UK ENERGY RESEARCH CENTRE

Towards Sustainable Energy Use for Transport

Working Paper

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THE UK ENERGY RESEARCH CENTRE

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To avoid duplicating research and development funded by other public and private sector programmes, much of ES's efforts are on co-ordination and networking rather than original research.

Introduction

This paper comprises a review of technology roadmaps on sustainable energy use for transport, including road, rail, shipping and aviation. The paper summarises the environmental impacts of ‘renewable’ energy use for transport and the advances in knowledge and technology required to mitigate negative environmental impacts and to ensure environmental sustainability. It will assess the extent to which these issues are addressed by roadmaps from both Europe and North America (roadmaps are indicated by number in parenthesis) and will highlight omissions and apparent gaps in knowledge.

1. Transport Biofuels

1.1. Environmental impacts of transport biofuel production

Roadmaps covering the production of transport biofuels fall into two categories: (i) general sustainable energy technology roadmaps which are wide-ranging but include information on biomass and biofuel production; and (ii) specific bioenergy roadmaps covering biomass and/or biofuel production. All of these documents highlight the environmental impacts of crop cultivation for the production of transport biofuels. These include loss of habitat, reduction in biodiversity and other consequences of agricultural processes. Some also indicate that the full extent of these impacts is unknown.

The negative effects of intensive agricultural practices on the environment are well-documented (5, 7, 8, 11, 17, 19). For example, cultivation of sugar cane to produce ethanol tends to reduce biodiversity and increase soil erosion. When sugar cane fields are burned (done to make harvesting easier), fires increase levels of CO and ozone and can spread to nearby native vegetation. Cleaning the sugar cane consumes vast quantities of water. This demand coincides with the dry season, contributing to water shortages and damaging river life (9). Disposal of vinasse, the liquid residue from sugar cane, can lead to alterations in the physicochemical characteristics of groundwater, with resulting high concentrations of magnesium, aluminium, iron, manganese, and chloride. The high BOD values of vinasse might also affect groundwater and rivers. However, none of the roadmaps cite this problem.

Corn causes more soil erosion than any other crop grown in the United States; it also needs relatively large quantities of fertilizer and water. If pesticides are used then these pollute soils and waters, and pose a further threat to biodiversity (8). Furthermore, monocultures, in general, are associated with increased pest problems, diseases and soil degradation (1, 8), which reduce yields.

There is significant loss of habitat if uncultivated or 'set-aside' farmland (1) or forests (8, 17, 19) are used for cultivation of biofuel crops, and it can be particularly harmful to bring previously uncultivated land into agricultural use (7).

Some roadmaps claim that biofuel crop cultivation can have positive environmental impacts – improving soil quality, reducing soil erosion, expanding wildlife habitat and decreasing the environmental impacts of fossil fuel production (2, 3, 5). The European Commission's Biomass Action Plan (7), in particular, highlights the potential benefits to the environment from biomass production, with some provisos.

'Energy crop cultivation can help to improve the overall profitability of a farm business, contributing to the maintenance of farming in areas where this may have a positive impact from an environmental (or wider sustainable development) perspective. This is important in a number of regions to improve soil stability and prevent irreversible landslide damage. Another potential positive aspect of energy crop production is its contribution to the establishment of new crop rotation systems that are more advantageous from a wider environmental point of view (for example, alternatives to the monoculture of maize). [However, if] energy crops are grown on agricultural land that was previously used for food production, the change in environmental pressure depends on which biomass crops are cultivated. The plantation of tree crops to enhance soil cover on degraded land can also have a globally positive impact. However this *should* not take place on steppic or mountain habitats that have a high biodiversity value. The use of wastes and residues for energy purposes often gives an environmental bonus compared with other means of disposal. For forest residues …..in some regions … their extraction helps to reduce the risk of fire.' Furthermore, using grass cuttings from uncultivated land for biomass production can help to prevent the decline of biodiversity on species-rich grasslands due to land abandonment (7) and some biofuel raw materials, like jatropha, could allow the sustainable use of low-value land in third world countries.

Biomass production may appear to have fewer negative environmental impacts than liquid biofuel production, partly because biomass can be derived from a wide variety of crops instead of monocultures (18). However, removal of forest residues (in the US, for example) may destroy habitat and endanger biodiversity (14), and removal of crop residues can be detrimental to soil condition (15). In the marine environment - seaweed and other aquatic plants are proposed as sources of biomass (12), but without any apparent analysis of possible environmental consequences.

Only the Roadmap for Biomass Technologies in the United States (11) refers to problems associated with the storage of biofuels and biomass, but it does not explain what these problems are.

There is a serious risk that increased demand from the EU and USA for raw materials (such as vegetable oil) will cause agricultural expansion in developing countries and be responsible for further destruction of natural habitats and deforestation. EU roadmaps do predict the need for substantial imports from the third world (7, 8, 9) but US and Canadian government roadmaps do not (10, 17). The latter cite the importance of 'security of supply' of energy and the adequate availability of land in their own countries.

Several roadmaps state that biofuels and biomass have the potential to decrease transport-related greenhouse gas (GHG) emissions, improve air quality, and decrease biodiversity effects of conventional fuels e.g. oil spills (2-5, 7, 10, 19). However, the production of biofuels and biomass requires agricultural and industrial processes which generate pollutants (e.g. manufacture and transport of fertilizer, harvesting, distillation to produce ethanol) and these need to be considered in a comparative life-cycle assessment of biofuels (1, 11). These life cycle assessments are essential 'to identify and evaluate the emissions, resource consumption, and energy use of all processes …. such that efforts can be focused on mitigating negative effects' (Multi-Year Program Plan for Biomass (10)).

The Renewable Energy Road Map (EC, 2007 (5)) states that improvements in air quality through biofuel use are likely to be small due to the strong controls on pollution from transport in the EU. Ethanol combustion may increase ambient levels of pollutants (e.g. aldehydes), whilst biodiesel has higher NOx emissions than petro-diesel, but generally lower CO and particulate emissions. Biomass (such as sustainably-produced forest and wood products) offers the greatest GHG savings, but roadmaps do not directly favour use of these materials on this basis, although the Biomass Action Plan (7) concludes that increased development of "second generation" biofuels from wood and wastes could improve biofuels' environmental profile, and the EU Strategy for Biofuels (8) aims to give a high priority to research into these fuels.

Consequently, government policies aimed at reducing environmental externalities in the agricultural sector are essential. But none of the roadmaps produced for governments establish a strong system of safeguards for environmental protection. The Biomass Action Plan (7; produced by the European Commission) cites the 'need to guarantee that site-specific environmental requirements are observed when producing biomass', An EU Strategy for Biofuels (8) merely notes the need for 'measures to ensure optimal GHG benefits from biofuels' and states that 'only biofuels whose production in the EU and third countries complies with minimum sustainability standards will count towards the targets' (for a 5.75% market share for biofuels in 2010). However, in its 2007 Biofuels Progress Report the European Commission identifies that 'measures to guarantee the environmental credentials of biofuels, and regular monitoring and reporting of the well-to-wheel environmental impact of biofuels production and use' are essential. The WWF suggests that the EU 'should establish a legally binding certification system for both imported and domestic biofuels. The certification system must be based on enhancing the potential of biofuels to cut greenhouse gas emissions, while avoiding the wider environmental impacts of biofuel production. This will help to protect the environment in developing countries and contribute to CO_2 emissions reductions in the EU in a sustainable way. The certification system must also cover the climate benefits of any potential biofuel, as energy-intensive production methods mean many biofuels offer little advantage over conventional fuels in terms of overall greenhouse gas emissions. [The WWF itself] has already been instrumental in setting up the Roundtable on Sustainable Palm Oil, which has brought together producers, buyers, retailers, financial institutions and NGOs to develop practical criteria for the responsible production of palm oil.'

Roadmaps produced by consortia which include environmental groups, or those which involved stakeholder consultation (e.g. Roadmap for Agricultural Biomass Feedstock Supply in the United States (14)) have the greatest recognition of environmental impacts. One of the specific conclusions drawn from the consultation process for the Biomass Action Plan (7) was 'environmental concerns must also be addressed whenever biomass is grown for food, products or fuels. This has to be done by taking an overall systems approach and by comparisons with other alternatives and not in isolation.'

