuel

For diesel both scenarios assume Rape Methyl Ester (RME) which is a mature technology. For gasoline the replacement is ethanol, based on wheat grain as first generation, with a gradual phase-in of second generation fuel (where ligno-cellulosic parts of the biomass is utilized); based on straw processed in the so-called IBUS technology (Integrated Biomass Utilisation System). The efficiency is here increased through integration of biofuel production with production of electricity. Assumptions concerning second generation introduce additional uncertainty as these technologies only exist in small scale today.



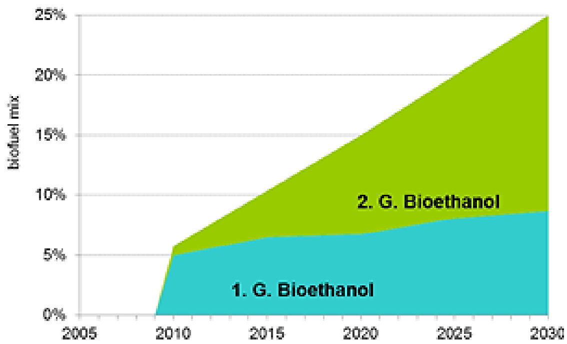


Figure 2.2 & 2.3 Distribution of 1st and 2nd generation bioethanol in HS1 and HS2.

Scenario 1 assumes a slow phase-in of second generation fuel adding to and gradually replacing first generation. Scenario 2 assumes that all new bioethanol phased in from 2010 and onwards is second generation.

2.3.5 Assumptions concerning biomass

The yield of agricultural products is assumed identical in both scenarios. Danish statistical data for 5-year average yield per crop is assumed for wheat and rape seeds. It is also generally assumed that land for cultivation of biofuel crops is obtained by substituting existing cultivated products; it is not replacing biomass assumed for other (stationary) purposes. Conversion of biomass to fuel (in tonne per tonne) is based on standard figures from recent literature for various production chains and conversion facilities, and with or without taking into account by-products.

2.4 Resulting energy and biomass needs

Baseline fossil fuel consumption is calculated on basis of the traffic forecast described in Chapter 3. This forecast (baseline with 0 % biofuel) is produced for two different oil prices, 65$ per barrel and 100$ per barrel, in the report called BAS_65 and BAS_100. The results based on a 65$ oil price are shown in 2.1. Biofuel and biomass requirements for the two biofuel scenarios are shown in 2.2 and 2.3, and the biomass demand to fulfil these requirements is shown in 2.4 and 2.5. Agricultural scenarios analysing the land use consequences of providing this amount of biomass are further analysed in Chapter 7.

Table 2.1 Fuel consumption (TJ) based on traffic forecast and 65$ oil price (BAS_65). (Jensen & Winther, 2009).

	2010	2015	2020	2025	2030
diesel	114.997	133.770	149.047	163.179	176.972
gasoline	63.728	56.529	55.632	56.621	58.379
total	178.725	190.299	204.679	219.800	235.351

Table 2.2 Biofuel requirements (TJ) in HS1.

	2010	2015	2020	2025	2030
biodiesel	6612	10568	14905	16318	17697
ethanol	3664	4466	5563	5662	5838
ethanol 1G	3188	2813	2503	2265	2043
ethanol 2G	476	1652	3060	3397	3795

Table 2.3 Biofuel requirements (TJ) in HS2.

	2010	2015	2020	2025	2030
biodiesel	6612	13912	22357	32636	44243
etanol	3664	5879	8345	11324	14595
ethanol 1G	3188	2822	2754	2831	2919
ethanol 2G	476	3057	5591	8493	11676

For HS1 it is for example calculated that around 24 PJ corresponding to 690.000 tonnes biofuel with the assumptions made will be needed in 2030. For HS2, the requirement of biofuel energy is around one third of the total energy consumption for road transport in Denmark in 2008.

Table 2.4 Biomass requirements (1000 tonnes) in HS1.

	2010	2015	2020	2025	2030
rape	463	740	1043	1142	1239
wheat kernel	426	376	335	303	273
wheat straw	85	295	546	606	677

Table 2.5 Biomass requirements (1000 tonnes) in HS2.

	2010	2015	2020	2025	2030
rape	463	974	1565	2284	3097
wheat kernel	426	377	368	379	390
wheat straw	85	545	997	1515	2082

The amount of biomass needed to fulfil the biomass requirements in the biofuel scenarios raises from around 0.5 million tonne rape in 2010 to 3 million tonnes rape in 2030 for the aggressive scenario HS2, or about five times the present Danish rape production. As shown in Chapter 6, the land needed to fulfil the biomass requirements would amount to around 12 % of the presently cultivated area for HS1 while one third would be needed for HS2, however, without taking limitations in the rotation into account, and given that the straw needed can be extracted from a waste fraction – assuming that the share used for marketed purposes is at the same level as today.

Calculations of well-to-wheel CO_2 and other emissions as well as welfare economic consequences were also performed and are reported in Chapter 7.

In summary, considerable amounts of biomass and cultivated land could be required to sustain a transition towards significantly higher share of biofuels in Denmark in the future, if this was to be supported by domestically cultivated crops. The scenario construction demonstrates the significant number of assumptions that has to be made in connection with such projections, and results are to a large degree the product of specific sets of assumptions with regard to single or multiple land uses, single or integrated conversion technologies, domestic or imported resources etc.

3 The traffic forecast

Researcher Thomas C. Jensen, DTU Transport, Department of Transport, Technical University of Denmark and Senior Adviser Morten Winther, Department of Environmental Science, Aarhus University.

3.1 Purpose

The traffic forecast presented in this chapter is made to form the baseline for the forecast of fuel consumption for road transportation vehicles described in Chapter 4.

3.2 Methods

In order to forecast the mileage driven by private cars and vans, the econometric ART (Aggregate Road Transport) model linking car ownership and mileage to GDP and fuel costs is used. For the total mileage the approximate long term income and fuel price elasticity are 1.06 and -0.6 for private cars and 1 and -0.55 for vans. The forecast of the mileage of heavy vehicles is made on an ad hoc basis: The kilometres driven by busses are assumed to remain constant like in the former 10 years and the kilometres driven by trucks have been assigned an exogenous growth rate based on historical evidence.

Two alternative road traffic forecasts to 2030 have been set up. The first is identical to the "low growth" forecast produced for the Danish Infrastructure Commission in 2007. It is based on a GDP growth of 1.2 % on average (according to a projection from The Danish Ministry of Finance from 2005) and an oil price assumption of approximately 65 $/bl. Truck driving is assumed to grow by 2.15 % a year. This forecast is called BAS_65 (baseline with 0 % biofuel) in the subsequent chapters. The second forecast differs only at two points: The oil price is assumed to remain high at 100 $/bl. which according to ART means less driving in private cars and vans, and truck driving is assumed to grow by only 1.5 % a year (BAS_100).

ART does not directly take into account the development of fuel efficiency of the vehicles in the future. Instead, fuel price - mileage elasticity is incorporated in ART based on the historical development. The omission of fuel efficiency as a direct parameter for mileage projection in ART is justified by observing the following two significant effects from the historical development. First of all, the fuel savings obtained by historical fuel efficiency improvements have partly been neutralised through upsizing of the cars and/or increasing performance. Secondly, the high fuel price-mileage elasticity for private cars and vans in ART means that the rebound effect will be strong: Fuel efficiency improvements would mean lower costs of driving and therefore more driving, to a high degree neutralizing the initial fuel savings.

3.3 Resulting DTU traffic forecast[2]

The resulting average annual growth from 2005 to 2030 in road traffic for all vehicles is 1.4 % in the 65$ scenario and 0.8 % in the 100$ scenario. Both pri-

[2] The traffic forecast developed by the Department of transport, Danish Technical University.

vate cars and vans grow by approximately 1.4 % and 0.8 % respectively in the two scenarios and trucks by approximately 0.7 per cent points more. Figure 3.1 shows the total vehicle kilometre in the two scenarios and Figure 3.2 shows the break-down of the 65$ scenario on the four vehicle types. Figure 3.2 also shows the historical development when available.

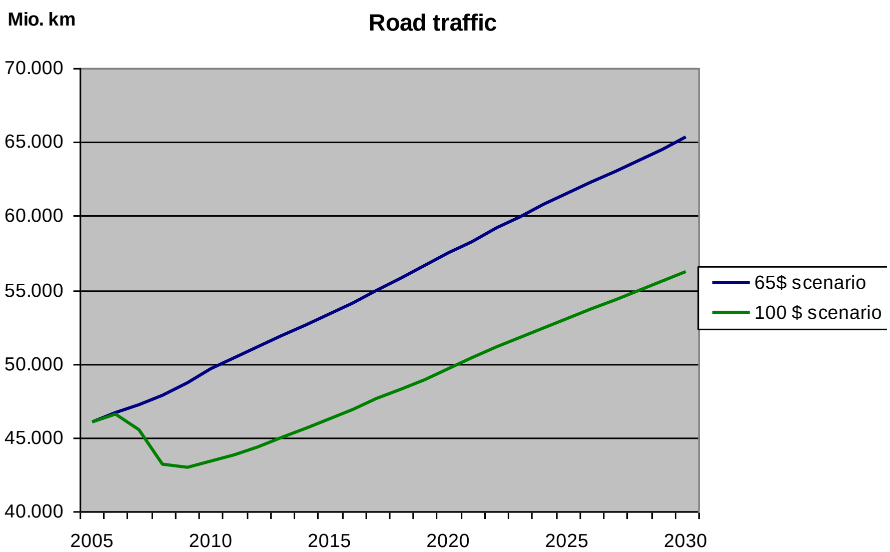


Figure 3.1 Total traffic in the two forecasts.

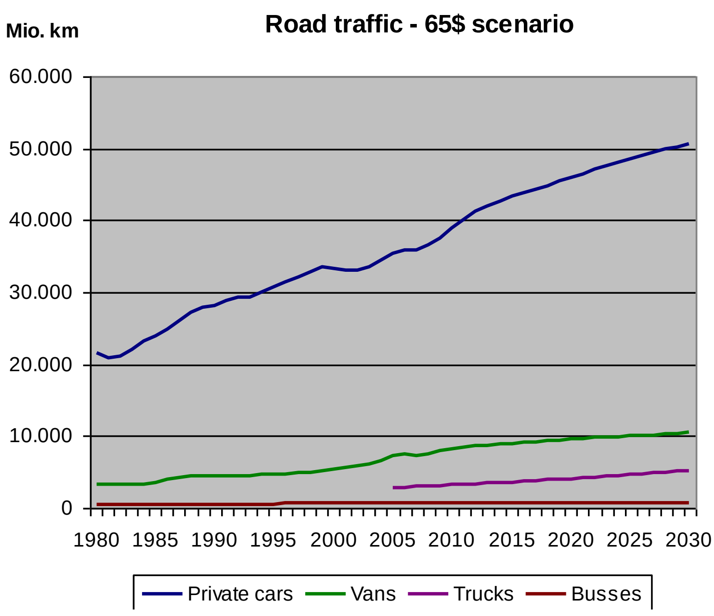


Figure 3.2 Traffic in the 65$ scenario broken down on vehicle types.

The 65$ scenario reflects to a high degree a continuation of the historical development in traffic amounts. The 100$ alternative also displays continued growth but an approximately 15 % lower level.

Of course, such forecasts suffer from large uncertainties originating from both model and assumptions. Likewise, the absence of future fluctuation in the forecast is entirely due to the assumptions. Fluctuations will appear in the future, but they are impossible to forecast accurately.

3.3.1 Traffic forecast split into COPERT layers

In order to make sufficiently detailed fuel consumption and emission estimates in REBECa, the mileage figures must be grouped into vehicles with the same average fuel consumption and emission behaviour; the so-called layers. An internal model developed by the then National Environmental Research Institute (NERI)[3] (Winther, 2008; Nielsen et al., 2009) uses a layer structure and calculation methodology similar to the model structure of the European emission calculation model COPERT. The layer splits are made according to fuel type, engine size/weight class and EU emission legislation levels. Figure 3.3 shows the final layer split of the mileage forecast for the 65$ scenario, aggregated by engine size (cars) and weight class (trucks).

In order to produce the figures shown in Figure 3.3, as a first step the annual mileage figures for the different vehicle types are updated in the NERI model so that for each year (2005+) the adjusted total mileage sum equals the DTU-forecast for cars, vans, trucks and buses, respectively. For the baseline year 2004, the DTU and NERI mileage sum for cars, vans, trucks and buses are based on the official statistics.

In a second step the mileage figures are adjusted so that the calculated gasoline and diesel consumption for 2004 in the NERI model (the sum of the product of annual mileage, vehicle number and fuel consumption factor for each layer, see Chapter 4) equals the statistical fuel sales reported by the Danish Energy Agency (DEA) for 2004[4]. For diesel vehicles the largest uncertainty on mileage driven is regarded for trucks, and hence the decision is to scale the mileage figures for this vehicle type only. In the case of gasoline, the energy balance is achieved by scaling the mileage figures for all gasoline vehicles with the same factor.

[3] Now: Danish Center for Environment and Energy (DCE).

[4] No DEA energy forecast existed which fully integrated the traffic forecast from DTU, and hence the DEA:NERI fuel ratio was used also for 2005+.

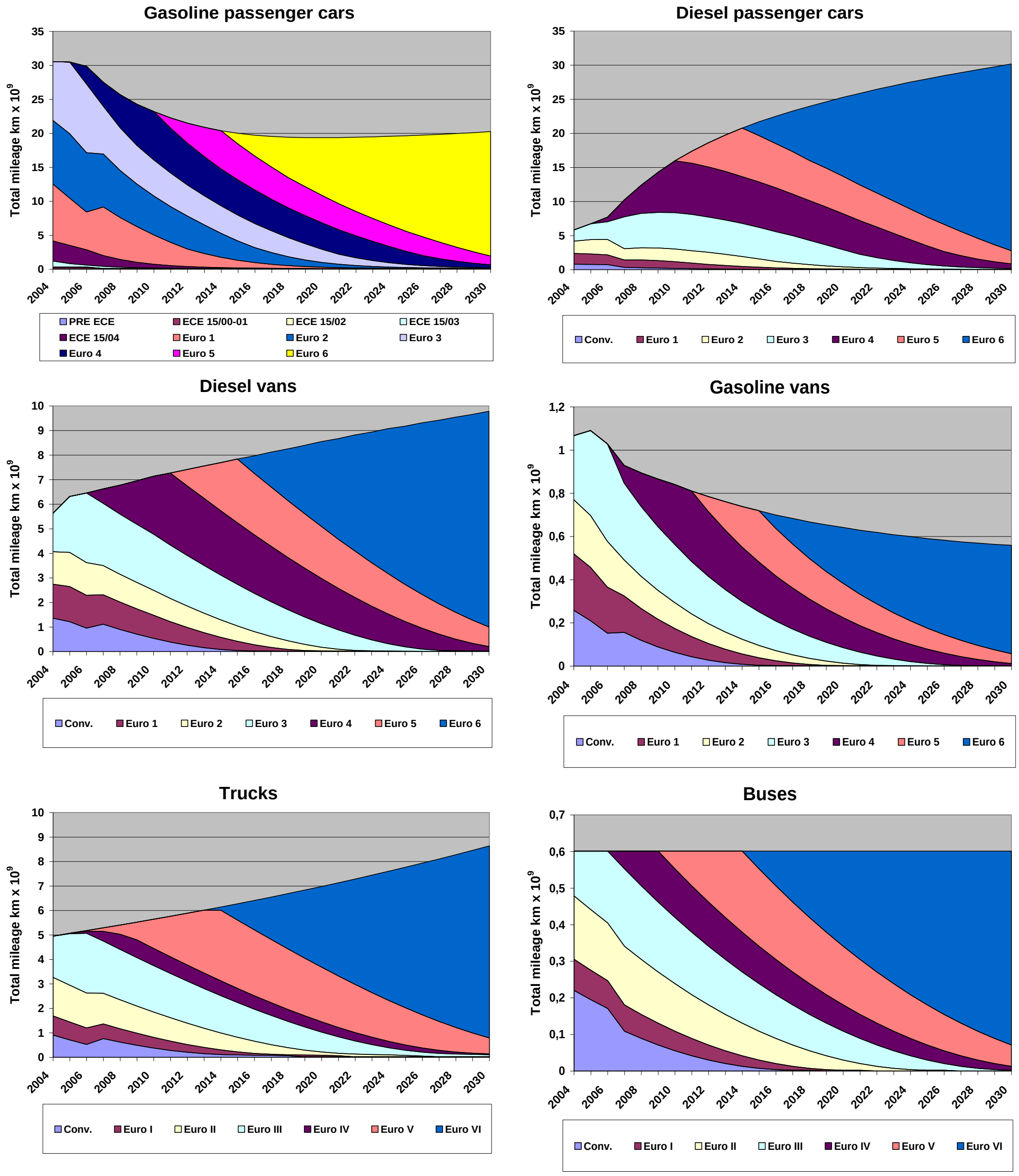


Figure 3.3 Layer distribution of total mileage per vehicle type in 2004-2030 (65$ scenario).

4 Emissions from road transport and their geographical distribution

Senior Adviser Morten Winther, Department of Environmental Science, Aarhus University and Academic Associate Marlene S. Plejdrup, Department of Environmental Science, Aarhus University.

4.1 Purpose

An important task of work package 2 (emission inventories) in REBECa was to estimate the fuel consumption and emissions for the two fossil fuel based forecasts (BAS_65 and BAS_100) for Danish road transport from 2004 to 2030, described in Chapter 3. For each of the forecasts, the two biofuel scenarios are considered with different penetration rates of biodiesel and bioethanol, as described in Chapter 2. For biodiesel full miscibility is assumed, whereas for bioethanol the definition is to add 5 % v/v mix of bioethanol in the standard gasoline fuel (E5), and let the surplus of ethanol available be used by FFV's (Flexible Fuel Vehicles) running on E85 (fuel mix containing 85 % bioethanol).

The purpose of the present chapter is to describe the emission inventory and the calculated results for fuel consumption and the emissions of CO_2, SO_2, NO_x, TSP, CO and VOC. The method is shortly described in terms of fleet model layers, baseline emission factors, biofuel emission difference functions and calculation method. In the results part, baseline emission results are given in time-series for 2004-2030. Further, comparisons are made for the baseline and biofuel scenarios in the discrete scenario years 2010, 2015, 2020, 2025 and 2030 in order to assess the emission impact of biofuel usage. Selected emission results are also displayed on GIS maps for Denmark. An in-depth documentation of all aspects the methodology is also given by Winther (2010a).

4.2 Methods

4.2.1 Fleet model layers

The mileage forecast in the 65$ baseline scenario used in the REBECa project is explained in Chapter 3. This forecast is grouped into vehicles with the same average fuel consumption and emission behaviour as illustrated in Figure 3.3. Table 4.1 shows the fleet disaggregation used in the NERI model.

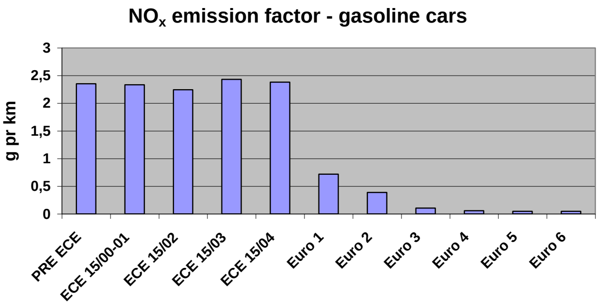
Table 4.1 Model vehicle classes and sub-classes, trip speeds and mileage split.

				Trip speed [km/h]			Mileage split [%]		
Veh. category	Fuel type	Engine size/weight	EU emission levels*	Urban	Rural	Highway	Urban	Rural	Highway
Cars	Gasoline	< 1.4 l.	5 conv.; Euro 1-6	40	70	100	35	46	19
Cars	Gasoline	1.4 – 2 l.	5 conv.; Euro 1-6	40	70	100	35	46	19
Cars	Gasoline	> 2 l.	5 conv.; Euro 1-6	40	70	100	35	46	19
Cars	Diesel	< 2 l.	1 conv.; Euro 1-6	40	70	100	35	46	19
Cars	Diesel	> 2 l.	1 conv.; Euro 1-6	40	70	100	35	46	19
Cars	LPG		1 conv.; Euro 1-6	40	70	100	35	46	19
Cars	2-stroke		1 conv.	40	70	100	35	46	19
Vans	Gasoline		1 conv.; Euro 1-6	40	65	80	35	50	15
Vans	Diesel		1 conv.; Euro 1-6	40	65	80	35	50	15
Trucks	Gasoline		1 conv.	35	60	80	32	47	21
Trucks	Diesel	3.5 – 7.5 tonnes	1 conv.; Euro I-VI	35	60	80	32	47	21
Trucks	Diesel	7.5 – 16 tonnes	1 conv.; Euro I-VI	35	60	80	32	47	21
Trucks	Diesel	16 – 32 tonnes	1 conv.; Euro I-VI	35	60	80	19	45	36
Trucks	Diesel	> 32 tonnes	1 conv.; Euro I-VI	35	60	80	19	45	36
Urban buses	Diesel		1 conv.; Euro I-VI	30	50	70	51	41	8
Coaches	Diesel		1 conv.; Euro I-VI	35	60	80	32	47	21
Mopeds	Gasoline		1 conv.; Euro I-II	30	30	-	81	19	0
Motorcycles	Gasoline	2 stroke	1 conv.	40	70	100	47	39	14
Motorcycles	Gasoline	< 250 cc.	1 conv.; Euro I-III	40	70	100	47	39	14
Motorcycles	Gasoline	250 – 750 cc.	1 conv.; Euro I-III	40	70	100	47	39	14
Motorcycles	Gasoline	> 750 cc.	1 conv.; Euro I-III	40	70	100	47	39	14

* EURO: emission norms, as defined by EU directives.

4.2.2 Basis fuel consumption and emission factors

Figure 4.1 presents the NO_x emission factors as an example for gasoline cars (year 2015, including cold start and catalyst wear) and diesel trucks, also weighted according to mileage per road type.



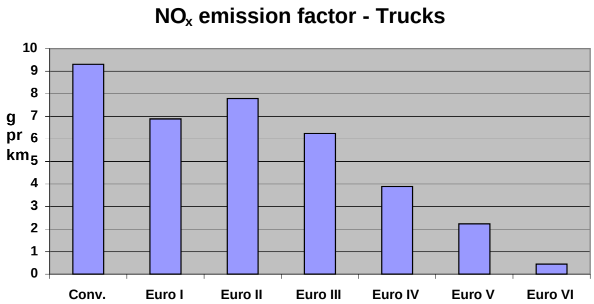


Figure 4.1 Layer specific NO_x emission factors for gasoline cars and diesel trucks using fossil fuels.

4.2.3 Emission factor differences between fossil fuels and biofuels

Biofuel blend in diesel fuel

For Euro 0-III heavy-duty engines the changes in fuel consumption and NO_x, PM, CO and VOC emissions as a function of biodiesel blend, is based on the findings from the US Environment Protection Agency (EPA 2002). The data from the latter source is also used for the future Euro VI engine technology, as assumed by Winther (2009). For Euro IV and V engines, the experimental basis behind the curves is measurement results from McCormick et al. (2005). The fuel consumption and the Euro 0-III/Euro IV-V emission curves for NO_x and PM are shown in Figure 4.2. For 100 % biodiesel, the NO_x *[PM,CO,VOC]*% emission changes for trucks and buses are 10*[-47,-48,-67]* and 30*[-80,-40,-25]*, for Euro 0-3 and Euro 4-5, respectively.

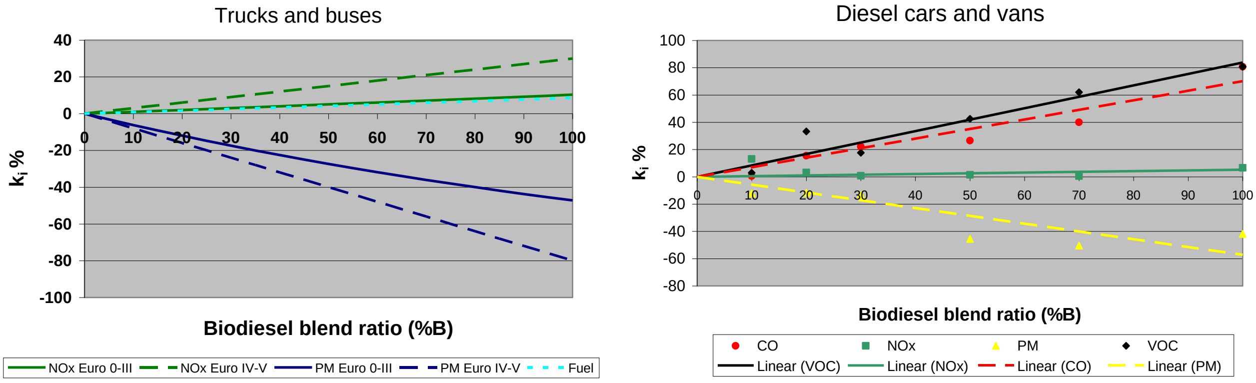


Figure 4.2 Fuel consumption/emission changes as a function of biofuel blend ratio for heavy-duty engines and diesel cars/vans.

In the case of passenger cars and vans, average emission differences for B10, B20, B30, B50, B70 and B100 are calculated based on the results from four experimental studies, see Winther (2009). The emission differences expressed as linear functions are shown in Figure 4.2 for NO_x, CO, VOC and PM. For fuel consumption the relative changes were not derived explicitly for passenger cars and vans, due to lack of data. For these vehicle types, the general relations for heavy-duty vehicles are used instead. This decision is discussed in Winther (2009).

Biofuel blend in gasoline

To characterise the energy consumption and emission factor differences between neat gasoline and E5 and E85, respectively, average differences are calculated from five European studies (three for E5, two for E85), see Winther (2010b). In the experiments using E85 fuels, the base fuel was E5 since in Sweden the baseline fuel quality for petrol is predominantly E5. However, noting the small average differences between neat gasoline and E5 - and due to lack of experimental data for modern European cars using neat gasoline and E85 - the E5 vs. E85 differences are used in REBECa for the neat gasoline vs. E85 case as well. This decision is discussed in more details by Winther (2010b).

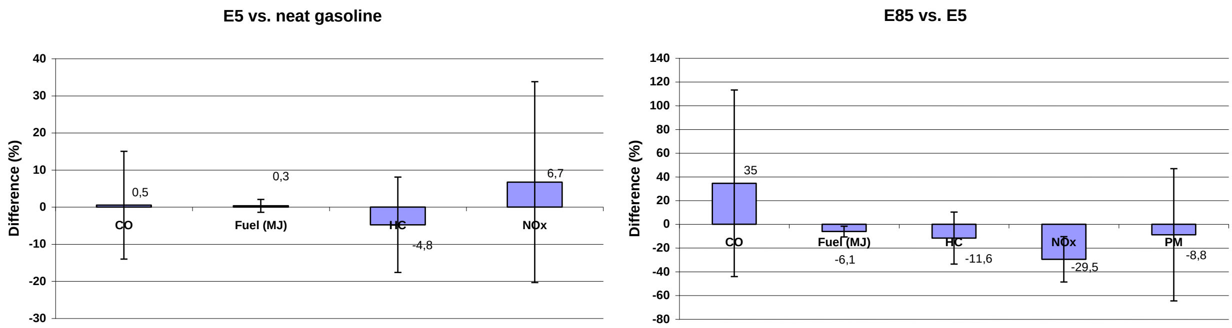


Figure 4.3 Fuel consumption and emission changes for neat gasoline and E5/E85 for gasoline cars and vans.

4.2.4 Calculation method

For each inventory year emission (and fuel consumption) results are calculated pr layer and road type. The procedure is to combine emission factors, emission change functions, number of vehicles, annual mileage levels and the relevant road-type shares:

$$E_{i,j,k,y} = emf_{i,j,k,y} \cdot (100 + k_i(B\%_V))/100 \cdot S_k \cdot N_{j,y} \cdot M_{j,y} \quad (1)$$

E = emission, emf = emission factor, ki = emission change function, i = emission component, y = inventory year, j = layer, S = road type share, k = road type.

For bioethanol it is assumed that in 2010 FFV's (Flexible Fuel Vehicles) that belong to the most modern Euro layer for gasoline cars (Euro 4) uses the amount of ethanol exceeding the amount being used as general E5 blends by traditional gasoline vehicles as such. In 2015 the share of Euro 4 vehicles being FFV's is maintained, hence assuming approximately the same rate of scrapping of vehicles irrespective of technology. Further, the remaining ethanol surplus is assumed to be used by the most modern Euro classes in 2015 (Euro 5 and 6). This stepwise ethanol allocation principle is also used for the years 2020, 2025 and 2030.

4.3 Results

Figure 4.4 shows the calculated results per vehicle category for the 65$ baseline scenario. The fuel consumption and CO_2 emissions increase by 43 % from 2004 to 2030. The relative emission increase is highest for heavy duty vehicles (trucks and buses) and vans, 51 % and 48 %, respectively, due to a larger traffic growth. For NO_x and PM, the emissions decrease by 81 % and 89 %, respectively. The NO_x and PM emissions decrease of 72 % and 83 %, respectively, for cars, are smaller than the total emission decreases; due to a gradually larger share of diesel cars expected in the future vehicle fleet. From 2004 to 2030 the CO and VOC emissions decrease by 82 and 78 %, respectively (not shown).

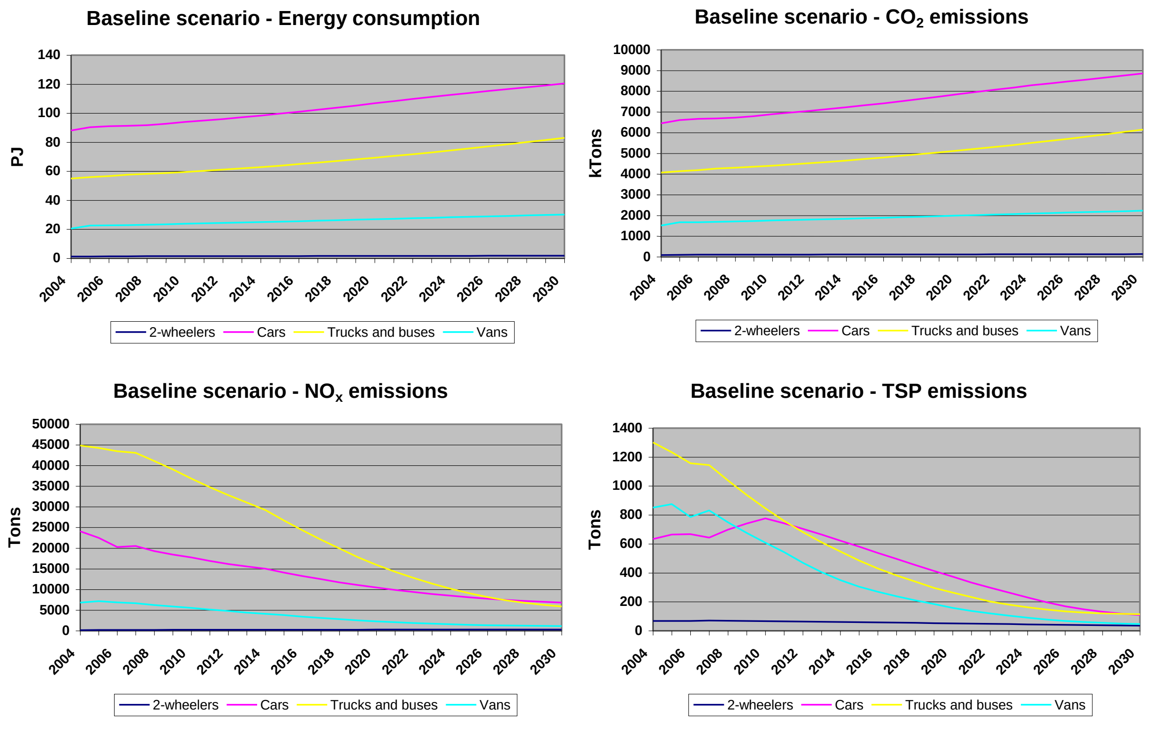


Figure 4.4 Total energy consumption and CO_2, NO_x and TSP emission baseline results pr vehicle type.