1.2. Advances in knowledge and technology required to mitigate negative environmental impacts and to ensure environmental sustainability

All the roadmaps listed in Tables 1 and 2 (except 2-4, 6, 9) cite a need for further research into (and development of) agricultural practices for biofuel crops, with the aim of reducing their negative environmental impacts. In particular, the Renewable energy technology road map (1) sets targets for studies 'into the long-term soil and water quality implications of combined energy cropping and effluent disposal schemes', and the development of 'low impact methods to harvest, collect, transport, process and integrate forest residues and short rotation crops'.
Key issues are:

- identifying the conditions under which crop residues can be removed without increasing erosion or reducing soil productivity (10, 14, 15)
- the development of 'selective harvest technology that can evenly remove only desired portions of the residue' (1, 10, 17)
- determining the proportion of corn stover which should be removed (7, 10)
- determining the effects on wildlife of forest thinning to supply biomass (14)
- establishing how energy crops should best fit within crop rotation cycles (8)
- new methods for soil erosion control and fertilization, reducing water use and reducing nitrogen input (11, 14, 15)
- reducing agricultural waste streams (1, 13)
- minimising environmental impacts of pre-processing, storage and transportation (1, 11, 14)

But few roadmaps (1, 11-14, 16, 17) provide precise details and targets for achieving these improvements. Specific omissions are the disposal of vinasse, reducing the use of water during pre-processing (e.g. washing sugar cane) and any investigation of the effects of harvesting seaweed and other aquatic plants on the marine environment.

The Roadmap for Biomass Technologies in the United States (11) cites the need to improve our 'technical understanding of plant biochemistry and enzymes and develop the ability to engineer enzymes within desired crop' which should lead to advances in the manipulation of plant biology (6, 11-13, 15, 17), for example, improving pathogen resistance in energy crops to increase yields and reduce pesticide use (16), and improving salt tolerance (11). Any improvements which increase crop yields could help to reduce the amount of land required for biofuel and biomass production and so minimise wildlife habitat loss.

All the roadmaps in Tables 1 and 2 (except 2) address the need for developing new and existing technologies for the efficient conversion of plant material into fuel on an industrial and economically-viable scale. A number of roadmaps (3, 6, 10-13, 17) provide details of specific R&D challenges, priorities and targets e.g. catalytic and enzymatic conversion of cellulose, hemi-cellulose and ligno-cellulose to bioethanol (3, 6, 10, 11, 17); genetically-engineering microbes to convert biomass to bioethanol (3); photolytic production of hydrogen from biomass; using enzymes or genetically-engineered microbes (3); thermo-chemical conversion of biomass residues to synthetic natural gas (SNG) (6, 10); and generating biodiesel from Fischer-Tropsch synthesis of gasified woody biomass (10, 17).

The release of new genetically modified organisms, e.g. bacteria which can convert cellulose to ethanol, is a potential threat to biodiversity. 'Genetic modification of dedicated crops for improved characteristics may create risks to native populations of related species.' This is noted only by the Roadmap for Agricultural Biomass Feedstock Supply in the United States (14), although the Biobased Products and Bioenergy Vision and Roadmap for Iowa (15) does state that genetically modified crops should be assessed to ensure that they have no negative environmental impacts.

Finally, the Renewable energy technology road map (1) cites 'Clean-up technologies for emissions from the combustion of biomass and wastes, particularly dioxins, heavy metals, and particulates' as a development need.

2. Road Transport

2.1. Environmental impacts of energy use in road transport

Each of the roadmaps (except 21) acknowledges the contribution of tailpipe emissions to climate change and highlights the need to reduce them. The European ERTRAC Research Framework (25) also recognises the need to reduce the impacts of surface run-off on water quality, and the impacts of the road transport system on natural habitats, but only the Foresight Vehicle Programme Technology Roadmap (20) sets 'environmental performance measures and targets [which] relate to the overall environmental burden of road transport, global warming, pollution, energy and material waste'.

2.2. Advances in knowledge and technology required to mitigate negative environmental impacts and to ensure environmental sustainability

Most road vehicle development roadmaps (20, 21, 23, 25) list the technical developments and innovations essential for improving engine performance, and increasing both cost-effectiveness and energy efficiency. These include development of fuel cells, hybrid engines, low viscosity lubricants and waste heat recovery systems. But only two roadmaps (20, 25) relate these advances directly to the environment and set targets for reducing the use of fossil fuels, generation of waste, emissions of GHG and other pollutants and enabling the utilization of biofuels and hydrogen. The ERTRAC Research Framework (25) provides an exhaustive assessment of essential advances in the areas of biofuel development, vehicle design, recycling, traffic management systems and road construction; a typical statement in this roadmap is 'Cost effective processes for large-scale hydrogen production from biomass, wind and other renewable energy sources are needed.' Greater detail of the research and technological 'break-throughs' required to achieve these advances is provided by the Foresight Vehicle Programme Technology Roadmap (20), which has the creation of an environmentally-sustainable road transport system as part of its 'vision'. This roadmap aims to achieve the specific targets for carbon dioxide emission reductions desired by the European Commission (to 140g/km new car fleet average in the EU by 2008 for passenger cars and to 120g/km by 2012). To meet these targets 'New sources of non-oil derived energy are required, which impacts the development of natural gas derived and bio-fuels as well as hydrogen. Improvements to conventional propulsion unit thermodynamic efficiencies will need continuing attention with the development of advanced, fuel efficient, high specific output, downsized engines a key. Advances in lubricants and tribological coatings are needed to reduce friction. Vehicle weight is also a factor in improving overall energy efficiencies. Lightweight materials and structures, whilst retaining or improving safety, are needed to enable gains to be realised.' Research priorities and challenges relating to each of these topics are described in detail. In contrast, Carbon to Hydrogen Roadmaps for Passenger Cars (21) aims to reduce well-to-wheels emissions of carbon dioxide, but it focuses on advances in vehicle technology alone and does not deal with the availability of sustainably-produced hydrogen.

Conflicts between technological developments contributing to different aspects of environmental sustainability are highlighted by two roadmaps (20, 24). The Foresight Vehicle Programme Technology Roadmap (20) notes that 'Engine efficiency improvements imply more, smaller particulates, with attendant post-combustion clean-up required.' And that 'the technologies required for pollutant reduction are generally at the expense of CO_2 reduction and continuing vigilance is required for prioritising the needs'. The Roadmap for Sustainable Mobility (24) highlights that reducing particulate emissions (by the installation of a particulate filter and the necessary adjustments to the engine management system) reduces fuel economy in diesel cars. Also that 'Fixed recycling quotas and bans on the use of certain materials, for example, render lightweight design concepts involving composite and hybrid materials more difficult to implement and prevent the potential for cutting weight – and thus fuel consumption – from being exploited to the full'.

3. Air transport

The documents included in Table 4 are strategies, not roadmaps; no roadmaps towards the sustainable use of energy for aviation have been identified during this study. However, for this study, the strategies listed in Table 4 do serve the same purpose as roadmaps. There are also other documents (not included in the table) which also describe the environmental impacts of aviation and explore the technological improvements which might offset these impacts and these documents will also be discussed.

3.1. Environmental impacts of energy use in air transport

Each of the five air transport development strategies (26-30) highlight that aircraft emissions (CO_2, NO_x, soot and other particulates) have a major impact on the environment, contributing to climate change and also reducing air quality, particularly in the vicinity of airports. These studies also recognise that condensation trail (contrail) and cirrus cloud formation are major contributors to the radiative forcing effect of aviation. In addition, The Environmental Effects of Civil Aircraft in Flight[1] states that 'the total radiative forcing due to aviation is probably some three times that due to the carbon emissions alone'. All the strategies note that the impact of aircraft exhaust gases on the climate is not fully understood. It is also highlighted that whilst aviation contributed only 3% of GHG emissions in 2005, growth on the industry could outstrip any gains in efficiency (30).