The emission consequences of using biofuel in road transport - even at blend ratios up to 25 % - are small. For NO_x and VOC the absolute differences between BAS_65 and the biofuel scenarios are less than 3 % (4.2). For CO and exhaust PM the largest emission differences, 8 % and -13 %, respectively, occur between the baseline and biofuel scenario 2 in 2030, related to a biofuel share of 25 %. However, CO is of less environmental concern and if for PM the emission contribution deriving from non-exhaust is included in a total PM assessment, the emission differences between baseline and biofuel scenarios become considerably smaller.

For the biofuel scenarios the percentage difference in CO_2 emissions between the baseline and biofuel scenarios are inversely proportional to the penetration percentage of biofuels during the forecast period. The reason is that according to conventional inventory guidelines, biofuels are regarded as CO_2 neutral for exhaust emissions (vehicle based emissions).

For CO_2, however, the calculated emission differences cannot be assessed by regarding road transport alone. Being a greenhouse gas, the emission impacts of CO_2 must be seen from a global warming perspective, and hence it is important to examine the full W-t-W system chain for production and use of biofuels. This is further examined in Chapter 8.

Table 4.2 Fuel consumption and emission differences (%) between baseline and biofuel scenario 1 and 2.

		Mileage forecast: 65 $									Mileage forecast: 100 $								
Scen.	Year	En	NO_x	VOC	CO	CO_2	PM	TSP	PM_{10}	$PM_{2.5}$	En	NO_x	VOC	CO	CO_2	PM	TSP	PM_{10}	$PM_{2.5}$
							Exh.	Exh. + Non exh.								Exh.	Exh. + Non exh.		
BS 1	2010	-0,3	1,5	-2,5	0,6	-6	-3,6	-1,6	-2	-2,5	-0,3	1,4	-2,4	0,5	-6	-3,6	-1,6	-2	-2,5
	2015	-0,4	1,5	-1,7	1	-8,3	-4,9	-1,5	-2	-2,8	-0,4	1,5	-1,6	0,9	-8,3	-4,8	-1,5	-2	-2,8
	2020	-0,6	1,6	-0,7	2	-10,5	-6	-1,2	-1,7	-2,5	-0,6	1,6	-0,7	1,9	-10,5	-6	-1,2	-1,7	-2,5
	2025	-0,6	1,5	-0,1	2,6	-10,5	-5,6	-0,7	-1	-1,5	-0,6	1,5	-0,1	2,5	-10,5	-5,6	-0,7	-0,9	-1,5
	2030	-0,6	1,2	0,1	3	-10,5	-5,2	-0,4	-0,6	-1	-0,6	1,2	0,1	2,9	-10,5	-5,1	-0,4	-0,6	-1
BS 2	2010	-0,3	1,5	-2,5	0,6	-6	-3,6	-1,6	-2	-2,5	-0,3	1,4	-2,4	0,5	-6	-3,6	-1,6	-2	-2,5
	2015	-0,6	1,8	-1,7	1,4	-11,1	-6,5	-2,1	-2,7	-3,7	-0,6	1,8	-1,6	1,3	-11,1	-6,5	-2,1	-2,7	-3,7
	2020	-0,9	2,2	-0,4	3,2	-16,2	-9,1	-1,9	-2,6	-3,9	-0,9	2,2	-0,4	3	-16,2	-9,1	-1,9	-2,6	-3,8
	2025	-1,3	2,5	1,1	5,8	-21,2	-11,2	-1,3	-1,9	-3	-1,3	2,5	1	5,5	-21,2	-11,1	-1,3	-1,9	-3
	2030	-1,6	2	2,3	8,3	-26,2	-12,7	-0,9	-1,4	-2,3	-1,6	2	2,2	8	-26,1	-12,4	-0,9	-1,4	-2,3

Figure 4.5 shows the geographical distribution of the NO_x emissions for road transport for the 65$ baseline situation for 2004 and 2030, respectively. The significant emission reductions shown on the GIS maps are due to the gradual introduction of the stronger EU Euro emission standards throughout the time period.

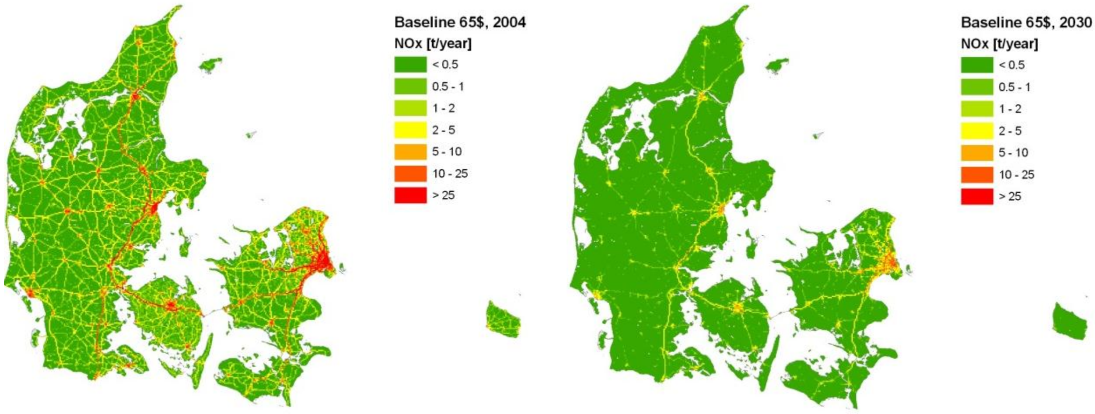


Figure 4.5 Baseline NO_x emissions for road transport in 2004 and 2030.

Significant emission decreases (in brackets) are calculated for NO_x (81 %), PM (89 %), CO (82 %) and VOC (78 %) from 2004-2030 in the 65$ scenario. This is predominantly due to the increasingly strengthened EU emission standards during the forecast period. Even in the most extreme case (biofuel scenario 2 in 2030), only small emission changes due to biofuel usage are expected compared to the baseline estimate. The relative emission changes are less than 3 % for NO_x and VOC, and 8 % and – 13 % for CO and PM, respectively. In absolute numbers these emission changes are very small, due to generally low emission levels by the end of the forecast period.

The trend towards an increase in NO_x emissions for diesel cars has been confirmed by laboratory tests on a single car, as illustrated in Box 2.

Box 1: Emission measurements

Senior scientist Jacob Nøjgaard, Department of Environmental Science, Aarhus University.

Emissions are changing as biodiesels are mixed in fossil diesels for vehicular transport, and this may impact human health and climate. In a static engine setup, the relative changes in gas-phase emissions (CO, CO, NO and NO_2), Volatile Organic Compounds (total VOC and selected organic aldehydes and ketones), particle-phase compounds (Polycyclic Aromatic Hydrocarbons, steranes and hopanes) and particle size, number and mass were measured for different fuels. Light-duty diesel engines included a modern Euro 4 with/without diesel particle filter and an older Euro 2 diesel engine, representative of the modern and older part of the passenger car fleet. Engine emissions were studied under conditions of maximum engine torque and power at different engine loads (25, 50 and 100 %). Changes in emissions were evaluated for 20 % (w/w) Rape seed Methyl Ester and Animal Fat Methyl Ester blends (AFME) relative to a fossil diesel (D_{100}). The samples were provided by The Technological Institute at their facility in Aarhus, and chemical analysis and related data analysis were provided by the Department for Environmental Science, Aarhus University. The experimental studies also provided sample material for Health Effects of Biofuels.

Key-results were: In accordance with most literature, generally higher emissions of NO_X and NO_2 were observed from the Euro 4 engines with and without diesel particle filter (DPF), when fuelled by $AFME_{20}$ and RME_{20} compared to the D_{100}. However, lower emissions were observed for a few choices of engine loads. The effect on NO_x and NO_2 in particular, is noteworthy in the light of the increasing NO_2 concentrations in urban environments. On the other hand, volatile carbonyls and particle-bound polycyclic aromatic hydrocarbons, which include the carcinogenic benzo(a)pyrene, were reduced in the biodiesel blend emissions. While the effect on carbonyl emissions appear to be quite complex, and opposite effects of replacing fossil diesel with biodiesel have been reported, most studies report reduced emissions of PAHs when fuelled by biodiesels. The particle number concentrations from the Euro 4 were reduced at all engine conditions for both biodiesel blends. The calculated particle mass in the range 10-700 nm as well as the geometric mean diameter of the corresponding size distributions were reduced for each of the different driving modes when changing from fossil diesel to biodiesel blend. Particle number concentrations from the Euro 4/DPF were 3-4 orders of magnitude below those of the Euro 4, except during conditions of 100 % load, where the number concentrations increased to levels from two orders of magnitude lower to comparable with the Euro 4 without DPF. In accordance with the majority of the literature, higher particle number concentrations were measured from the Euro 4/DPF at all engine conditions except idle, when fuelled by $AFME_{20}$. However, this was in contrast to the Euro 4 without DPF and suggests a more complicated relationship between biodiesel and ultrafine particles, depending on the actual engine conditions and fuel. Changed emissions will furthermore be of importance for source apportionment studies, which use chemical markers to apportion vehicular sources. Our results show consistent lower emissions of hopanes and steranes from Euro 2 and Euro 4 engines, irrespectively of DPF, fuelled by biodiesel blends.

5 Emissions and air quality

Senior scientist Steen Solvang Jensen, Professor Allan Gross, Senior scientist Matthias Ketzel, Senior adviser Morten Winther, Academic Associate Marlene Plejdrup, Senior scientist Jørgen Brandt and Senior scientist Jesper H. Christensen, all from the Department of Environmental Science, Aarhus University.

5.1 Purpose

The environmental impacts of using biofuels in the road transportation sector is described for the different biofuel scenarios with focus on emissions and its resulting influence on air quality, and the associated external costs of air pollution due to health impacts. The impacts are studied at different geographic scales, from regional to local scale using an interlinked air quality modelling system, and a system for economic valuation of air pollution.

5.2 Methods

5.2.1 Scenarios

This study includes both baseline forecasts (BAS_65 and BAS_100) and the two biofuel scenarios (HS1 and HS2) as described in Chapter 2.

The base year is 2004 and scenario years are: 2010, 2020 and 2030. Due to the combination of different years and different shares of biofuel blends a total of 19 different emission scenarios are included in the study.

5.2.2 Emissions

Firstly, travel demand and fuel consumptions have been forecasted for the different scenarios, as described in Chapter 2 (Jensen &Winther, 2008).

Secondly, the differences for fuel consumption and emission factors for NO_x, CO, VOC and particulate matter (PM) between petroleum-based diesel and various blends of biodiesel have been estimated based on a literature review, as well as differences between petroleum-based gasoline, and E5/ E85 gasoline-bioethanol blends (Winther 2009; 2010b).

Thirdly, based on the forecasted fuel consumptions for the different scenarios and the established fuel consumption and emission differences between fossil fuels and biofuels national emissions for Denmark have been estimated for the road transportation sector using the emission model COPERT IV (Winther & Plejdrup, 2010; Winther 2010a; 2010c).

Fourthly, a model was developed to distribute emissions from the national emission inventories on a 1x1 km grid covering Denmark for emission input into the air quality models (Plejdrup & Gyldenkærne, 2011).

5.2.3 Air Quality and Associated External Costs

On the regional scale, an air chemistry transport model – the Danish Eulerian Hemispheric Model (DEHM) - was used to estimate air quality on a coarse grid that covers the entire area of Denmark (17x17 km^2) and the rest of Europe (Gross et al. 2010; 2011). On the local scale the Greater Copenhagen Area served as a case study area. Urban background concentrations were modelled on a detailed grid (1x1 km^2) with the Urban Background

Model (UBM) and street concentrations were modelled with the Operational Street Pollution Model (OSPM).

For assessment of the external costs of air pollution the EVA system (Economic Valuation of Air pollution) is used. The EVA system is based on the impact pathway methodology and includes the DEHM and UBM models, gridded population data, exposure-response functions for health impact assessment, and monetary valuation of the health impacts. The DEHM model is run in a tagged mode that enables accurate estimation of concentration differences between two scenarios with small differences in emissions (Gross et al. 2010; 2011).

5.3 Results and discussion

5.3.1 Emissions

The combined effect of more travel demand and fuel consumption and more strengthen EU emission standards is an overall decrease in vehicle emissions from the road transportation sector in the future, as described in the chapters 2, 3 and 4.

The literature study on the emission differences between neat diesel/gasoline and biofuels revealed some difference between fuel type and vehicle type (light-duty/heavy-duty). For diesel-powered heavy-duty vehicles fuel consumption and NO_x emissions increased with increasing blends of biodiesel whereas PM, VOC and CO emissions decreased. Diesel-powered light-duty vehicles showed a different picture where VOC and CO emissions increased with increasing blends of biodiesel (NO_x emissions also slightly increased) and PM emissions decreased as for heavy-duty vehicles (Winther, 2009). As an example, a 10 % biodiesel blend reduces $PM_{2.5}$ exhaust emissions by about 5 % and a 20 % blend about 10 % for light-duty vehicles. Similarly, for heavy-duty vehicles $PM_{2.5}$ exhaust emissions are reduced about 7-9 % for a 10 % biodiesel blend and 12-16 % for a 20 % biodiesel blend. For total $PM_{2.5}$ (exhaust and non-exhaust) the reduction will be less as non-exhaust emissions constitute about one third of total PM emissions. Non-exhaust emissions include PM from road wear, tire wear, brake wear and re-suspension. Non-exhaust emissions are proportional to travel demand and hence the fraction non-exhaust/total $PM_{2.5}$ is increasing in the future due to increase in travel demand.

The emission differences between neat gasoline and E5 (5 % bioethanol blend) are on average close to zero, however, with a very high standard deviation. For E5 versus E85 (85 % bioethanol blend) the percentage differences for energy consumption, PM, VOC, NO_x and CO are -6 %, -9 %, -12 %, -30 % and +35 %, respectively. The emission reductions are proportionally lower for bioethanol blends of 10 % and 20 %. The lowest standard deviations are seen for energy consumption and NO_x, and much larger deviations are found for PM and CO. Due to the small difference between neat gasoline and E5 the energy consumption and emission differences between E5 and E85 are used to represent difference between neat gasoline and bioethanol (Winther, 2010b).

The estimated emission differences are the foundation for the calculation of national emissions. As an example the development of national PM emissions are shown in Figure 5.1 since PM is the most important parameter affecting health impacts of air pollution (Gross et al., 2010; 2011).

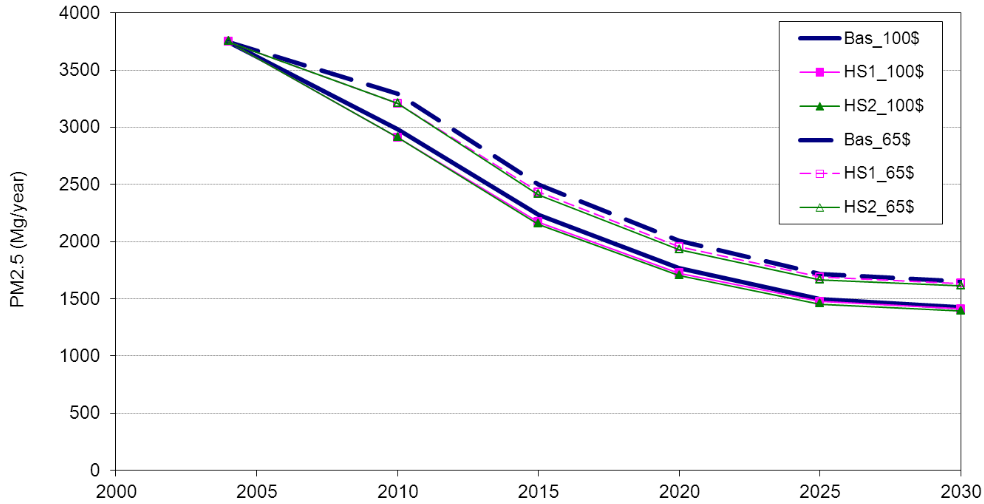


Figure 5.1 National road transportation $PM_{2.5}$ emission (exhaust and non-exhaust) for the baseline scenario, scenario HS1 (up to 10 % biofuels for either \$65 or \$100 a barrel) and scenario HS2 (up to 25 % biofuels for either \$65 or \$100 a barrel). Units: Mg pr year.

The overall trend of $PM_{2.5}$ emissions for national road transportation is a decrease due to introduction of more stringent Euro emission standards in the baseline scenarios. A similar pattern is seen for other regulated emissions (NO_x, CO and VOC) as shown in Chapter 4. The low oil price scenario (65\$) will have somewhat higher emissions than the high oil price scenario due to more transportation demand. The biofuel scenarios only add marginal to emission reductions compared to the overall decreasing trend of the baseline scenarios. The high-blend biofuel scenario (HS2) provides a little less emission than the low-blend biofuel scenario.

For the development in total emissions the scenario year is the most important factor, the oil price also impacts emissions but different biofuel scenarios only have marginal positive impacts on emissions of a few percentage.

Emissions from the road transportation sector only constitute a minor share of total emissions from all sectors. For the case of $PM_{2.5}$ the road sector constitutes about 17 % in 2004 decreasing to about 11 % in 2030. This means that the marginal positive impacts of the biofuel scenarios compared to the baseline scenarios for the transportation sector becomes even smaller when comparing the total emissions from all sectors.

The geographic distribution of emissions on a 1x1 km^2 grid was produced as input to the air quality models (Plejdrup & Gyldenkærne, 2011).

5.3.2 Air Quality and External Costs

The EVA system was run for selected paired scenarios in so-called 'tagging mode' for economic valuation of air pollution. Tagging enables accurate estimation of concentration differences between two scenarios with small differences in emissions. Only a selection of paired runs are feasible to conduct as there are 171 possible paired scenario runs due to the combination of scenario years, oil prices and biofuel blends.

Concentrations of O_3, NO_2 and $PM_{2.5}$ decrease from 2004 to 2030 for the baseline scenarios due to decreasing emissions. This is a very strong trend that outweighs marginal concentration differences between the baseline and the biofuel scenarios similar to what were seen for emissions. On the regional scale O_3 is reduced due to increases in precursor emissions of NO_x and VOC.

However, looking at a specific scenario year regional concentrations of pollutants of NO_2 is marginally higher in the biofuel scenario compared to the baseline due to higher NO_x emissions whereas O_3 are lower, because less NO and VOC emissions are available for depletion of O_3. $PM_{2.5}$ concentrations are lower in the biofuel scenarios than the baseline scenario as a combination effect of lower $PM_{2.5}$ emission that is not outweighed by the formation of secondary PM due to higher NO_x emissions.

In Figure 5.2 an example of output from the EVA system is shown for regional concentrations as the concentration difference between the high-blend biofuel scenario in 2030 (HS2_$100) and the baseline scenario in 2030 (Bas_$100) (Gross et al. 2010; 2011). In Figure 5.3 a corresponding output is shown for the Greater Copenhagen Area.

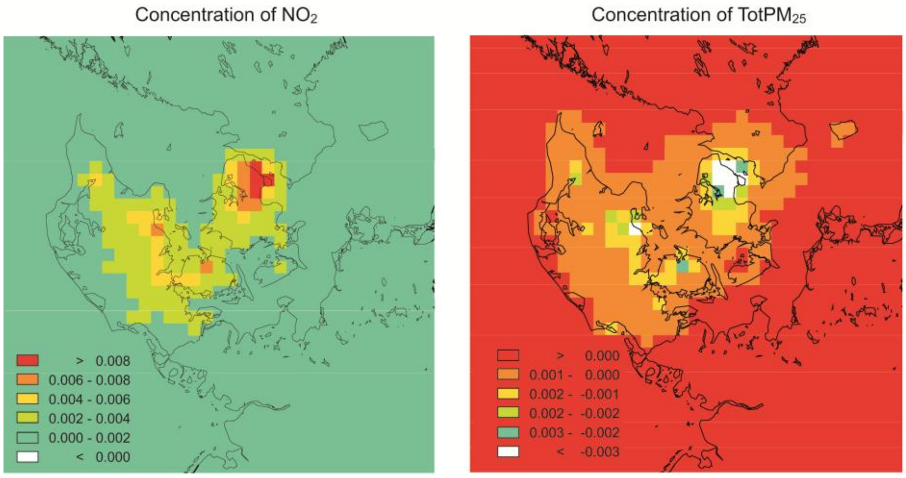


Figure 5.2 Regional concentration differences: the high-blend biofuel scenario in 2030 with oil price of $100 (HS2_$100) minus the baseline scenario (Bas_$100). Left: NO_2 concentration differences in ppb. Right: $PM_{2.5}$ concentration differences in µg/m^3.

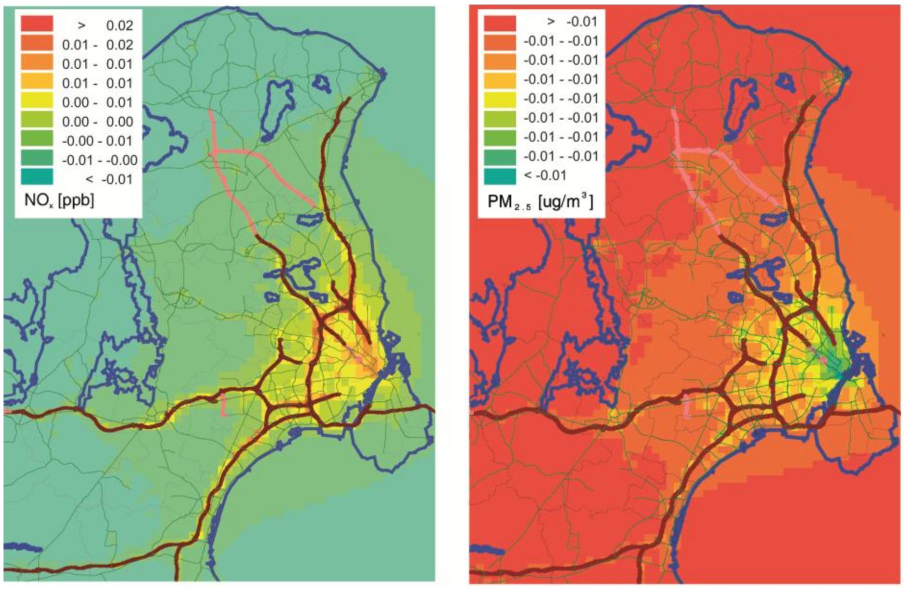


Figure 5.3 Local concentration differences for the Greater Copenhagen Area: the high-blend biofuel scenario in 2030 with oil price of $100 (HS2_$100) minus the baseline scenario (Bas_$100). Left: NO_2 concentration differences in ppb. Right: $PM_{2.5}$ concentration differences in µg/m^3.

The EVA system calculates concentration differences for paired emission scenarios, and based on gridded population data and exposure-response functions health impacts are estimated. Then health impacts are given a monetary value for estimation of the external costs of air pollution (Brandt et al. 2011). The absolute external costs in this work should be used with precaution. The external costs are, of course, associated with a certain degree of uncertainty, which on the other hand is very difficult to quantify in such a complex model system. The main uncertainties in the integrated model system is associated with the emissions (which have an uncertainty of +/- 30 % on annual basis) and the uncertainty related to the health impacts from the individual chemical compounds associated to air pollution. With our present knowledge we are not able to distinguish between the impacts from different particle types. However, there are many research studies linking the total mass of $PM_{2.5}$ with health effects, showing strong and significant correlations. In order to assess the influence from assuming different toxicity from primary and secondary formed particles, we made a sensitivity analysis with the EVA system. This sensitivity analysis did not change the overall conclusions of the work. The results from the EVA system have been compared to the CAFE results and have proven consistent with results used to support the decision making in the EU Commission.

Calculations were made for Europe based on the regional air chemistry transport model – DEHM with a geographic resolution of 17x17 km^2. Here Europe includes Russia to the Ural Mountains. At the local scale the Greater Copenhagen Area served as a case study area where the Urban Background Model (UBM) was used with a geographic resolution of 1x1 km^2.

The external costs are summarized in Table 5.1 for selected paired scenarios and broken down for the Greater Copenhagen Area, Denmark and Europe. A negative value indicates a positive benefit with reduced health impacts and hence reduced external costs (Gross et al. 2010; 2011).

Table 5.1 External costs differences between different scenarios. Total costs in all Europe and costs in Denmark and Greater Copenhagen Area.

Topic	Paired scenarios	Total costs (M euro)	Danish costs (M euro)	Copenhagen (M euro)
	Base, 2004, $65 ↔ Base, 2010, $65	-535	-99	-13
Impact of year	Base, 2004, $65 ↔ Base, 2030, $65	-237500	-1501	-550
Business-as-usual)	Base, 2004, $65 ↔ Base, 2010, $100	-588	-111	-19
	Base, 2004, $65 ↔ Base, 2030, $100	-238500	-1511	-555
	Base, 2010, $65↔ Base, 2010, $100	-51	-11	-5.6
	Base, 2030, $65 ↔ Base, 2030, $100	-36	-9.6	-4.4
Impact of oil price	HS2, 2010, $65 ↔ HS2, 2010, $100	-51	-11	-5.5
	HS2, 2030, $65 ↔ HS2, 2030, $100	-31	-6.7	-4.9
Impact of biofuel (HS2)	Base, 2010, $65 ↔ HS2, 2010, $65	5.3	-1.5	-1.1
	Base, 2030, $65 ↔ HS2, 2030, $65	1.4	-2.2	-1.5
	Base, 2010, $100 ↔ HS2, 2010, $100	4.9	-1.3	-.94
	Base, 2030, $100 ↔ HS2, 2030, $100	1.7	-0.79	-1.0

Even though marginal concentration differences are calculated, the external costs add up when considering large exposed population groups and the strong exposure-response relations for $PM_{2.5}$.

External costs are largely reduced from 2004 to 2030 in the baseline scenarios with a reduction up to 1500 million euro for Denmark. This is a much higher reduction than those obtained for impact of oil prices and biofuels. This is due to the fact that not only the emission change from transport is included in the future simulations compared to the baseline scenario but also the change from the other sectors.

A difference between a low and high oil price also shows up although it is small compared to the general trend of the baseline scenario. The low oil price scenarios have higher external costs compared to the high oil price scenario with 11 million euro in 2010 and 7-10 million euro in 2030 for Denmark.

The high-blend biofuel scenarios only reduce the external costs of air pollution marginally compared to the baseline scenario with about 1.3-1.5 million euro in 2010 and 1-2 million euro in 2030 for Denmark for the different oil prices. Note that the biofuel scenarios increase the total external costs in Europe. This is due to slightly higher NO_x emissions from combustion of biofuel blends compared to the neat fuels. The higher NO_x emissions decrease the ozone concentration over Denmark forming nitrogen dioxide, which is transported out of Denmark.

It is seen that the Copenhagen Area constitutes a relatively large share of total external costs in Denmark as the area has the highest concentrations in Denmark and the highest population density. The area includes about 1.8 million people out of the population of 5.6 million people in Denmark.

The EVA system also provides urban background concentrations. The geographic variation of urban background concentrations have been evaluated in the Greater Copenhagen Area and modelled concentrations have been compared to measured concentrations at a urban background station (H.C. Ørsted Institute in Copenhagen) using UBM and two street stations (Jagtvej and H.C. Andersens Boulevard) using OSPM for 2004 and 2010. In Table 5.2 the development in modelled urban background concentrations at the location of H.C. Ørsted Institute in Copenhagen is shown (Ketzel 2011).

Table 5.2 Modelled urban background concentrations at H.C. Ørsted Institute in Copenhagen for the baseline scenario ($100).

Baseline $100	NO_x µg/m³	NO_2 µg/m³	O_3 µg/m³	CO µg/m³	PM_{10}* µg/m³	$PM_{2.5}$* µg/m³
2004	21	18	60	207	11	10
2010	16	14	63	168	11	10
2020	9	8	68	134	7	5
2030	6	5	70	130	7	5

*Only about half of the mass is accounted for by the model (well-known mass closure problem)

All concentrations decrease except O_3. Urban background O_3 increases as a combination effect of slightly lower regional O_3 concentrations but large reductions in local NO_x emissions outweighs this since NO is not available for depletion of O_3 and hence O_3 increases.

Differences between the baseline and the high-blend biofuel scenario (HS2_$100) is shown in Figure 5.3 for $PM_{2.5}$ and in Figure 5.4 for NO_2. It is seen that the two curves almost overlay one another indicating marginal impacts of the biofuel scenarios on urban background concentrations. $PM_{2.5}$

concentrations are marginally lower in the biofuel scenario and NO_2 concentrations are marginally higher than the baseline scenario. Reduction of $PM_{2.5}$ concentrations level off between 2020 and 2030 due to the influence of non-exhaust PM emissions that increase with increasing travel demand. At the same time the reduction in PM exhaust diminishes as most vehicles in 2020 comply to emission standards with very low PM exhaust emission.

Calculations with the OSPM model show similar marginal impacts of the biofuel scenarios for street concentrations as were seen for urban background concentrations although a marginally larger effect is observed due to the proximity to the traffic source.

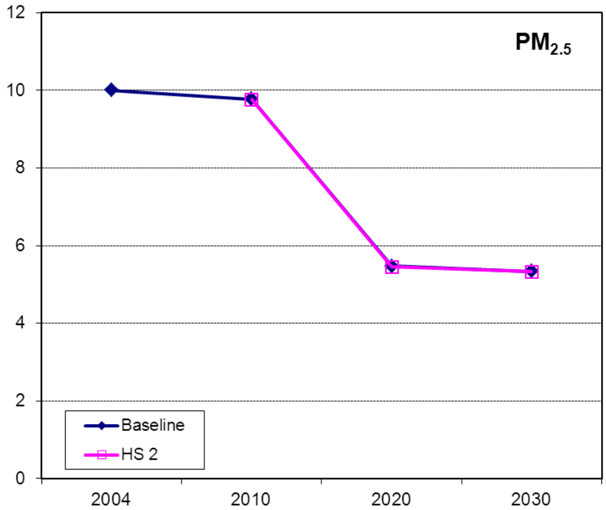


Figure 5.3 Development of $PM_{2.5}$ urban background concentrations at location of urban background station in Copenhagen. Difference between baseline and high-blend biofuel scenario (HS2_$100). Units: µg/m^3.

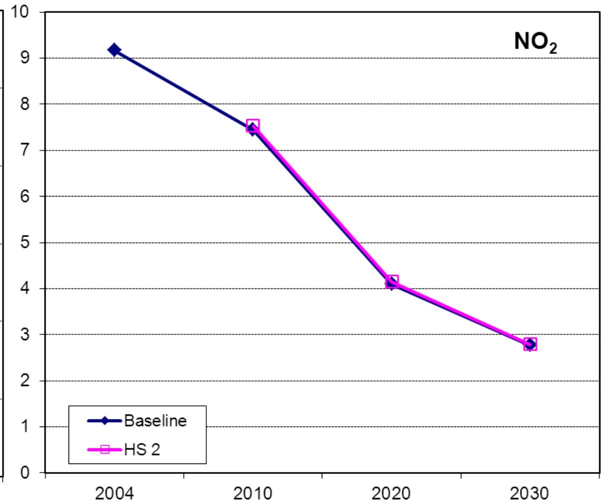


Figure 5.4 Development of NO_2 urban background concentrations at location of urban background station in Copenhagen. Difference between baseline and high-blend biofuel scenario (HS2_$100). Units ppb, (1 µg/m^3=1.88*ppb).