3.2. Advances in knowledge and technology required to mitigate negative environmental impacts and to ensure environmental sustainability

The Environmental Effects of Civil Aircraft in Flight[1] produced by the Royal Commission on Environmental Pollution states that 'the ambitious targets for technological improvement in some industry announcements are clearly aspirations rather than projections'. This suggests that the gap between current knowledge and technology and that required for environmental-sustainability is too great for any organisation or government to envisage bridging on a 5-20 year timescale, and in this context the setting of research priorities is particularly important

Four of the strategies (26-28, 30) highlight that an important environmental research priority in this field is elucidating, in detail, the effects of aircraft emissions (particularly water vapour, particulates and NOx) on the atmosphere and on climate. The Study into the Potential Impact of Changes in Technology on the Development of Air Transport in the UK (29) concludes that this knowledge is essential to direct effective technological development and that, currently, 'the technology mitigation potential remains largely uncertain and unverified. This study, along with the Strategic Research Agenda, recognises that contrail and cirrus cloud formation are identified as major contributors to the radiative forcing effect of aviation. Whilst operational procedures and to certain extent technology developments are being developed to mitigate contrail formation, specific information from technology developers on these options remain vague and the levels and certainty of the mitigation potential remain largely un-quantified.'

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[1] Royal Commission on Environmental Pollution (2002) The Environmental Effects of Civil Aircraft in Flight: Special Report.

Greater understanding of the different impacts of the components of aircraft exhaust gases is also crucial for resolving conflict between the measures taken to reduce NO_x emissions and CO_2 production, for example. As explained by Air Travel – Greener by Design, Mitigating the Environmental Impact of Aviation: Opportunities and Priorities (26), "It is clear that total environmental impact can be reduced by setting different priorities in design. For example, NOx emission can be reduced by reducing engine pressure ratio and ozone generation by NOx might be reduced by optimising designs to cruise at lower altitudes. In both cases, the result is likely to be an increase in fuel burn, CO_2 emission and operating cost. Contrail and cirrus cloud formation and ozone creation might also be reduced by operational measures, but at the expense of an increase in fuel burn.' A strategy towards sustainable development of UK aviation (27) states that 'technology measures to reduce noise at source can have a negative impact on fuel efficiency; operational measures such as flying lower to avoid formation of cirrus cloud would lead to increased carbon dioxide (CO_2) production because of the reduced fuel efficiency at lower altitudes.' This strategy also points out that whilst hydrogen-powered aircraft produce no CO_2 they would generate significant quantities of water vapour. Another potential dilemma is that the development of higher pressure ratio engines will increase fuel efficiency but will lead to more NO_x per unit of fuel burnt (29).

Reducing the climate change impact of aviation identifies that 'while research aimed at narrowing remaining uncertainty and further improving understanding of the effects of aviation on climate should continue, higher priority must be given to EU aeronautics research aimed at actually reducing the negative impacts of air transport on climate change'. Each of the strategies describes in detail, future developments and new technologies proposed for reducing emissions and increasing fuel efficiency of kerosene-fuelled engines. The majority of these relate to improving engine and airframe design (including the use of light-weight, high-strength materials) and propulsion efficiency. Only one strategy (29) explores the potential of hydrogen-powered aircraft (the Cryoplane), and the aviation industry has expressed little enthusiasm or optimism concerning biofuels until recently, although this is a rapidly changing situation. Air Travel – Greener by Design, Mitigating the Environmental Impact of Aviation: Opportunities and Priorities (26) states that 'further research in alternative fuels was … not seen by the Sub-Group as a priority for aviation' whilst A strategy towards sustainable development of UK aviation (27) states that 'it is unlikely that alternative fuels will play a significant role in aircraft propulsion in the foreseeable future. Nonetheless, the industry will support and encourage research projects to find possible replacements for kerosene'. More positively, The Strategic Research Agenda (28) written by the Advisory Council for Aeronautics Research in Europe, predicts that 'the next step will be the availability of alternative fuels (e.g. liquid H2, bio fuels, synthetic fuels, LNG) or power sources (e.g. fuel cells), provided that it is demonstrated that they can reduce radiative forces.' Consequently, these strategies do not provide information concerning the technological advances (for example, in engine design) essential for the use of alternative fuels (other than hydrogen). There have been studies which explore the feasibility of renewables for aviation, for example The Potential for Renewable Energy Sources in Aviation[2], produced by the Imperial College Centre for Energy Policy and Technology, which assesses the environmental impacts of different renewable fuels, and Transitioning to Biomass Fuels in General Aviation[3], produced by the Baylor Institute of Air Science, and The Present and Future Potential of Biomass Fuels in Aviation[4] (June 2000), produced by the Renewable Aviation Fuels Development Centre, Baylor University. The latter concludes that ethanol is a viable aviation fuel for existing aircraft engines (in contrast with the Imperial College Centre for Energy Policy and Technology study which proposes only hydrogen, biodiesel and Fischer-Tropsch kerosene).

Three of the strategies (27-29) predict that targets for reducing CO_2 and NO_x emissions by 50% and 80%, respectively, by 2030 are achievable, even using kerosene as the sole aviation fuel. However, the Study into the Potential Impact of Changes in Technology on the Development of Air Transport in the UK (29) points out that 'taken together these new technologies cannot offset the additional environmental impact associated with forecast growth in air traffic and therefore the net or overall environmental impact from aviation is predicted to increase from today's levels'.

Post-2020 technologies envisaged by The Strategic Research Agenda (28) include 'Creating propulsive power from new forms of energy; Solar Power, Nuclear Energy, Hydrogen from the sea, Beamed Energy devices using laser or micro-wave and ground-powered energy forms'; 'morphing the aircraft structure into different shapes or aerodynamic forms under computer control. Thrust may be vectored to give directional or lift control. Plasma jets may replace the burnt fuel exhaust as the means of delivering thrust. Lift mechanisms may use alternative forces to fluid dynamics to derive the vehicle lift.'

4. Sea transportation

The development of sustainable energy for shipping has not held a high priority in transport policy in industry and government until very recently. Three (31, 32, 35) of the five documents included in Table 5 describe strategies, not roadmaps and no detailed roadmaps towards the sustainable use of energy for sea transportation have been identified during this study. However, all but one of these publications highlights environmental impacts and potential means of remediation. For example, one of the strategic objectives of the Maritime Administration Strategic Plan for Fiscal Years 2003-2008 (32) (produced by the US Department of Transport) is to 'Promote maritime and intermodal transportation solutions that enhance environmental stewardship', and the

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[2] Saynor, B., Bauen, A. and Leach, M. (2003) The Potential for Renewable Energy Sources in Aviation (PRESAV Final report).

[3] Transitioning to Biomass Fuels in General Aviation, produced by the Baylor Institute of Air Science

[4] The Present and Future Potential of Biomass Fuels in Aviation (June 2000) produced by the Renewable Aviation Fuels Development Centre, Baylor University.

outcome should be 'reduced pollution and other adverse environmental effects of transportation and transportation facilities'. Remarkably, the Marine and Ocean Industry Technology Roadmap (34) (produced by the National Research Council, Canada) does not address environmental issues at all. However, following the publication of A European Union strategy to reduce atmospheric emissions from seagoing ships (31) in November 2002, the European Commission adopted the Green Paper Towards a future Maritime Policy for the Union: A European vision for the oceans and Seas[5] in June 2006.

There are other published strategies which encompass sea transportation, including An Ocean Blueprint for the 21st Century Final Report of the U.S. Commission on Ocean Policy[6], Canada's ocean strategy "our oceans, our future"[7] and the Portuguese National Oceans Strategy[8]. But these documents, whilst promoting the concept of environmental stewardship of the oceans in general terms, provide no useful information for this study; the latter document refers only 'in passing' to 'the urgent need for the oceans to be managed with an eye to conservation and sustainable utilisation'.