Box 2: Effect of Biodiesel on Diesel Particulate Filter Performance

Brian Brun Hansen, Peter Arendt Jensen and Anker Degn Jensen, DTU-Chemical Engineering, Technical University of Denmark.

Introduction

The automotive diesel engine equipped with a particulate filter provides both a high thermal efficiency and low particulate emissions. Cleaning/regeneration of the filter can be obtained within a normal driving cycle due to the presence of catalytic material in the filter. However, long-term accumulation of impurities/salts from the fuel and oil take place and the introduction of biodiesel may change the impurities in question as well as particulate emissions and potentially affect filter performance.

Methodology

This investigation has been carried out in lab-scale as well as pilot-scale. A diesel engine setup (418 cc) and filter test facility have been constructed and the experimental work was on-going until June 2011. Lab-scale experiments have been focused on a fundamental study of the influence of various biodiesel salts on the catalytic combustion required to regenerate a particulate filter. Experiments have been performed by subjecting mixtures of soot (12 wt.%), catalytic material (59 wt.%) and various chemical elements as salts (29 wt.% Na, K etc.) to simultaneous thermal analysis (Netzsch STA 449) in 10% O_2. Salts of alkali metals have been of particular interest as they are introduced to the system by biodiesel (content in biodiesel is limited by EN 14214).

Results and discussion

Figure 1 presents the temperature at which soot conversion peaked (T_m) for selected mixtures of soot, catalyst and salts. The commercial cerium-based catalyst caused a favourable decrease in T_m (from 658±7 to 526±19 °C) thereby making filter regeneration easier. The presence of sodium or potassium as carbonates caused a further 100-120 °C decrease of T_m while chloride or sulphate salts did not influence the T_m temperature significantly. An 80% lower Na_2CO_3/K_2CO_3 dosage still decreased T_m70-100 °C. Alkali carbonates (Na_2CO_3 and K_2CO_3) have also been reported to enhance carbon black/model soot oxidation (Neeft et. al., 1998) and gasification of carbonaceous materials (McKee, 1983. The laboratory study indicates that even long term use of biodiesel will not be detrimental to the catalytic capacity of diesel particulate filters.

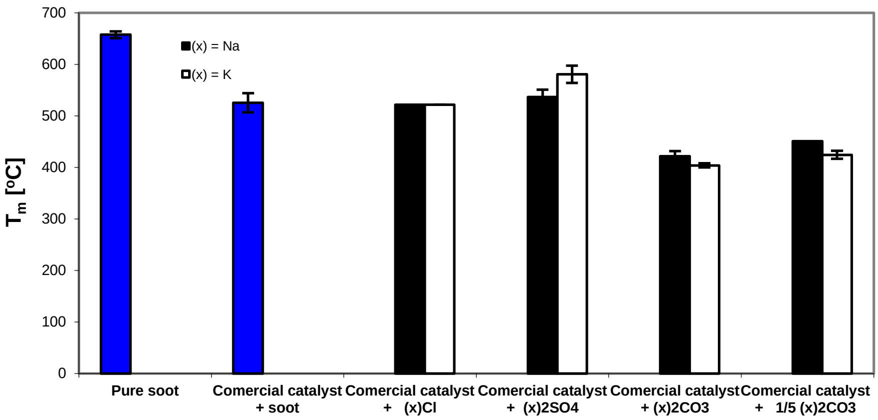


Figure 1 Temperature at which soot conversion peaked (T_m) in STA tests for selected mixtures in 10 % O_2

References: Neeft, J.P.A.; Makkee, M.; Moulijn, J.A. Catalytic oxidation of carbon black – I. Activity of catalyst and classification of oxidation profiles. Fuel 1998, 77(3), 111-119.

McKee, D.W. Mechanisms of the alkali metal catalysed gasification of carbon. *Fuel* **1983,** 62(2), 170-175.

6 Health hazard characterization of biofuels

PhD student Jette Gjerke Hemmingsen, professor Peter Møller and professor Steffen Loft, Institute of Public Health, University of Copenhagen.

6.1 Purpose

Diesel engine emission of particulate matter (PM) has been associated with oxidative stress, inflammation, genotoxicity with resulting adverse effects including lung and cardiovascular diseases as well as cancer. Efforts have been made to reduce emissions of hazardous compounds by development of better engines. Still, there is a need to reduce the combustion fossil fuel due to limited resources and increased burden of green-house gasses. The pur-pose of this investigation was to assess the effect on DNA damage, produc-tion of reactive oxygen species (ROS), inflammation, and expression on cell adhesion molecules in cells by PM from combustion of conventional diesel fuel (D_{100}) and biodiesel with 20 % blend of methyl esters of animal fat ($AF\text{-}ME_{20}$) or Rape seed Methyl Ester (RME_{20}) in an old (EU2) or new (EU4) type of diesel engine, as described in Box 1.

6.2 Methods

Three types of cells was used in this study to mimic the target organs in human exposure to particles: A549 cells which represent the epithelial cells of the lung, THP-1 cells with mimics the inflammatory response to particles by monocytes and macrophages, and the HUVEC cells, which represent endothelial cells from the vascular system. The main route of human exposure to diesel exhaust particles (DEP) is by inhalation. DNA is considered to be an important target for reactive oxygen species (ROS) generated by ambient air particles. Oxidatively damaged DNA may be implicated with cancer risk (Risom et al. 2005). ROS production, DNA damage and cytotoxicity were measured on A549 cells.

The release of mediators such as chemokines and cytokines is associated with recruitment of inflammatory cells and initiation of the inflammation re-sponse to particles. The ROS production and mRNA levels of CCl2, LFA-1, IL-8, TNF- α were measured in THP-1 cells.

Endothelial activation by particulate matter is link to pro-inflammatory factors released in the lung or to direct contact of particulate matter with the endothelium (Montiel-Davalos et al. 2007). ROS production, cytotoxicity and expression of adhesions molecules VCAM-1 and ICAM-1 were measured in endothelial cells as markers of atherosclerosis and cardiovascular disease risk.

6.2.1 ROS production

Unrestricted ROS generation and/or deficient antioxidant defense may expose healthy tissue to antioxidant damage. The mechanisms of particulate matter induced health effect are believed to involve inflammation and oxida-tive stress. Oxidative stress mediated by particulate matter may arise from direct generation of reactive oxygen species on the surface of the particles or metals and organic compound that have been leached from the particles.

6.2.2 DNA damage

ROS can react with bases in the DNA strand and this can lead to GC→TA transversion, if it not repaired. DNA damage or oxidation of purines was measured as the formation of formamidopyrimidine DNA glycosylase (FPG) sensitive sites and strand breaks (SB).

6.2.3 Cytotoxicity

Cell viability was assessed by the tryphan blue method.

6.2.4 mRNA

The gene expression of inflammation molecules was determined by real-time (RT)-PCR

6.2.5 VCAM and ICAM measurements

The amount of vascular cell adhesion molecule-1 (VCAM-1) and adhesion molecule-1 (ICAM-1) was measured by means of ELISA.

6.3 Results and discussion

The Euro 4 engine generated particles with smaller size in cell culture media, more ability to induce ROS with and without cells, and more extensive con-centration-dependent DNA damage in A549 lung epithelial cells, but less cy-tokine mRNA expression in THP-1 monocytic cells compared with the Euro 2 engine. The PM from biodiesel had larger size in medium than that from D_{100}, but similar capacity for inducing ROS, DNA damage and mRNA ofCCl2, TNF-α, IL-8 or LFA-1 in THP-1 cells. Only the D_{100} particles from the Euro 4 engine increased the expression level of cell adhesion molecules in endothelial cells.

The small particle size profile of PM from the combustion of diesel fuel in the Euro 4 engine also had a steep concentration-dependent increase in the acellular ROS generation, whereas the PM derived from the Euro 2 engine and SRM2975 had a slowly rising concentration-response relationship. This difference in ROS production was observed in the culture cells too, although the difference in ROS production was less dramatic. The results suggest that the small particles from the Euro 4 engine have more ROS production be-cause of the larger surface area. This is in keeping with the notion that especially small size particles are associated with oxidative stress as for instance observed by a strong correlation between the particle size and depletion of intracellular glutathione levels (Stone et al. 1998).

All preparations of PM generated SB and FPG sensitive sites in A549 cells in a concentration-dependent manner, whereas there was only a difference between the fuels for the Euro 4 engine where the combustion of RME_{20} generated particles that were associated with less generation of FPG sensitive sites than the D_{100} particles. In addition, the type of engine had a stronger effect than the fuel of the generation of DNA damage, possibly due to the differences in size and associated ROS production. We have previously observed that authentic particles collected from the air in a traffic street had the same ability to generate SB and FPG sensitive sites in cultured A549 cells as the particles from biodiesel in this study (Danielsen et al. 2008). This implies that increased levels of oxidatively damaged DNA by the biodiesel-generated PM are relevant as hazard identification.

The expression of ICAM-1 and VCAM-1 was only increased compared to the control in HUVECs exposed to D_{100} generated by the Euro 4 engine, although the differences between the samples were related to the type of fuel rather than the engine. The expression of cell adhesion molecules on HUVECs suggests that PM from combustion of 20 % biodiesel is less potent than conventional diesel. It has recently been reported that inhalation of emission from combustion of 50 or 100 % soybean-based biodiesel or reference diesel (a blend containing 3 % biodiesel) in a diesel electrical generator showed that the biodiesel promoted stronger cardiovascular effects as well as pul-monary and systemic inflammation in mice (Brito et al. 2010). Our findings may not be at odds with these results because the fuel and content of bio-diesel was different, and the types of engines were substantially different. Our data are supported by another study showing unaltered pulmonary in-flammation and signs of alveolar tissue injury in mice exposed by intra-tracheal instillation of PM from combustion of soybean-based biodiesel in an engine complying with Euro 2 emission standard (Tzamkiozis et al. 2010).

We found limited inflammatory responses in terms of mRNA expression of cytokines and LFA-1. Only PM from combustion of $AFME_{20}$ in the Euro 2 engine induced significantly elevated mRNA levels in terms of TNF-α in THP-1 cells. For both TNF-α and LFA-1 the PM from the Euro 4 engine the mRNA expression levels caused less expression than did the PM from the Euro 2 engine, which is in contrast to their ability to induce oxidative stress. At high levels oxidative stress can induce inflammatory responses (Li et al. 2008). The inflammation response related to the PM from the Euro 2 and 4 engines was also different from that of endotoxin which only increased the expression of IL-8 and CCL2 in our system. We have previously found increased mRNA expression of IL-8, TNF-α and/or CCL2 in THP-1 cells exposed to different wood smoke particles under similar conditions as in the present study (Danielsen et al. 2008).We have also found increased mRNA expression of IL-8 and TNF-α in cells exposed to diesel emission particles for 2-24 hours at concentrations up to 500 μg/mL (Dybdahl et al. 2004).

The overall assessment of the results in our study indicates that the PM collected from the combustion of D_{100} by the Euro 4 light-duty diesel engine was more hazardous in terms of expression of cell adhesion molecules, than PM collected by combustion of $AFME_{20}$ or RME_{20}. The Euro 4 diesel engine is representative of the present day type of engine and the results thus suggest that benefits could be achieved by promoting the use of biodiesel instead of conventional diesel oil. Our assessment was based on equal mass concentration and the health benefit could be substantially larger if the total emission of PM is reduced by combustion of biodiesel. Similarly, breathing air from traffic emissions of Euro 4 type of engine is likely to be less hazardous than Euro 2-derived PM because the maximum emission is 0.08 and 0.025 g per km, respectively, even though the former generated particles of smaller size and more potency in terms of ROS production and genotoxicity than the PM collected from the latter Euro engine. Advanced after-treatment technologies especially filter in diesel engines is even more efficient than cleaner fuels in reducing PM emissions (Cheung et al. 2010). Indeed, we at-tempted to collect PM from a similar Euro 4 engine equipped with a particle filter, but this was so efficient that it would probably have required an ex-tended period of time to collect a sufficient amount of material for the analysis in cell cultures.

7 Agricultural scenarios, land use and emissions

PhD student Lars Ege Larsen and Senior researcher Pia Frederiksen, both at Department of Environmental Science, Aarhus University.

7.1 Purpose

A baseline scenario for the agricultural production and land use until 2030 was developed based on estimations of the land requirement corresponding to the scenario energy demands. The aim was to evaluate the land use consequences under different scenario conditions. Two scenarios were investigated and evaluated: a biofuel scenario assuming that efforts to achieve self-sufficiency in biofuel displace part of the domestic production of fodder, and a scenario allowing continuous growth in the now dominant livestock branch. The results for the low oil price traffic forecasts and the 10 % blend scenarios in 2030 (HS1) are reported here.

7.2 Methods

According to the 'REBECa HS1' scenario the biofuel demand will reach around 20,4 PJ in 2020 as the 10 % target is met but will continue to grow due to the increasing demand for transport. In 2030 the biofuel demand will be 23,4 PJ.

The demands for bio-ethanol and bio-diesel in the 'REBECa HS1' scenario (see 2.2) was converted to demands on agricultural land to allow for analysis of competing land use claims. In this case an approach was chosen, where the conversion efficiency only accounts for the relationship between the main feedstock and the final product. Hence, the area needed to produce enough feedstock for a given demand on biofuel only depends on two independent variables: The average yield for the related feedstock (crop or residue), and the conversion efficiency in the related fuel production technology going from the feedstock to the final product. The crop yields are based on average yields in Danish agricultural production, taking into account soil types, irrigated land, and crop rotation effects. It is also necessary to know the energy content of the feedstock and the product in order to handle data on the conversion efficiency. The technology conversion factors used were based on Slentø et al. (2010). The resulting land area demands are shown in Table 7.1.

Table 7.1 Land area demands for biofuel crops and residues in ha with current efficiency under scenario HS1.

	2010	2015	2020	2025	2030
	Area demand for biofuel crops and residues in ha				
Biodiesel (rape)	137.666	219.104	309.695	339.060	367.719
Bio-ethanol 1g (wheat)	55.686	48.872	43.515	39.378	35.531
Bio-ethanol 2g (straw)	19.473	67.174	124.470	138.234	154.429

Next we established a baseline for agricultural development for the period 2010-2030, describing a 'business-as-usual' situation concerning land use practises (hereafter referred to as the baseline). The point of departure for the baseline is the agricultural area for 2007 (2.662.703 ha). The basic assumption for the baseline is that adopted policies affecting available land for agriculture as well as known forecasts are implemented, while no further development was assumed concerning efficiency gains or policies. Hence, within this area, existing environmental policy targets that contain an explicit demand on land or could easily be interpreted as land claims were implemented. This included afforestation targets and action plans for the aquatic environment. Subsequently, the trends in urbanization and infrastructural development were extrapolated and deducted from the arable area. These first two steps resulted in a reduction in the area available for agricultural production towards 2030.

The third step was to estimate the future demands for high-value agricultural crops (including grass seed and domestically produced vegetables) and for livestock and dairy products, and finally, in the fourth step these future product demands were converted to demands on specific crops and agricultural land area. We used the crop specific land cover categories from the annual Danish agricultural statistics and grouped them in broader land use categories: roughage, concentrates, high value crops, set aside.