'Sustainable shipping, progress in a changing world' was a conference was held on the 1st/2nd of February 2005 in London and was organised by the Maritime and Coastguard Agency in conjunction with the Institute of Marine Engineering, Science and Technology (IMAREST). Presentations included -

1. Sustainable Energy in Marine Transportation, by Lloyd's Register EMEA, which proposed a simple roadmap for a transition to electrical ships fuelled by hydrogen via duel fuel diesel engines, but with no timescale;
2. A Path to Sustainable Shipping, BSR's Sustainable Transport Initiative and Clean Cargo by 'Business for Sustainable Responsibility', merely promoted a shift to oceanic transportation from other methods and made the prediction that 'Ocean transportation may gain in importance in a sustainable transport network' due to the relatively high energy efficiency and relatively low GHG emissions of shipping.
3. Sustainable Shipping, the vision of the port of Rotterdam, by Edo Donkers (Rotterdam Port) was pessimistic in outlook, concluding that the shipping industry is not keen to innovate technologically, that there is little funding available for this, and that there is no R&D drive.

4.1. Environmental impacts of energy use in sea transportation

Three of the publications (31-33) listed in Table 5 highlight the environmental impacts of SO_x and NO_x emissions. Sustainable Energy in Marine Transportation (33) notes that the Energy Intensity (KJ/t-km) of, and CO_2 and NO_x intensity (g/t-Km) from, shipping are low relative to other transport modes, but that SO_x intensity is high (significantly more than rail transport, but less than from

[5] EC (2006) Towards a future Maritime Policy for the Union: A European vision for the oceans and Seas Green Paper COM(2006) 275 final. Volume II - ANNEX
[6] US Commission on Ocean Policy (2004) An Ocean Blueprint for the 21st Century: Final Report
[7] Canada's ocean strategy "our oceans, our future" (2002) Department of Fisheries and Oceans, Canada.
[8] National Ocean Strategy 2006-2016 (2004) Portuguese Republic.

aviation) because marine (red) diesel is not Ultra-low sulphur like that use for road transport in the UK. The UK Department for Transports 2007 report on Low Carbon Commercial Shipping (35) focuses specifically on environmental impacts of shipping and technological solutions, but solely on CO_2 emissions and not on other pollutants. The Maritime Administration Strategic Plan for Fiscal Years 2003-2008 (32) also highlights the role of ballast water in the transfer of 'nuisance species' between habitats. None of these publications mention the environmental consequences of wrecking and collisions of oil tankers.

4.2. Advances in knowledge and technology required to mitigate negative environmental impacts and to ensure environmental sustainability

The Maritime Administration Strategic Plan for Fiscal Years 2003-2008 (32) notes that 'historically, investment in research, development, and deployment of air pollution reduction technologies in the maritime sector (including port equipment and vessels) has been minimal. As a result, while landside transportation has seen vast improvements in pollution control technologies and processes, marine transportation has advanced slowly. Emphasis must be given to identifying technology transfer and adaptation opportunities'. 'Means and strategies' include 'research on marine applications of hydrogen technologies', evaluation and implementation of 'ballast water treatment technologies' and 'conduct research and identify, demonstrate, and promote energy efficient, alternative fuels, and air pollution reduction technologies for maritime applications.' Sustainable Energy in Marine Transportation (33), highlights current technological developments in areas of alternative fuels (e.g. low sulphur fuels), alternative technologies (e.g. fuel cells) and energy efficiency, and the need for new engine designs (principally, for employing low sulphur fuels) and conversion technology (for generating hydrogen). Neither of these documents provides any detail of current and future research priorities. A European Union strategy to reduce atmospheric emissions from seagoing ships (31) focuses on regulatory measures to reduce emissions, not on technological innovation. However, the Commission has funded a number of reports which describe in detail the technological solutions for abatement and their feasibility, these are General Report, Shore-side electricity, NOx abatement, SOx abatement.

Most recently the Low Carbon Commercial Shipping (35) report by the UK DfT identified a range of research topics which should be pursued in order to achieve low carbon shipping. They concluded that the most promising in the short-term were: improvements to current propulsion technologies; expansion of biodiesel use (economic rather than technical barriers); and wind-assisted propulsion, although hydrogen fuel cells; and electric/hybrid-electric technology were identified as technologies for the long-term.

Other informative documents, not included in Table 5, include the Environmental Information Portal for Maritime Industries[9] which details environmental impacts of maritime emissions and remediation technologies and the Marine Sector

[9] Environmental Information Portal for Maritime Industries, Norwegian Maritime directorate.

Technology Plan[10] (Version 1, September 2005), produced by the DTI Aerospace, Marine and Defence Unit. The latter provides an overview of key technologies and R&D requirements for the UK marine engineering sector, and highlights the key areas for technology development (e.g. renewable energy, improvements in exhaust systems, improvements in sealing technologies to minimise accidental spills) relevant to environmental concerns. These include navigation and traffic management, as there are 'significant fuel savings to be obtained through more accurate ship's course holding'. Improvements in this area should also reduce collisions at sea involving oil tankers, which is one of the aims of the Galileo satellite navigation system.

There are several innovative ships in service which are designed to have a reduced environmental impact e.g. Ecoship (NYK Line, Japan); and Super Eco-Ship (National Maritime Research Institute, Japan). There has also been a number of projects trialling biodiesel use in commercial shipping including the UK Seafish project, and the Canadian BioMer and Bioship projects. All of these have demonstrated great potential for biodiesel use in shipping with economic rather than technological barriers to wider deployment.

Examination of environmental issues can be found within other publications, including the Advisory Council for Waterborne Transport Research in Europe (WATER*BORNE* TP) publication Vision 2020[11]. One of the aims of this document is 'safe, sustainable and efficient water transport' and it includes targets such as 'In 2020 the environmental impacts of air and water emissions will be reduced drastically', and it highlights the relevant 'innovation challenges' e.g. 'A 'zero emission' approach, notably on substances like SO_x, NO_x, CO_2, PM, VOCs is an enormous technological challenge. Reducing one pollutant may well have a negative effect on other pollutants, while no single option will be suitable for all types of ships' but this document provides no details of essential technological advances.

5. Rail transport

Five documents (36-40) have been identified which promote the sustainable use of energy for rail transport. Each of the documents refers to the lower environmental impact of rail transport compared to road and air but highlights the importance of reducing this further. Rail21: Sustainable rail systems for a connected Europe (37) and the Strategic Rail Research Agenda 2020 (40), both produced by the European Rail Research Advisory Council (ERRAC) in 2006-07, state that 'railway transport is (and will remain) by far the most environmentally friendly form of motorised transport. Nevertheless, the railway does not rest on its green laurels but continuously strives to improve in order to meet the growing expectations of society and become an ever better, quieter and cleaner neighbour.' ERRAC believes that 'the most effective contribution to the greening of transport in Europe is to encourage a modal shift to rail and highlights 'that

[10] Marine Sector Technology Plan (Version 1, September 2005) An overview of key technologies and R&D requirements for the UK marine engineering sector. Prepared by DTI Marine team.

[11] Vision 2020: Waterborne transport and operations. A key asset for Europe's development and future.

new standards and regulations must not only increase the level of environmental protection but also safeguard the commercial competitiveness of the mode while reducing dependence on fossil fuels, reducing exhaust emissions, improving design and offering a systematic approach to noise and vibration'.

5.1. Environmental impacts of energy use in rail transport

Rail21: Sustainable rail systems for a connected Europe (37) and the Strategic Rail Research Agenda (40) do not describe any environmental impacts of rail transport. The Railroad and Locomotive Technology Roadmap (38) (produced for the US Department of Energy) makes only indirect references to NO_x but does identify 'that diesel fuel for locomotives can contain 10 times more sulphur than diesel fuel for trucks. Sulphur contributes to formation of engine-out particulate matter, corrosive exhaust gases, and rapid poisoning of some after-treatment devices.'

Only The Rail Industry – A way forward on sustainable development (36) (UK Rail Safety and Standards Board, Feb. 2006) points out that locomotive diesel engines create emissions which contribute to global warming. It also compares these emissions favourably with those from road and air transportation; railways produce 'lower NO_x and particulate emissions per passenger km or freight Tkm than road and air [but] higher SO_2 emissions than road due to high Sulphur content of fuel. Two further key advantages of rail are the lower CO_2 emissions per freight tonne and passenger kilometre and the contribution the rail network makes to managing road congestion.' This strategy points out that 'diesel engine emissions have been the subject of new regulation from the EC and there is a threat of further tightening of these requirements. Key issues in this area are sulphur in fuel, exhaust emissions treatment and retrofitting cleanup technology.'

5.2. Advances in knowledge and technology required to mitigate negative environmental impacts and to ensure environmental sustainability

Each of the documents listed in Table 6 highlight that the focus of technological development in this sector should be on increasing energy efficiency and reducing emissions. Rail21: Sustainable rail systems for a connected Europe (37) proposes research in a number of general areas: to improve and deliver achievable standards for noise, emissions, diesel engines, etc; to develop new lightweight and low noise freight wagons; and to green the existing fleet. The Strategic Rail Research Agenda (40) identifies priority research areas for energy and environment as energy efficiency, environmental impact, design and the need to prepare for reduced availability of fossil fuels. The Rail Industry – A Way Forward on Sustainable Development (36) lists future research under general topics e.g. for reducing carbon emissions 'Future of grid distributed power technologies: power station efficiency, distribution loss, new materials technologies for power lines etc. Maglev [trains]'. Neither details nor targets are provided in either document. But The Rail Industry – A Way forward on sustainable development (36) makes two very important points:

1. Taxation issues, not technological barriers, are preventing the uptake of low sulphur fuels.

2. The widespread implementation and retrofitting of technology currently available - regenerative braking and exhaust treatment systems - could significantly reduce carbon and NO_x/particulates emissions, respectively.

In contrast, the Railroad and Locomotive Technology Roadmap (38) from 2002 describes in detail the advances in knowledge and technology required to reduce negative environmental impacts and to advance towards the environmental sustainability of rail transport. However, the principal driver for investment appears to be economics, not concern for the environment, or for sustainability; for example 'U.S. railroads spend over $2 billion per year, or approximately 7% of their total operating expenses, on diesel fuel.' The roadmap highlights that 'Some of the technologies that could be employed to meet new emission standards may negatively affect fuel economy — by as much as 10–15% when emissions are reduced to Tier 2 levels. Unfortunately, most of the techniques for reducing NO_x (e.g. exhaust-gas recirculation (EGR), very low sulphur diesel fuels, and after-treatment devices) also decrease the fuel efficiency of the engine and raise PM [particulate matter] emissions'. They observe that this decrease in fuel efficiency would have a serious negative effect on the financial stability of the railroads.

This document identifies and describes in detail 'critical research and development needs for reducing fuel consumption and emissions while maintaining or enhancing system performance.' These needs are in the following four areas:

- Train Systems – Aerodynamics, Wheel/Rail Friction, Rolling Resistance
- Locomotive Systems - Idle Reduction, Energy Recovery, Motors and Drives
- Locomotive Engines - High-Efficiency Turbo, Sensors and Controls, Fuel Injection/Combustion, NO_x Adsorber, PM Trap
- Advanced Power plants and Fuels – HCCI [homogeneous-charge compression ignition], Alternative Fuels, Fuel Cells

Consequently, they predict that 'a focused research and development program could enable the locomotive diesel engine to achieve thermal efficiencies of 50-55%, resulting in a reduction in specific fuel consumption of about 20%.'

Concerning alternative fuels the roadmap stated that 'most alternative fuels, with the exception of biodiesel and oxygenated diesel (oxydiesel), cannot be used directly without substantial modifications to engine and locomotive systems, as well as to the refuelling infrastructure'. However, more positively, they also point out that much of the alternative fuel technology developed for the automotive and trucking industries may be transferable to the railroad industry. Again, 'the primary barriers for alternative fuel use are not technical — they are cost, market acceptance, reliability, and deployment. However, there has been relatively little basic research and optimization with regard to locomotive engines using these or other alternative fuels. The roadmap lists the R&D activities that 'would need to be undertaken to determine which of these fuels offer the benefits in emission control and support after-treatment device development.' These activities include 'basic research on liquid fuels and blends to better understand the combustion process.'

Table 1. General Sustainable Energy Technology Roadmaps

Roadmap	Source	Environmental impacts highlighted	Research topics and targets proposed to address environmental sustainability issues
1 Renewable energy technology road map	Australian Government, Department of Industry, Tourism and Resources October 2002	Generation of biomass would require exploitation of marginal agricultural land and the harvesting of native forests, but the roadmap notes that 'there is a lack of knowledge about potential biomass resources and the roles that they play in their host ecosystems' and that there is a risk of land degradation and loss of habitat. Also that 'Significant fossil fuel inputs may be associated with land preparation, cultivation, fertilisation, harvesting and transport'.	Highlights and sets targets for 'Studies into the long-term soil and water quality implications of combined energy cropping and effluent disposal schemes', and the development of 'low impact methods to harvest, collect, transport, process and integrate forest residues and short rotation crops' and 'Clean-up technologies for emissions from the combustion of biomass and wastes, particularly dioxins, heavy metals, and particulates', as well as efficient conversion technologies.
2 Winning the Oil Endgame	Amory B. Lovins September 2004	'Sound biofuel production practices wouldn't …cause water or environmental problems, and can actually enhance soil fertility'. Use of biofuels reduces emissions of GHG and of other pollutants.	None
3 GTL Roadmap: systems biology for energy and environment	US Department of the Environment Office of Science. August 2005	Cellulosic ethanol crops have a role in reducing GHG levels and 'these crops improve air and soil quality, reduce soil erosion, and expand wildlife habitat'.	Details research and technological advances essential for achieving (a) industrial-scale enzymatic conversion of cellulose to ethanol, followed by use of genetically-engineered microbes to convert biomass to ethanol in one step; (b) photolytic production of hydrogen from water, biomass or via nitrogen fixation, by enzymes and genetically-engineered microbes. No projected time scales are indicated for achieving these goals.
4 Mobility 2030: Meeting the Challenges to Sustainability	World Business Council for Sustainable Development 2004	Use of biofuels reduces emissions of GHG and of other pollutants.	Highlights technological advances required for commercial conversion of biomass to biofuels.

5 Renewable Energy Road Map and Renewable energy Road Map: Impact Assessment	European Commission, January 2007	Roadmap includes summary of impact assessment of roadmap. Environmental impacts covered include GHG emissions, air quality and biodiversity. GHG emissions, including CO_2, from renewable energy sources are either low or zero. Increasing the share of renewables in the EU fuel mix will therefore result in significantly lower GHG emissions. Different scenarios and models produce different savings estimates from 430-900 Mt CO_2 by 2020. Replacing conventional transport fuels with biofuels will have minimal air quality effects because of the strong controls on pollution from transport. "It is certain that the effect of the "20%" scenario on biodiversity is substantially positive relative to BAU, although energy production facilities can have local biodiversity impacts which need to be avoided. Benefits also include reducing biodiversity effects of conventional fuel e.g. oil spills.	None. Document focuses on policy direction including biofuel targets.