Next, we constructed a scenario for biofuel crop production in Denmark with the aim of fulfilling the demand for a 10 % mix of biofuels in the fuel consumed by the transport sector in 2030 (hereafter referred to as the Biofuel Scenario). The Biofuel Scenario shares most of the baseline's assumptions but allow biofuel crops to replace certain other crops. In contrast to the baseline the Biofuel Scenario prioritizes land for biofuel crop production at the expense of land for livestock feed production. The 'high value crops' are however still allocated a higher priority. In case of conflicting demands from biofuels and livestock the production of pig meat and live pigs are reduced first, to reflect that farmers in this branch of the livestock production are the least competitive and most financially vulnerable of the livestock branches.

The production of 1st generation bio-ethanol and bio-diesel (RME) both have residuals which are interesting for farming and which were therefore also taken into consideration. From 1st generation bio-ethanol plants Dried Distiller Grains with Soluble (DDGS) is a by-product, which is applicable as a high protein feed. Rape cake, a residue from bio-diesel production (both RME and bio-oil), is also a high protein feed. Like DDGS, rape cake cannot replace other concentrates entirely. Rape cake is already in use as a feed, as Denmark currently produces both biofuel (primarily for export) and vegetable oils for food on basis of rape.

By comparing the baseline and the Biofuel Scenario we explored the impacts on crop and livestock production from using land for biofuel crops. While the majority of 'substituted' crops for the global market only give a marginal contribution to fulfilling biofuel crop demands in the long run, the effect of land competition between biofuel and livestock production can best be described as a trade-off, due to the large land claims for fodder.

The baseline scenario display a rather abrupt halt in agricultural development after 2015 due to the decision only to implement known policies and forecasts, but in the Agri-export scenario, we allowed livestock production to grow unlimited until the end of the scenario period. The scenario shows how agricultural land use will develop if the short term growth rates applied in the baseline and in the biofuel scenario are allowed to continue, until there are trade-offs with biofuels production. Feed production is allowed to spread on to all cropped areas as well as the category 'Set aside'. In case of the pig and poultry production the growth beyond 2015 is an extrapolation of the annual growth in 2010-2015.

Sensitivity to efficiency was assessed by producing variants of the baseline and the scenarios. Border situations are present productivity and productivity increases of 0,67 % yearly for crops and 1,07 % yearly for milk until 2030. The extremes are: One with current efficiencies and one with improved efficiencies in all agricultural production branches throughout the scenario period (2010-2030). These efficiencies are mainly based on Dalgaard et al. (2011). A more thorough description of methods is found in Larsen et al. (forthcoming).

7.3 Results and discussion

7.3.1 Baseline

The main agricultural driver of change in the baseline is the increasing demand for feed. Areas for roughage production are almost constant throughout the scenario period while the areas for production of concentrates see a gradual increase until 2015. As the expansion of non-agricultural land use reduces the size of the agricultural land, the share of agricultural land taken up by feed production increases. The land use development for the current efficiency variant of the baseline can be seen in Figure 7.1.

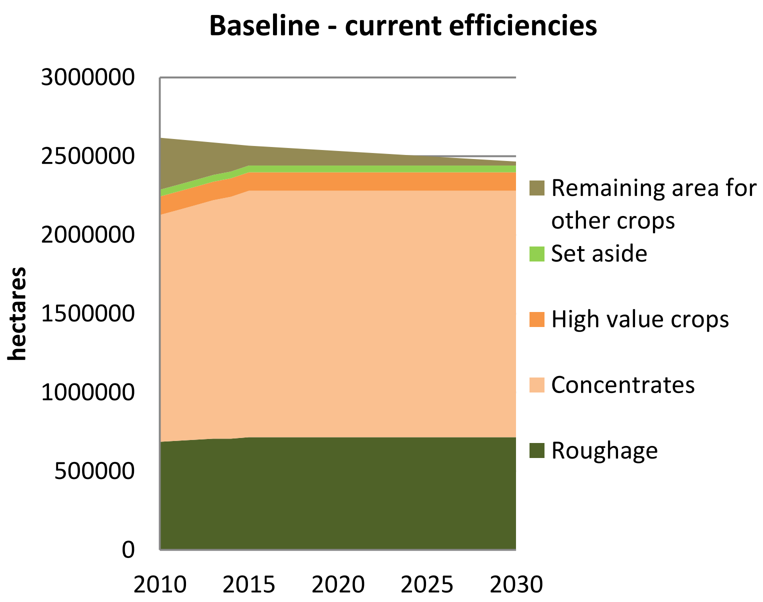


Figure 7.1 Land use development in the Baseline Scenario.

7.3.2 The Biofuel Scenario

The Biofuel Scenario prioritizes biofuel production at the expense of the livestock sector in order to meet policies on renewable energy. However, as it was chosen that the increase in area for biofuel crop production takes place at the expense of feed production for pigs before cattle, the trend in the area for roughage production is similar to the baseline. The area for production of concentrates is, however, reduced over the full period to make room for '1st generation bio-ethanol' from wheat and 'bio-diesel' from rape.

With the current levels of productivity the concentrates supply is thereby reduced by approximately 380.000 ha by 2030 compared to the baseline (see Figure 7.2). Biofuel crop production is also expanding onto the remaining agricultural areas, and from 2012 the only other crops produced are the high value crops 'seeds for sowing' and 'vegetables for food'.

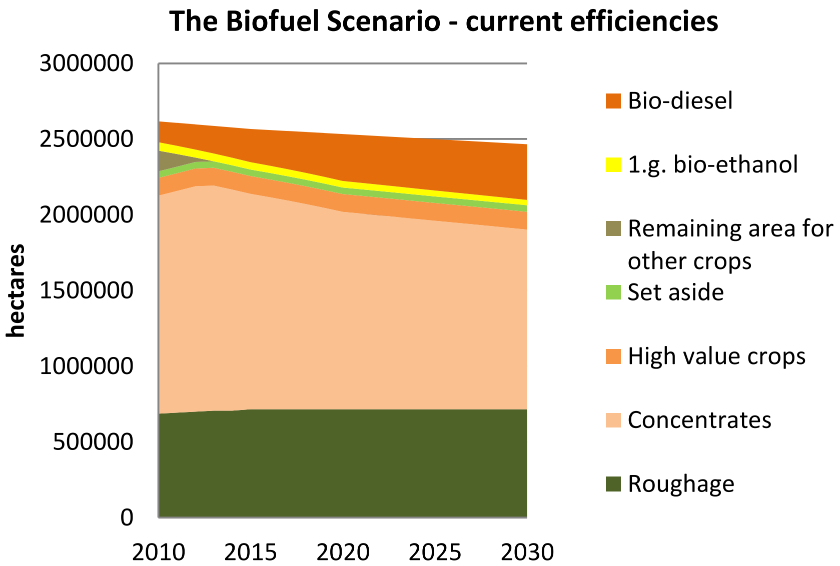


Figure 7.2 Land use development in the Biofuel Scenario.

The only crop with expanding area is winter rape for biodiesel production while winter wheat is decreasing to make room for rape, see Figure 7.3. This partly reflects the relatively low rape yields compared to wheat, but also the modest demand for 1st generation bio-ethanol throughout the Biofuel Scenario.

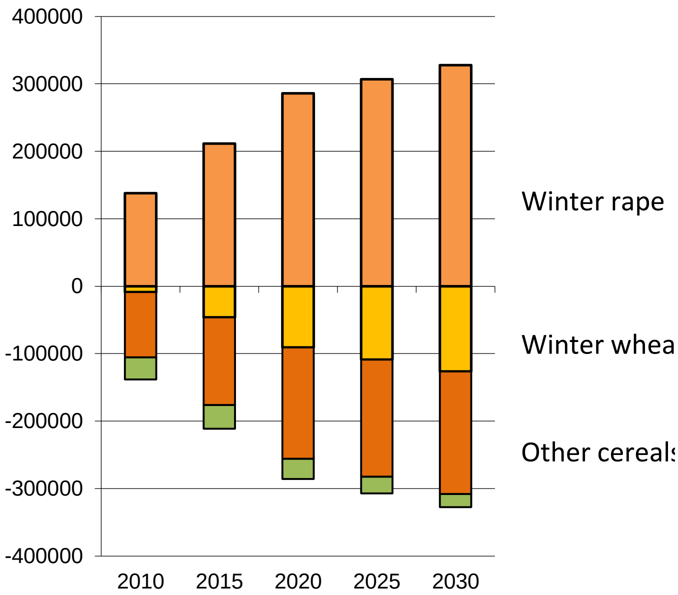


Figure 7.3 Changes in land use following Biofuel Scenario HS1, rape increasingly substituting winter wheat, other cereals and root crops.

The demand for bio-ethanol is increasingly met by 2nd generation production based on straw, which in turn is dependent on the size and accessibility of the straw production related to the total production of wheat - or on the total production of cereals or oil seeds depending on the flexibility of the receiving 2nd generation ethanol conversion technologies.

7.3.3 The Agri Export Scenario

Assuming current efficiency, in the Agri Export Scenario feed production (concentrates and roughage) takes over all agricultural land by 2022 – mainly due to increased concentrates demand (see Figure 7.3). Rape grown for biodiesel and wheat grown for 1.g. bio-ethanol production is only viable until 2016-17.

If higher efficiencies are taken into account, the developments are postponed, but only around 4-6 years.

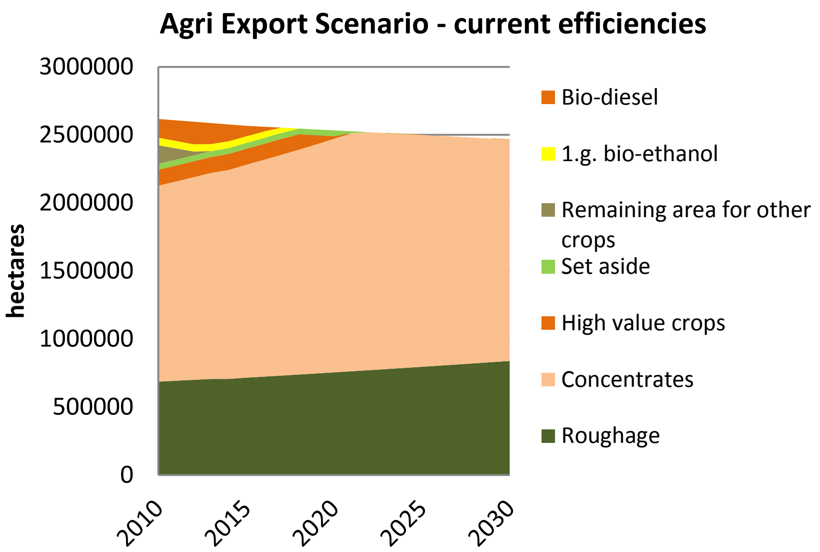


Figure 7.3 Land use development in the Agri Export Scenario.

7.3.4 Other effects

Presently, a little less than half of the wheat straw is left on the fields, while the remainder is used for combustion in power plants, and for fodder and bedding. In the current efficiency variant of the Biofuel Scenario, only 10 percent of the produced straw could be left on the fields in 2030.

Seemingly there is a large potential for utilizing by-products in the Biofuel Scenario's biofuel production in the feed supply and thereby freeing areas otherwise used for production of grains (mainly wheat and barley) for other purposes such as increasing the potential biodiesel supply. However, Denmark currently has a large import of high protein feed from the South American region (the main part of the 3.090 M SFU concentrates import in 2006). The likely effect of the increase in rape cake and DDGS (Dry Destillers Grains with Solubles) supply would therefore be a 44 % reduction in import needs.

Summarising, the three scenarios illustrate that the potential for self-sufficiency with biofuels related to the biofuel share of the total fuel consumption for transport assumed in the scenarios is strongly dependent on the assumptions made. In 2020 it would be possible to produce up to 62 % of the feedstock for biofuels needed to fulfil the 10 % policy target, without changes to the animal and high value crop production, even in the baseline situation, but only by using the rape oil, which is presently used for export and other purposes. If animal and related feed production is allowed to continue growth after 2015, up to 68 % of the demand could be met in 2020, based on the rape oil used for export and other purposes, and including a slightly higher production of rape cake for fodder. The biofuel scenario is constructed to fulfil a 100 % supply, without using rape oil for other purposes. If prices or policy favour biofuel rather than fodder, the full supply of nationally produced biofuels will reduce the areas for fodder production as well as other crops, while high value crops can still be produced. Estimations based on higher efficiencies would result in areas freed for other purposes, and in the Agri Export Scenario up to 80 % of the biofuel demand can be supplied before touching high value crops or rape oil for other purposes. If the latter is included, self-sufficiency is more than secured.

At some point going towards 2030 a political ambition to fulfil biofuel demands by domestic crops might establish a trade off with other high value products such as meat (feed), ‘seeds for sowing’ or ‘vegetables for food’ because of a land supply shortage. Even if efficiency increases are accounted for, a growing biofuel demand would meet its physical limits at some point not long after 2030 since both wheat straw residues and available areas are almost used up in 2030. The value or income stability from producing biofuel feedstock vs. other products would then become the crucial factor for the individual farmer’s choice of crop.

The Biofuel Scenario (current efficiency) shows that the supply of concentrates will decrease as biofuels enter the stage. If this reduction is imposed solely on the population of pigs the result is a 19 % reduction of the then expected population of pigs compared to the baseline. Compared with the 2006 population the decrease in population is still considerable (10 %).

The study has shown that introduction of biofuel production from domestic crops in Denmark can be accommodated by the land resources going towards 2030. However, the scale of the demand in 2030 means a substantially lower production of animal products and thereby a lower export, if agricultural crop production efficiencies and yields does not increase. Also, 2nd generation bio-ethanol from straw seems feasible until around 2030. Feed imports will lessen somewhat due to residues from the biofuel production. However, in the long run increased efficiencies cannot accommodate the demand growth rate portrayed in this scenario period. It is beyond the scope of this study to address whether this is favourable or not from a national socio-economic perspective. The study also does not account for the effect on land use at a global scale. However, the results highlight that increased biofuel use in Denmark cannot be achieved in the long run (2030 plus) without increasing the demand on foreign agricultural products and arguably also land resources.

8 Well-to-wheel assessment and welfare economy

Senior researcher Flemming Møller, academic associate Erik Slentø and Senior researcher Pia Frederiksen.

8.1 Purpose

Evaluation of scenarios of energy provision and consumption derive from different societal discourses. Concerns for climate change emphasises the resulting emissions of greenhouse gasses, while an energy security perspective may lead to analyses of the potential for energy production from various domestic sources. Concern for optimal allocation of society's scarce resources – e.g. competition between food and bioenergy production as well as alternative use of resources – leads to welfare economic analysis.

Consequently, various methods exist (e.g. LCA, SWA and CBA[5]) for evaluation of the different aspects of biofuel production and use, with different scopes and different analytical frameworks (Møller et al. forthcoming). The REBECa project has aimed to integrate some of these methods to evaluate both the resource and environmental consequences of the production of biofuels and their use in the road transport sector. The integrated method focus on fossil energy consumption, CO_2 emissions and total welfare economic changes within the whole well-to-wheel (WtW) flow chain comprising both the production of biomass and the subsequent conversion into biofuel and combustion in vehicles. The method is applied on the two biofuel scenarios with inputs from the analyses described in the above chapters on road transport, energy demand, agricultural production and emissions.

8.2 Methods

As described in Chapter 2, the agricultural crops used in the biofuel scenarios are rape for biodiesel, and wheat grains and straw for first and second generation bioethanol, respectively. The well-to-wheel production chain of biofuels involves a number of production processes which lead to use of energy, other inputs and scarce production factors (land, labour, capital) and also to different emissions that are harmful to the environment and to the human health. The use of scarce production factors implies that other production and consumption is displaced and emissions connected with these disappear.

The diagram in Figure 8.1 illustrates the well-to-wheel production chain of biofuels exemplified by the RME system. Starting from the third column from the left, the diagram shows that the production of rape diesel and final substitution of fossil diesel with RME involves agricultural production of rape, transport of rape seed to the RME conversion plant, production of RME at the conversion plant, transport of rape diesel to petrol stations and finally combustion in vehicles.