Table 2. Biofuels/Biomass Roadmaps

Roadmap	Source	Environmental impacts highlighted	Research topics and targets proposed to address environmental sustainability issues
6 The Path forward for Biofuels and Biomaterials	Arthur J. Ragauskas *et al.*, January 2006	Only notes that biorefineries will generate biomass residues 'which need to be treated in an environmentally compatible manner'; suggests thermochemical conversion to SNG.	Details promising new methods for conversion of cellulose, hemi-cellulose and ligno-cellulose. Details methodologies under development for production of SNG from

			biomass, and for anaerobic fermentation of SNG into biofuels.
7 Biomass Action Plan	European Commission, December 2005	Details positive and negative environmental impacts of biomass cultivation. Notes that 'it can be particularly harmful to bring previously uncultivated land (permanent grassland) into agricultural use. On the other hand, using grass cuttings from such land for biomass production can help to prevent the decline of biodiversity on species-rich grasslands due to land abandonment.' 'Energy crop cultivation can help to improve the overall profitability of the farm business, contributing to the maintenance of farming in areas where this may be useful from an environmental (or wider sustainable development) perspective. This is important in a number of regions to improve soil stability and prevent irreversible landslide damage. Another potential positive aspect of energy crop production is its contribution to the establishment of new crop rotation systems that are more advantageous from a wider environmental point of view (for example, alternatives to the monoculture of maize).' 'If energy crops are grown on agricultural land that was previously used for food production, the change in environmental pressure depends on which biomass crops are cultivated.' 'The plantation of tree crops to enhance soil cover on degraded land can also have a globally positive impact. However this should not take place on steppic or mountain habitats that have a high biodiversity value.' 'The use of wastes and residues for energy purposes often gives an environmental bonus compared with other means of disposal. For forest residues, the environmental impact depends on the local soil nutrient balance and the risk of erosion, which may require a certain amount of the residues (especially foliage) to be left on site. In some regions, however, their extraction help to reduce the risk of fire.' Notes that 'that increased demand from the EU could translate into an increased rate of deforestation' in developing countries. Predicts reduction in greenhouse gas emissions of 209 million tonnes CO_2 eq./yr if biofuel targets are met. Notes that 'Like fossil fuels, biomass emits pollutants. Advanced emission control	'The Commission will also take steps to improve understanding of the costs and environmental impacts of all transport fuels, including conventional biofuels.' '"Second-generation" biofuels from wood and wastes are currently more expensive than first generation biofuels from agricultural crops and have not yet been fully demonstrated on a commercial scale. Once that has been achieved, they will widen the range of raw materials that can be used and could also further improve biofuels' environmental profile. It should be underlined, however, that first-generation biofuels already offer significant benefits and that any significant contribution from second-generation biofuels will not materialise until after 2010. Therefore, the emphasis of this action plan is on first-generation biofuels.' However, 'The Commission plans to substantially increase its support for the development of second-generation biofuels through its research budgets'. Describes the range of technological advances required for effective conversion of biomass to "second generation" biofuels.

		equipment can virtually eliminate this, however. Such equipment is already standard in transport'.	
8 An EU Strategy for Biofuels	European Commission, February 2006	Notes environmental concerns relating to 'pressures on eco-sensitive areas, like rainforests', and 'regarding the effect on soil fertility, water availability and quality, and pesticide use.' But proposes no real safeguards, only that (a) 'It is essential that appropriate minimum environmental standards apply to feedstock production for biofuels….. Addressing these concerns requires attention to … the avoidance of negative effects on biodiversity, water pollution, soil degradation, and the disruption of habitats and species in areas of high nature value', and (b) 'only biofuels whose production in the EU and third countries complies with minimum sustainability standards will count towards the targets' (for a 5.75% market share for biofuels in 2010). Notes need for 'measures to ensure optimal greenhouse gas benefits from biofuels'.	Vaguely, 'attention to where energy crops would fit within rotations generally; work to ensure the sustainability of biofuel feedstock cultivation in the EU and third countries'. Also 'Give a high priority to research into the "bio-refinery" concept – finding valuable uses for all parts of the plant – and into second-generation biofuels'. The Commission will 'explore and, where appropriate, propose measures to ensure optimal greenhouse gas benefits from biofuels'
9 Bio-Energy's Role in the EU Energy Market: A view of developments until 2020	produced by BTG for the European Commission, April 2004	Predicts that the Biofuels Directive 2010 target will not be met unless fuel is imported into the EU and/or existing arable land is used to grow biomass for fuel production. Does not address possible environmental consequences.	Parsimonious in expectations re. achievable advances in biomass conversion technology and engine design prior to 2020.
10 Multi-Year Program Plan for Biomass 2007-2012	U.S. Department of Energy (DoE), August 2005	'Existing data on the environmental effects of feedstock production and residue collection are not adequate to support life-cycle analysis of biorefinery systems. The lack of information and decision support tools to predict effects of residue removal as a function of soil type, and the lack of a selective harvest technology that can evenly remove only desired portions of the residue make it difficult to assure that residue biomass will be collected in a sustainable manner. Until the residue issue is addressed, particularly with regard to corn stover, deployment of the Agricultural Residue Pathway will be severely constrained. The production and use of perennial energy crops also raise a number of sustainability questions (such as water and fertilizer inputs, establishment and harvesting impacts on soil, etc.) that have not been comprehensively addressed.'	'Life cycle assessment is used to identify and evaluate the emissions, resource consumption, and energy use of all processes …. such that efforts can be focused on mitigating negative effects.' Despite highlighting these issues, does not propose research to reduce water and pesticide use, soil degradation. Does describe very detailed pathways, with milestones, for the development of technologies required for the utilization of a wide range of raw materials (including farm, forest and paper mill

		No effect on other countries as no raw material will be imported, but 'energy production from biomass calls …. may involve dramatic changes in the U.S. agriculture system that will take time to evolve.' Thorough GHG comparison with fossil fuels.	residues), resulting in fully-operational, economically-viable biorefineries by 2012.
11 Roadmap for Biomass Technologies in the United States Following - The Vision for Bioenergy and Biobased Products in the United States	Biomass Research and Development Technical Advisory Committee for the U.S. DoE and the U.S. Department of Agriculture. December 2002 Biomass Technical Advisory Committee. October 2002	Recognises that all stages of biofuel production have impacts on the environment. Even recognises the potentially negative environmental impacts of 'pre-treatment, collection, storage, and transport of plant and animal residue-based biomass feedstocks'. But the roadmap includes no targets for production, so does not address need for land use change and its consequences.	Aims to 'improve sustainable systems for developing, harvesting, and processing biomass resources' Needs: 'New methods in erosion control, fertilization, and pre-processing'; 'research into the agronomic, economic and environmental impacts of harvesting ligno-cellulosic material to ensure that these materials have beneficial life-cycle impacts' Proposes basic research (with milestones over 10+ years) e.g. 'on the fundamental structure of ligno-cellulosic materials' 'Improved technical understanding of plant biochemistry and enzymes'. Aims to 'Improve biomass production and delivery systems to reduce water use, nitrogen input, and salt tolerance^ and develop advanced methods for overcoming the resistance of … feedstocks to enzymatic and fermentation treatments' Describes very detailed pathways (with milestones) for technology development essential for both thermochemical- and bio-conversion, and for the creation of biorefineries. Also, to minimise potential negative environmental impacts of a biofuel, e.g. 'develop standards for biodegradability'. During development of new technologies states need to 'Continually

			assure that process and conversion developments …. leads to environmental improvements'. Also, concerning storage and distribution, aims to 'Evaluate and assure that new biobased products are environmentally beneficial relative to their fossil fuel equivalents.' Recognises need to include environmental safeguards in legislation and incentives to promote biofuel production and use.
12 Biobased Products and Bioenergy Roadmap: Framework for a Vital New U.S. Industry	Sponsored by the U.S. DoE. July 2001	Proposes the utilization of seaweed, algae, and other aquatic plants, but with no comment on possible environmental consequences. Highlights need to ensure that changes in farming practices to improve yield must also reduce 'the environmental impacts of agriculture, silviculture, and aquaculture. All of these advances must be made while maintaining biodiversity and ensuring the safety and sustainability of the technologies utilized.'	Details technological advances required in all relevant fields, from plant science, feedstock production, processing and conversion through to product uses and distribution. Sets clear goals for technologies (in general) to be developed by 2010, implemented by 2020 and commercially-viable/fully-operational by 2050.
13 The Technology Roadmap for Plant/Crop-based Renewable Resources 2020	U.S. DoE Office of Industrial Technology. February 1999	Notes that increased pressure on the land and competition with foodstuffs is an issue – to be mitigated by engineered improvements in plant biology. No reference to imports of biomass from other countries. But there is an intention to 'Improve marginal land use' and it is implied the proposed development of plants that need less water will enable pastureland to be used for crop production. States need to develop technology to 'minimize impact on land, air, and water use, for long-term sustainability (neutral impact)' and to 'Create infrastructure to expand the use of agricultural waste streams: zero waste'.	Details technological advances required in all relevant fields, from plant science, plant/crop production, processing to utilization. Sets clear goals (with milestones set for 2002, 2010 and 2020) for achievement of each of the technological advances, but not for full commercially-viable implementation.
14 Roadmap for Agricultural Biomass Feedstock Supply in the	U.S. DoE, Office of Energy Efficiency and Renewable Energy.	Focuses on the utilization of crop residues and wood but states that 'achieving the goal of 1 billion dry tons of ligno-cellulosic feedstock will require the use of other biomass sources such as dedicated energy crops'. The latter are proposed to be grasses and short-rotation trees but there is no reference to the extra land required for their cultivation.	This is a detailed technical R&D roadmap for the area of "feedstock handling". 'For each step in the biomass supply process—production, harvesting and collection, storage, pre-processing,