[5] Life cycle assessment (LCA), Systems wide assessment (SWA) and Cost Benefit Assessment (CBA).

In each production link inputs are needed. Some of the most important direct inputs to the RME production chain are shown in the second column. Rape cultivation uses seeds, fertilizers and pesticides as input as well as energy in the form of diesel and electricity for agricultural machinery. Transport of rape to the conversion plant uses diesel as direct input and conversion of rape into rape diesel at the RME plant uses various energy and chemical inputs. Of main importance is methanol for the trans-esterification process, which converts rape seed oil into RME. Finally diesel is needed for the transport of rape diesel to fuel stations.

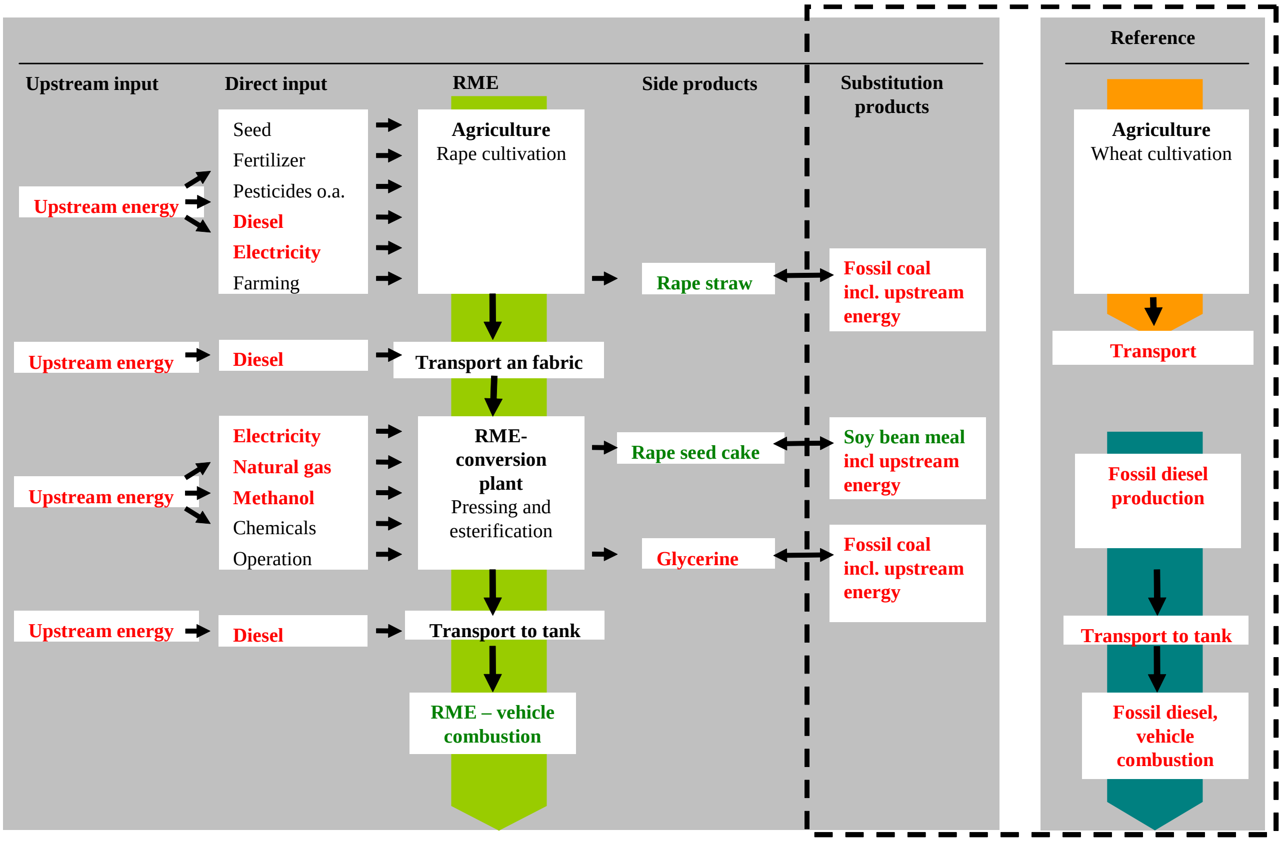


Figure 8.1 Conceptual diagram of inputs and outputs related to the production of RME and compared to a reference situation.

Besides the direct inputs shown in Figure 8.1 each production process also uses production factors capital and labour and the rape production uses land. As production factors are scarce, other production will be affected. These production consequences depend on how the reference scenario is formulated.

Emissions related to the different production links are not shown in Figure 8.1. This analysis includes emissions to the air of greenhouse gasses CO_2, CH_4 and N_2O and other pollutants NO_x, SO_2, NH_3, NMVOC, CO and particulate matter (PM_t). Furthermore, the analysis includes the leaching of N and P from farm land.

Production of inputs to the described production activities uses energy, which is indicated in leftmost column. Typically only upstream energy use and emissions related to this are calculated. The fourth column shows co-products emerging from the production of RME. Rape straw, rape seed cake and glycerine are supposed to substitute typically imported goods such as coal for power plants and soy bean meal. These products are part of the reference system indicated by the broken line box and as they are substituted by the co-products from the RME production energy and production factor use from production of coal and soy bean meal are saved. Emissions related to their production are also reduced.

The final column shows the reference situation which together with the direct and indirect input use in biofuel production determines the total consequences of substituting fossil fuel with biofuel. Land use is changed and the consequences for energy and production factor use and for emissions depend on what has until now been cultivated on the land. Similarly reference production of fossil diesel at oil refineries will be reduced as fossil diesel is going to be substituted by RME. This releases resources from the production of direct inputs and upstream inputs to the refineries and emissions related to fossil fuel and input production are reduced.

The consequences of substituting fossil fuel with biofuel are calculated as the difference between production, energy, input and production factor use and emissions in the situation with biofuel production called the scenario situation and in the reference situation respectively. Through the consequential approach chosen, we elucidate the losses and gains to society of reallocating resources from the current fossil fuel based reference situation to a new scenario situation where some fossil fuel is replaced by biofuel. In the following presentation of results the focus is on consequences for fossil energy consumption, CO_2 equivalent emissions and welfare economy. The welfare economic results also include the value of other emission consequences. The background reports describe the full analysis and details of the scenarios (Slentø et al. 2010, Møller & Slentø 2010), Møller et al. forthcoming). Table 8.1 summarises the main characteristics and assumptions of the biofuel scenarios with regard to agricultural production, fuel production, transportation and vehicle combustion. More details on the scenarios are given in Chapter 2.

Table 8.1 The most important assumptions of biofuel and reference scenarios.

	Scenarios			Reference
	RME	1st generation Bioethanol	2nd generation Bioethanol	
Agriculture				
Crop	Rape	Wheat	Wheat	Wheat
Grain usage	RME-biofuel	Bioethanol	Animal feed	Animal feed
Straw usage	25 % Power plant fuel 75 % Ploughed down	25 % Power plant fuel 43 % Ploughed down 32 % Animal feed and litter	50 % Bioethanol production 25 % Power plant fuel 25 % Ploughed down, animal feed and litter	25 % Power plant fuel 43 % ploughed down 32 % animal feed and litter
Soil type (Danish averages)	70 % loamy 30 % sandy	70 % loamy 30 % sandy	70 % loamy 30 % sandy	70 % loamy 30 % sandy
Irrigated land	15 % sandy	15 % sandy	15 % sandy	15 % sandy
Fuel production	Similar to existing plant Emmelev A/S Emmelev, 2010) implying rape seed oil is extracted by pressing and RME produced by esterification process.	Average European technology according to the well-to-wheel study (J-E-C, 2007)	Similar to Danish system IBUS (Hedegaard & Thyø 2007). However, reconfigured as a stand-alone plant not taking surplus steam energy input from nearby located Combined Heat and Power plant.	Fossil fuel refineries in Denmark equal to international technological standards. Raw oil input from Danish North Sea extraction sites is regarded as imported oil.
Transportation of raw materials and fuel products	Transportation by trucks fuelled by fossil diesel	Transportation by trucks fuelled by fossil diesel	Transportation by trucks fuelled by fossil diesel	Transportation by trucks fuelled by fossil diesel
Vehicle combustion and emissions	As modelled and calculated by (Winther & Plejdrup, 2010)	As modelled and calculated by (Winther & Plejdrup, 2010)	As modelled and calculated by (Winther & Plejdrup, 2010)	According to present traffic and fuel consumption standards (Winther & Plejdrup, 2010)

It is normal practice in LCA, WtW and SWA analyses to use global system delimitation. This practice is also followed in this analysis with regard to the consequences for energy consumption. This implies that energy consumption or savings are included in the analysis no matter if it takes place in Denmark or in another country which might be the case with upstream energy consumption related to input production. Regarding emission consequences the analysed system is delimited to the Danish border. This geographical delimitation is chosen because hereby the calculated emission consequences can be compared to official Danish emission inventories submitted to the international authorities UN and EU. This means that emissions related to production of imported products are not included in the analysis just as emission consequences related to reallocation of scarce production factors in other countries than Denmark are not included. In practice it is also very difficult to estimate such emission consequences because they might depend on nation specific conditions.

Consequently, calculated emission and welfare economic consequences can be interpreted as the consequences for Denmark of producing and using biofuels from biomass grown on Danish farm land. A total analysis should in principle also include emission and welfare economic consequences for other countries, but this has not been within the scope of the present study.

8.3 Results and discussion

As welfare economic analysis includes all consequences of biofuel production and consumption relevant to society, results from this analysis count as the main results of the present analyses. However, even if energy and emission consequences are only a part of the total consequences their separate assessment may reveal important information. E.g. although a certain biofuel may be welfare economically beneficial to society the climate gas impacts or the fossil energy consumption may be unfavourable in comparison with other measures to reduce the climate change impact of the transport sector.

Table 8.2 shows the consequences for fossil energy consumption, CO_2-equivalent emissions as percentage changes relative the reference situation when 1 kg of biofuel substitutes about the same amount of fossil fuel adjusted for differences in energy content. The welfare economic benefits are given in €.

Table 8.2 Consequences of producing and consuming biofuels relative to the reference scenario.

	RME	1st generation Bioethanol	2nd generation Bioethanol
Fossil energy consumption (MJ/MJ)	- 54 %	- 49 %	- 37 %
CO_2-equivalent emissions (kg/kg)	- 49 %	- 46 %	- 33 %
Welfare economic net-benefits (€ pr. kg biofuel)	-0.35	-0.14	+ 0.16

The changes in fossil energy consumption are significant. RME leads to a 54 pct. reduction, 1st generation bioethanol leads to a 49 pct. reduction and 2nd generation bioethanol leads to 37 pct. reduction in fossil fuel consumption. This implies that RME production and consumption are more fossil energy efficient than both 1st and 2nd generation bioethanol, under the assumptions made.

The results are scenario specific and wholly dependent on these assumptions. Moreover, they depend on methods for allocation of energy to co-products. In the project the substitution method has been used. For example in the RME scenario we have assigned the co-product glycerine a fuel energy quality since it substitutes coal in power plants. However, if sold to the pharmaceutical industry or used as animal feed, glycerine would not have a fuel energy quality.

This shows that the overall results on fossil energy substitution and emissions do not follow the direction of the welfare economic costs. While the largest gains in terms of fossil fuel saving is related to the RME production chain, the welfare economic benefits show the largest positive results for 2nd generation biofuel. This is especially related to the co-product values. On the other hand, the welfare economic losses related to the RME production are heavily influenced by the wheat production lost. This value would to some extent change if it was assumed that rape would substitute lower value crops.

Tables 8.3, 8.4 and 8.5 shows the detailed results for RME, 1st generation bioethanol and 2nd generation biofuel respectively, in terms of the consequences of substituting fossil fuel with 1 kg of biofuel.

Table 8.3 RME substituting fossil fuel. Consequences to society with respect to fossil energy consumption, CO_2 emissions and welfare economic costs (-) and benefits (+).

	Fossil energy consumption MJ per kg RME	CO_2-equivalent emission g CO^2 eqv. per kg RME	Welfare economy euro per kg RME
Agricultural production	-1.38	13	-1.11
Co-product: Lost wheat straw substituted by coal in power plants	14.08	1,221	-0.06
Co-product: Rape straw to substitute coal in power plants	-9.56	-828	0.04
Transport to conversion plant	-0.10	-8	0.02
RME conversion at the plant	7.17	173	-0.14
Co-product: Rape seed cake to substitute soy meal for animal feed	-4.86	0	0.32
Co-product: Glycerine (fossil C) to substitute coal in power plants	-0.20	-10	0.01
Fossil diesel production at refinery	-2.84	-145	0.55
Transport from conversion plant	0.01	1	0.00
Vehicle combustion	-39.36	-2,915	0.03
Total	-37.02	-2,498	-0.35

Table 8.4 1st generation bioethanol substituting fossil fuel. Consequences to society with regard to energy consumption, CO_2-equivalent emissions and welfare economic costs (-) and benefits (+).

	Fossil energy consumption MJ per kg Bioethanol	CO_2 equivalent emission G per kg Bioethanol	Welfare economy euro per kg Bioethanol
Agricultural production	0.00	0	-0.64
Transport to conversion plant	0.00	0	0.00
Ethanol conversion at plant	14.61	886	-0.08
Co-product DDGS substituting soy bean meal for animal feed	-3.16	0	0.16
Fossil gasoline production	-2.04	-101	0.42
Transport from conversion plant	-0.02	1	0.00
Vehicle combustion	-28.24	-2,058	0.00
Total	-18.81	-1,273	-0.14

Table 8.5 2nd generation bioethanol substituting fossil fuel. Consequences to society with regard to fossil energy consumption, CO_2 equivalent emissions and welfare economic costs (-) and benefits (+).

	Fossil energy consumption MJ per kg Bioethanol	CO_2 equivalent emission G per kg Bioethanol	Welfare economy euro per kg Bioethanol
Agricultural production	0.00	0	0.00
Transport to the conversion plant	0.13	10	-0.02
Ethanol conversion at plant	31.27	2,638	-0.51
Co-product Molasse substituting wheat grain animal feed	-1.19	-35	0.17
Co-product "dry matter biomass" substituting coal at power plant	-33.46	-3,174	0.12
Fossil gasoline production	-2.04	-101	0.42
Transport from the conversion plant	0.01	7	-0.02
Vehicle combustion	-28.24	-2,058	0.00
Total	-33.52	-2,714	0.16

It is evident from the tables that the assumptions regarding co-products are highly influential on the final results to society. In order to test some of the assumptions, sensitivity analyses were carried out on changes in agricultural assumptions on the use of straw, the conversion process on the use of heat from CHP plant, and on a number of the price assumptions.

These analyses showed that the integration with a CHP plant will increase the relative fossil energy savings and CO_2 reductions of 2nd generation bioethanol to reach the same level as for 1st generation bioethanol and the welfare economic profitability becomes even more positive. On the other hand, the positive welfare economic results on the 2nd generation biofuel disappear, if straw is not considered a free resource, but is transferred from use in power plants and substituted by coal. This will turn the fossil fuel saving to an increase in consumption, and will no longer provide a welfare economic gain. A thorough assessment of the benefits of increasing the use of straw in power plants will require analysis of the entire heat and electricity system. This was beyond the scope of this study. The analyses do show how sensitive profitability of biofuel production is to assumptions about alternative use of the biomass.

In addition to these analyses, prices on oil, wheat, co-products and enzymes were tested, and not surprisingly, the oil price assumptions were quite influential on the welfare economic benefits. An oil price increase to 100$ per barrel makes 1st generation bioethanol production welfare economical profitable and also RME production becomes almost profitable.