United States builds on Roadmap for Biomass Technologies in the United States (see above)	November 2003	Recognises that thinning forests to supply biomass may have negative consequences to wildlife (the US Forest Service is investigating this). Notes that 'The regional- and/or watershed-level effects of biomass feedstock production on water flows, water quality, biodiversity, and crop productivity have not been addressed' and that 'Genetic modification of dedicated crops for improved characteristics may create risks to native populations of related species.'	system integration, and transportation this roadmap addresses the current technical situations, performance targets, technical barriers, R&D needs, and R&D priorities to overcome technical barriers and achieve performance targets.' Notes that 'Ongoing research is needed in identifying conditions under which (crop) residues can be removed without increasing erosion or reducing soil productivity.'
15 Biobased Products and Bioenergy Vision and Roadmap for Iowa	U.S. DoE Office of Industrial Technology. October 2002	Intention is that 'Iowa biorefineries model production, processing, and merchandising practices and technologies that consistently *improve the environmental conditions and ecological diversity* of the state.' Recognises need to leave proportion of corn stover in the fields to ensure soil conservation and the need to reduce usage of water, fertilizers and pesticides. Notes that 'The impacts of genetically enhanced crops should be assessed on a species-specific and ecosystem level to ensure there are no negative impacts associated with the genetic alteration.'	Describes technical goals for 'Optimization of biomass and/or crop-based material production' from advances in plant science to development of biorefineries, but not in detail.
16 A Strategic Roadmap for the Northeast Region of the Sun Grant Research Initiative	produced for the North-eastern United States. July 2004	'Bioenergy feedstock production on marginal (non-prime) farmland could increase the value these nutrient-poor or environmentally-sensitive areas' and proposes use of forest residues, but without highlighting the possible environmental impacts.	Describes technical goals for feedstock development, biomass conversion processes and systems integration (including development of biorefineries), but not in detail. Notes that 'Improved pathogen resistance for energy crops (e.g., soybean, corn) will increase yields and reduce pesticide requirements.'

17 Innovation Roadmap on Bio-based Feedstocks, Fuels and Industrial Products	Industry Canada. 2003	Notes negative effects on the environment of intensive agricultural practices and of deforestation e.g. loss of biodiversity, and the need for more efficient use of water in agriculture.	Describes technical advances required in areas of genetic engineering of plant species (including the development of drought-tolerant crop varieties), harvesting and conversion of biomass in biorefineries; some specific examples are described in detail. R&D targets are set for the year 2010.
18 The Basis for Sustainable Mobility	Volkswagen May 2004	Notes need to reduce GHG and other emissions. Notes that liquid fuels generated from biomass 'can be obtained from a larger selection of fast-growing crops, helping to avoid monocultures'.	Biofuels will 'influence the engine development process, opening the door to new combustion processes with the potential to bring about further tangible reductions in fuel consumption and emissions'. But no detail is provided.
19 Biofuels progress report and Review of economic and environmental data for the biofuels progress report	European Commission, 2007	Progress report notes variability of GHG emissions savings dependant on fuel type, conversion process, first or second generation fuel. Concern about types of land used for cultivation. Inappropriate land for biofuel cultivation identified as wetlands, rainforest, or habitat of high nature value. The review of environmental data identifies that impacts of biofuel cultivation through land-use change on soil carbon stocks are not taken into account, due to the absence of a global land use model. Most significant impacts could occur if energy crops mostly expand into set-aside areas. Increasing biofuel share will also result in a decrease in the environmental impacts associated with the oil industry.	Describes steps needed to achieve a 10% biofuel share of the market by 2020. Environmental issues include: measures to guarantee the environmental credentials of biofuels; discouraging the use of biofuels which create more GHG emissions or lead to major biodiversity loss; regular monitoring and reporting of well-to-wheel environmental impact of biofuel production and use.

Table 3. Road Vehicle Development Roadmaps

Roadmap	**Source**	**Environmental impacts highlighted**	**Research topics and targets proposed to address environmental sustainability issues**
20 Foresight Vehicle Programme Technology Roadmap Version 2	produced by Foresight Vehicle for the Department for Trade and Industry. 2004	Sets 'Environmental performance measures and targets (which) relate to the overall environmental burden of road transport, global warming, pollution, energy and material waste'. 'reduction of emissions of greenhouse gasses, noxious substances and particulates is seen as a major challenge for the industry', but the roadmap does not compare or prioritise different fuels in this, or in any other, respect.	Sets '*Technological* performance measures and targets relate to energy and power, electronics and control, materials and structures, together with the processes and systems that support development of these technologies.' Details technological innovations required in each of these areas.
21 Carbon to Hydrogen Roadmaps for Passenger Cars	produced by Ricardo Consulting Engineers Ltd. for the UK DTI updated November 2004	'The report focuses on vehicle technology, and does not deal with … the availability of sustainably-produced Hydrogen.'	Details advances required in vehicle technology to reduce well-to-wheel emissions of CO_2. Notes that hydrogen storage needs improvement.
22 CARS 21: A Competitive Automotive Regulatory System for the 21st century	produced by CARS 21 High Level Group for the European Commission. December 2005	Highlights need to reduce CO_2 emissions, and airborne particulates and ozone as being the pollutants of most concern from road transport. Also mentions GHG produced by mobile air conditioning systems.	Proposes changes in policy and areas for technological development, for example, 'The Commission is considering reducing limits of pollutant emissions.' 'To maximise the potential for road transport CO_2 emissions' reduction, the group strongly endorses applying an integrated approach involving vehicle manufacturers, oil/fuel suppliers, repairers, customers/drivers and public authorities. The integrated approach should aim at producing clear and quantifiable reductions in CO_2 along the lines of the Community target through a range of options (e.g. vehicle technology, alternative fuels, taxation, eco-driving, gear shift indicators, consumer information and labelling, consumer behaviour and congestion avoidance). One of the recommendations is to 'Develop policy to encourage

			use of biofuels which offer greater greenhouse gas savings and support research and development efforts into 2nd generation biofuels'. 'Hydrogen should receive major research and development effort as a promising opportunity for the longer-term.' 'Alternative fuels should always be assessed on a comprehensive well-to-wheel basis, looking at cost-effectiveness and at all environmental consequences.'
23 Fuel Cell Vehicles: Race to a New Automotive Future	Office of Technology Policy, Technology Administration, US Department of Commerce. January 2003	Mentions CO_2 and pollutant emissions reduction as being one of the drivers for fuel cell vehicle development.	Details the major advances required in fuel cell technology to achieve cost-effectiveness. Notes that 'Fuel cell vehicles could eventually be powered by hydrogen derived from distributed domestic sources of energy, such as wind, solar, biomass, and hydro' but does not describe the technological advances required to generate hydrogen from these sources.
24 A Roadmap for Sustainable Mobility	DaimlerChrysler	This is a 'strategy for reducing CO_2 and tailpipe emissions'.	Highlights conflicts in technological developments e.g. reducing particulate emissions reduces fuel economy in diesel cars, e.g., 'Fixed recycling quotas and bans on the use of certain materials, for example, render lightweight design concepts involving composite and hybrid materials more difficult to implement and prevent the potential for cutting weight – and thus fuel consumption – from being exploited to the full.'
25 Research Framework Based on Strategic Research Agenda and Vision 2020 and Challenges	European Road Transport Research Advisory Council April 2006 December 2004 June 2004	Recognises the need to reduce GHG emissions, and to reduce the impacts of surface run-off on water quality and the road transport system on natural habitats.	Very environment–focused. Sets specific environment and energy-related research targets to be achieved by 2020. Provides an exhaustive and detailed description of all technological advances required to meet the goals of reducing GHG emissions, energy use and many other environmental impacts of road transport. Research areas include second-generation biofuel development, vehicle design, recycling, traffic management systems and road construction.