It is very important to notice that the value of alternative land use is highly influential on the profitability of RME and 1st generation bioethanol production. The sensitivity analyses was only made for higher and lower wheat price respectively, but these analyses also covers other assumptions about the value of lost agricultural production from changed land use. The analyses show that a 50 pct. lower wheat price will make both RME and 1st generation bioethanol production welfare economically profitable. This also indicates that if rape and wheat necessary for biofuel production can be cultivated on land of little economic value or substitute lower value crops, this will make biofuel production more advantageous to society.

The traffic energy forecasts and the biofuel phase-in scenarios to 2030 were not implemented in the integrated analysis. The reductions in emissions would follow the fossil fuel reductions closely, while it was decided that a forecast of the welfare economic costs did not make sense, based on the present analyses. While the RME technology and the 1st generation bioethanol conversion is mature technologies, this is not the case with 2nd generation bioethanol conversion, and as the project has not dealt with technology scenarios, or effects of up-scaling from 1 kg production to full-scale, it would be far-fetched to forecast the welfare economic results to 2030.

9 International perspectives on biofuels

Researcher Maria Figueroa, DTU Transport, Department of Transport, Technical University of Denmark; Senior researcher Pia Frederiksen, Department of Environmental Science, Aarhus University and Senior researcher Henrik Gudmundsson, DTU Transport, Department of Transport, Technical University of Denmark.

9.1 Introduction

This chapter summarizes international perspectives on biofuels and reports on themes that have relevance to the REBECa project on biofuels development for the Danish transport sector. The first part presents a short status of four prominent issues raised in the biofuel debate, namely, the global and regional biofuel potential, impacts of biofuels on climate, the 'food versus fuel' debate, and sustainability of biofuel production and use. The second part discusses developments in Europe in the form of the EU Directives and its implementation in two European countries that have followed different trajectories: United Kingdom, and Sweden. The methodology followed has been a desktop analysis of more than 20 scientific publications in the area of biofuel assessment. It also draws on information in policy and legal documents, informative material (conference presentations[6]), country reports, and general studies.

9.2 Areas of international debate concerning biofuel development

9.2.1 Global and Regional potential of bioenergy crops

Several assessments of the potential for bioenergy crop production have been carried out in a European and global perspective (EEA, 2007; WBGU, 2008; IEA, 2009; Zah et al. 2007; Dornburg et al. 2010; Fischer et al. 2010).

Dornburg et al. (2010, p 263) summarizes the global biomass potential in three categories:

- Organic waste and residues from forestry and agriculture: 30-180ExaJoule per year (EJ per year, (mean estimate 100EJ per year).
- Likely surplus forest growth available : 60-100EJ per year
- Biomass from assuming perennial cropping systems, ranging widely from
  - 120EJ per year from surplus good quality lands,
  - Additional 70EJ per year if degraded and marginal lands are included, and
  - Extra 140EJ per year assuming improved agricultural management

Depending on limitations assumed, the global potential is estimated to be between 200-500EJ per year by 2050. However it is substantially lower if good quality agricultural lands were excluded (Dornburg et al. 2010). One example taking such restrictions into account estimates the economically viable and sustainable potential for global bioenergy (energy crops and

[6] Two of the authors participated in two World Bioenergy Fuel Conferences during 2009 and 2010 both held in Sweden. The number of participants between the two conferences swelled from 800 to 4000.

waste/residues) to only 40-85EJ per year by the middle of this century (WBGU, 2008).

First generation biofuels for transport provided only 0.3 % of global final energy consumption in 2006 and 1.8 % of total transport fuels in 2007 (OECD/FAO 2008). In a short to medium term reference scenario, the IEA (2007) expected that biofuels for transport would increase from 0.8EJ in 2005 to 2.4EJ in 2015 and 4.3EJ in 2030, contributing to an increasing share of up to 0.9 % of global total energy consumption in 2030 (UNEP, 2009).

There is less geographical concentration of the global biofuel potential compared to the distribution of fossil fuel resources in the world (IEA 2007), but there are countries that have clear advantages, in particular in tropical areas and for the development of the so called first generation biofuels (based on sugar, starch and vegetable oil – often derived from food or fodder crops). At present, the two major biofuel-producing countries are the US and Brazil; 46 % of global production takes place in the US, 42 % in Brazil, 4 % in Europe, and 8 % in the rest of the world (World Bank, 2008). The contribution that biofuels can make to independence and security of energy supply may hinge upon further technological advancements and commercial development of second generation (use of non-food feedstock, including cellulosic material) and even third generation biofuels (algae) (Sims et al. 2008).

9.2.2 Biofuels contribution to climate mitigation and the issue of Indirect Land Use Change

A wide range of studies have been conducted to assess the maximum obtainable carbon emission reduction potential from replacing conventional fossil fuels with biomass based alternatives. One of the most widely used methods is Life Cycle Analyses (LCA) of different feedstock and product chains. The United Nations Environment Program UNEP conducted a review of a number of these studies. Figure 9.1 shows the emission results from different crops and biomass types.

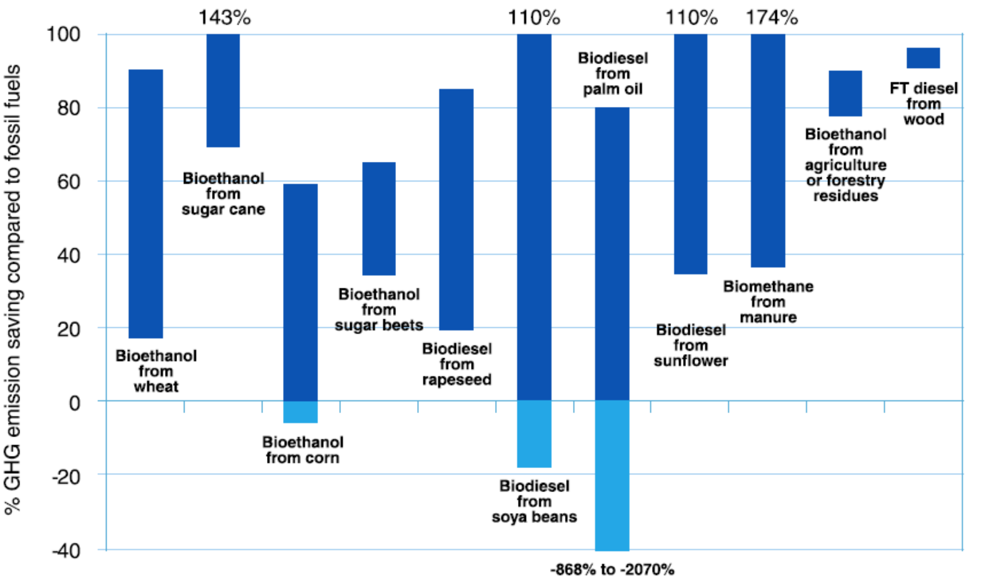


Figure 9.1 Greenhouse gas savings of biofuels compared to fossil fuels.
Source: UNEP (2009) compiled from various studies.

Indirect land use effects have emerged as a critical aspect of biofuels production (e.g. Searchinger et al. 2009). Indirect land use change refer to effects that follow if biofuel production displaces agricultural production, which is moved to other areas, potentially leading to additional greenhouse gas emissions, and a further loss of biodiversity, not directly caused by the biofuel production itself (Stehfest et al. 2010). Some studies have concluded that if these effects are included in the LCAs, biofuels for transport may produce more emissions than fossil fuels (e.g. Searchinger, 2009), taking into account the former land use. Such effects are currently not considered in biofuel certification schemes (UNEP, 2009), nor in many LCA based studies.

9.2.3 Food versus fuels

The impact of biofuels on food prices has created a wide and heated debate. The rapid expansion of biofuel productions already observed and expected in the coming years will affect agricultural markets and food systems.

The scientific literature on the food vs. fuels debate is led by studies from the United Nations Food and Agriculture Organization, who also produces highly cited statistics, such as the Food Price Index. Often the popular media respond to the simple statistics rather than the more complex research, suggesting simple correlation, which then trail the political debate (see for example[7]).

In 2008, during a previous spike of food prices, a debate on food vs fuels escalated (FAO 2008). The further prospects that extreme climate events (draughts, flooding, intensive rain) may again negatively affect agricultural systems and food production gives prominence to the need to ensure that the promotion of biofuels can take place under sustainable forms of production. Food price hikes and induced food insecurity will likely continue to engage the public and decision makers, even when biofuels development is only one of the many other intervening factors (e.g. meat based diets, production of high-protein animal feed, agricultural policies in EU and US) (Cockerill et al. 2008).

9.2.4 Sustainability

In the last years attempts have been made to provide comprehensive assessments connecting the above mentioned and several more issues involved in biofuel exploitation. This often takes the form of sustainability analysis or criteria (EEA 2006; Elghali et al. 2007; Petrou et al. 2009). However, so far no generally accepted way to approach sustainability issues has yet emerged. There are different frameworks, country-regional studies and scenario studies.

The earlier literature suggest that biofuels systems show moderate to strong fossil fuel substitution potential and GHG savings compared with conventional petroleum-based fuels (Blottnitz & Curran, 2007). Evaluations on these terms have tropical sugar crops, in particular ethanol from Brazilian sugar cane, as one of the most productive feedstock (De Almeida 2007, Goldemberg, 2007). Such advantages has led Brazilian bioethanol to become the first resources to be verified by application of international sets of sus-

[7] http://www.nytimes.com/2011/04/07/science/earth/07cassava.html?_r=1&hp

tainability criteria, although notably without including more recently considered factors such as indirect land use effects.

A number of other systemic sustainability-related effects have been less discussed so far. One example is how observable recurrent draughts or flooding may change patterns of agricultural production and affect the balance of biofuels vs. food production. Sustainable development issues of greater concern to stakeholders in developing countries do not figure strongly in current sustainability schemes, considering topics such as land rights, land use changes (not in terms of carbon but in terms of tenure), access to water supply, soil erosion, inclusion of communities of small farmers and especially women as part of the economic model (poverty vulnerability), low cost for land and labour etc. (Martinelli et al. 2008).

9.2.5 Biofuel development in Europe

In EU a set of sustainability criteria have been included in the regulatory framework of energy consumption, notably in the Directive 2009/28/EC of 23 April 2009. The directive prescribes that each Member State shall ensure at least 10 % of energy consumption for transport in 2020 is from renewable sources. It also defines a set of sustainability criteria, which include among others: a) GHG saving of at least 35 % (50 % from 2017 and 60 % for new installations from 2018; default values and calculation methods provided); b) No raw material from converted land with high biodiversity value or high carbon stock is allowed. The criteria are not mandatory specifications for production or use of renewable fuels, but they must be fulfilled if a particular consignment is to be counted towards the national target. Some weaknesses have been claimed (see e.g. (Eickhout et al. 2008), such as the lack of attention by the Directive towards the indirect land use changes and associated emissions, an insufficient definition and hence protection of 'highly bio-diverse grasslands', and that the initial 35 % substitution limit for Greenhouse gasses prevents almost no biofuel from entering the market, assuming the allocation methods and default values established in the Directive, and gives no incentives to improve practices or to reduce administrative cost.

Two different strategies adopted in two individual European countries are described as examples of addressing the sustainability issue.

SWEDEN: Sweden has followed a market and technology oriented approach supported by clear state initiatives at national and local level. An example of those has been the market promotion of a *clean fuel vehicle* acting to resolve the so called *chicken-and-egg* problem by also investing in the infrastructure of fuel stations. Both initiatives have facilitated the presence of 200.000 'clean vehicles' in Sweden[8]. In addition, initiatives between power companies like Vattenfall and Volvo for the electrification of the transport sector includes the use of bioenergy for electricity production. The developments of biofuels so far in Sweden appear to follow a successful combination of development of energy systems and energy efficiency, with a production system consisting of bio-refining plants with by-products for the chemical industry (Di Lucia & Kronsell, 2010). Sustainability verification is mainly done through independent verification companies.

[8] Jonas Ericson (2009), City of Stockholm, Presentation BioEthanol for Sustainable Transport BEST www.best-europe.org

UNITED KINGDOM: The UK Government has been attentive to the advice given on scientific reports to formulate its policy on biofuels (Stern 2007, RFA 2009). The level of domestic production of biofuels is low. The UK has developed a full institutional approach with the creation of the Renewable Fuels Agency (RFA) which manages the system to evaluate sustainability. Under current UK policy the Renewable Transport Fuel Obligation (RTFO) includes a carbon reporting and sustainability certification scheme, and creates incentives based on the carbon performance of the biofuel used, taking the feedstock source, processing and distribution into account. The reporting strategy is based on open disclosure of company performance (RFA, 2008/2009). There are several proposals to build domestic bioethanol plants utilizing wheat and sugar beet. The UK considers biofuels an expensive option for greenhouse gas mitigation (Stern, 2007), rather than a means of strengthening energy security or supporting British farmers to diversify activities to food and fuels, which reflects a contrasting approach to countries like Sweden.

9.3 Conclusion

This summary review has reported some important strands in the current state of international debates on biofuels. A substantial potential of biomass resources exists worldwide. The majority of studies reviewed agree that biofuels carry promises for transport energy. Alongside there is a recognition that the proper utilization of the biomass potential requires that a significant number of conditions are in place. Chief among those conditions are the need for a strong sustainability framework as a system that can recognize indirect effects, improved agricultural management, and good governance in the management of land, labour, water and interrelated resources. The setting of targets or criteria for CO_2 replacement is a highly political element, driven by climate concerns on the one side, and economic considerations for protecting bioenergy providers and not impeding global biofuel market development.

The intensity of debates on biofuels countries in Europe has followed different trajectories. This summary discussed the cases of Sweden and the United Kingdom adopting two very distinct approaches. Sweden, together with a small group of countries (Germany, Austria), have pushed for expansion and has achieved a larger than 3 % biofuel (bioenergy refer to also other sectors than transport) share in their markets by 2008. The United Kingdom has followed a more market driven approach but has created a governmental agency charged with defining and administering an assessment framework to promote the sustainability of their biofuel development. The future path in many other European countries will likely resemble something in between these two paths.

While scientific analysis and methodology has progressed and continues to do so in terms of providing more comprehensive assessments, it remains the case that significant amount of assumptions of a non-scientific nature and political trade-offs are made. A review of the international scene also reveals that there is still limited understanding of how biofuels will function as a system of globally traded commodities, agricultural products, energy products, with specific global, long-term effects on natural resources and ecosystems.

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SCENARIOS FOR BIOFUELS IN THE ROAD TRANSPORT SECTOR - ENVIRONMENTAL AND WELFARE ECONOMIC CONSEQUENCES

Synthesis report from the REBECa project

The project, Renewable energy in the transport sector using biofuel as energy carrier (REBECa), aimed to investigate the potentials for providing biofuels for the road transport sector based on domestically cultivated bioenergy crops, and to analyse the consequences for air quality, land use, GHG emission and welfare economy. Moreover, a review of international perspectives on sustainability of biofuels was carried out. Different scenarios for the introduction of biofuels were developed – one aiming at 10 % share of biofuels in 2020, and another aiming at 25 % share in 2030.

A forecast of the road transport until 2030 was produced and ensuing energy demand modelled. Estimates of the resulting demand for biomass, based on wheat grain, straw and rape, were introduced in agricultural scenarios of production and land use, and the possibilities for responding to the biomass requirements were analysed. Well-to-wheel emissions to air were calculated and impacts on air quality and health hazard investigated. Welfare economic effects corresponding to the well-to-wheel analytical framework were analysed. Results show that changes in air emissions (apart from CO_2) resulting from substitution of fossil fuel with biofuel were small, due to the general reduction of air emissions owing to EU policy implementation and technological development. The provision of sufficient home-grown bioenergy crops would at some stage influence the production of fodder. The overall results for fossil fuel reductions, CO_2 emissions and the welfare economic costs using rape, wheat grain and straw as bioenergy crops, may point in opposite directions for the different fuels. While the largest gains in fossil fuel saving is related to the Rape Methyl Ester (RME) production chain, the welfare economic benefits show the largest positive results for 2nd generation biofuel. Results are highly dependent on decisions related to the analysis of co-products, and the prices of oil and wheat

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