Table 4. Air Transport Development Strategies

Roadmap	**Source**	**Environmental impacts highlighted**	**Research topics and targets proposed to address environmental sustainability issues**
26 Air Travel – Greener by Design, Mitigating the Environmental Impact of Aviation: Opportunities and Priorities	Greener by Design Science and Technology Sub-Group, DTI, UK July 2005	Reviews current understanding of the impact on the environment (particularly on climate) of air pollution around airports, and emissions at altitude, generated by civil aircraft operations. Notes that the three main contributors to aviation's impact on climate are contrails, CO_2 and NO_x.	'assesses the potential for mitigating *environmental impacts* by advances in technology and changes in design priorities and operating procedures…. considers possible future research, technology demonstration and design studies and suggests priorities.' Describes in detail future developments and new technologies proposed for improving engine and airframe design (including the use of light-weight, high-strength materials) and propulsion efficiency, with the aim of reducing NO_x and CO_2 emissions. Highlights that the most important environmental research priority should be 'the effect of aviation emissions on the atmosphere and on climate', particularly stresses the need for more research to assess 'the impact on climate of NO_x, water vapour and of contrails and aviation related cirrus.' However, 'further research in alternative fuels was … not seen by the Sub-Group as a priority for aviation.'
27 A strategy towards sustainable development of UK aviation	Sustainable Aviation June 2005	Notes that 'Aircraft operations generate CO_2, a direct greenhouse gas, and lead to other effects in the atmosphere linked to ozone generation, methane reduction and cirrus cloud formation.' But 'impact of aircraft exhaust gases on climate is not fully understood.'	Targets for technology development include 'improve fuel efficiency and CO_2 emissions by 50% per seat kilometre' ('will be addressed through airframe, engine and air traffic management improvements'); 'reduce NO_x emissions by 80%' ('to be achieved largely through aircraft and engine improvements')' Reduction of CO_2 should be a priority. No further detail is provided. Highlights that 'further research is necessary in order to understand fully the impacts that aviation's contrails, particle emissions and NO_x emissions have on climate.' However, 'it is unlikely that alternative fuels will play a significant role in aircraft propulsion in the foreseeable future. Nonetheless, the industry will support' and encourage research projects to find possible replacements for kerosene'.
28 The Strategic Research Agenda	Advisory Council for Aeronautics Research in	'Climate change…is a global issue and strongly linked to CO_2 and NO_x emissions, but also to soot, particulate, water vapour, etc. ….	Technological advances required are described in detail with timescale targets upto 2020. Reducing CO_2 emissions by 50 % by 2020 can be achieved by improving fuel efficiency 'through aerodynamic improvements, weight reduction and fuel efficient engines and systems.'

(2nd Edition) arising from European Aeronautics: A Vision for 2020	Europe October 2004 European Commission January 2001	In particular condensation trails created by water vapour and particulates are suspected to have a significant effect on global warming. … further work is needed in this area.'	NOx levels can be reduced (by 80%) via the development of 'new combustion and fuel injection systems'. 'The next step will be the availability of alternative fuels (e.g. liquid H2, bio fuels, synthetic fuels, LNG) or power sources (e.g. fuel cells), provided that it is demonstrated that they can reduce radiative forces.' Post-2020 technologies envisaged include 'Creating propulsive power from new forms of energy; Solar Power, Nuclear Energy, Hydrogen from the sea, Beamed Energy devices using laser or micro-wave and ground-powered energy forms'; 'morphing the aircraft structure into different shapes or aerodynamic forms under computer control. Thrust may be vectored to give directional or lift control. Plasma jets may replace the burnt fuel exhaust as the means of delivering thrust. Lift mechanisms may use alternative forces to fluid dynamics to derive the vehicle lift.'
29 Study into the Potential Impact of Changes in Technology on the Development of Air Transport in the UK	Arthur D. Little Limited for the Department for the Environment, Transport and Regions (DETR) December 2000	Notes that the three main contributors to aviation's impact on climate are contrails, CO_2 and NOx, and that emissions have a negative impact on air quality around airports. 'This study recognises that contrail and cirrus cloud formation are identified as major contributors to the radiative forcing effect of aviation'	Future critical technologies are 'development of technologies for improving aerodynamics, research on structures and materials to reduce weight, and development of new engine designs with improved efficiency' for reducing CO_2 emissions and 'Development of new combustor concepts to achieve substantial NOx reductions'. These should be sufficient to achieve targets of reducing individual aircraft emissions of CO_2 and NO_x by 50% and 80%, respectively, by 2030. Furthermore 'This study has applied a screening methodology to identify and define the significant environmental benefit criteria for describing the environmental benefits of future aviation technologies'. Consequently, 'CO_2 and NO_x emissions per passenger km are defined as the most significant environmental benefit criteria.' In contrast, the report notes that less is known about the impacts of contrail and cloud formation so for these impacts 'technology mitigation potential remains largely uncertain and unverified.' Relevant technological developments (including the Cyroplane concept) are described in great detail, each with an assessment of their environmental benefit and take-up potential. Alternative fuels are not explored.
30 Reducing the climate change impact of	European Commission, 2005	Aviation releases a range of GHG into the atmosphere including CO_2 and water vapour. Aviation share of GHG emissions is 3%, but growing rapidly.	Research targeted at reducing the environmental impact of aircraft, in particular CO_2 and NO_x. A stronger orientation towards "greening" air transport and a greater focus on its impact on climate change. Further research on alternative fuels may reveal additional potential for reducing GHG emitted by aircraft.

aviation			Implementation of more efficient air traffic management should be a priority. Recommends inclusion of aviation in EU Emissions Trading Scheme

Table 5. Sea Transport Roadmaps and Strategies

Roadmap	**Source**	**Environmental impacts highlighted**	**Research topics and targets proposed to address environmental sustainability issues**
31 A European Union strategy to reduce atmospheric emissions from seagoing ships	European Commission November 2002	Highlights the environmental impacts of SOx and NOx emissions	Focuses on regulatory measures to reduce emissions, not on technological innovation.
32 Maritime Administration Strategic Plan for Fiscal Years 2003-2008	US Department of Transport September 2003	Highlights the role of ballast water in the transfer of 'nuisance species' between habitats and the 'adverse contribution of maritime transportation activities to air quality'	Promotes 'research on marine applications of hydrogen technologies', evaluation and implementation of 'ballast water treatment technologies' and the need to 'conduct research and identify, demonstrate, and promote energy efficient, alternative fuels, and air pollution reduction technologies for maritime applications.' No detail provided.
33 Sustainable Energy in Marine Transportation	Lloyd's Register EMEA, presentation at IMarEST, February 2005	Notes that NOx intensity (g/t-Km) from shipping is significant and that SOx intensity is high.	Highlights technology developments in areas of alternative fuels (e.g. low sulphur fuels), alternative technologies (e.g. fuel cells) and energy efficiency, and need for new engine designs (for use of low sulphur fuels) and conversion technology (hydrogen). Proposes transition to electrical ships fuelled by hydrogen via duel fuel diesel engines. No detail provided, nor targets.
34 Marine and Ocean Industry Technology Roadmap	National Research Council, Canada	Does not address environmental issues	None

35 Low carbon commercial shipping	Department for Transport, March 2007	Environmental impacts focused on are CO_2 emissions. Commercial shipping contributes 1% of UK's annual carbon emissions, but estimates which include international shipping estimate that UK emissions from the shipping sector are approx 5 MtC.	Research topics identified include: improvements to current propulsion technologies; expansion of biofuel use (economic rather than technical barriers); hydrogen fuel cells; electric/hybrid-electric technology; and use of renewable energy sources, e.g. wind kite technology.

Table 6. Rail Transport Roadmaps and Strategies

Roadmap	**Source**	**Environmental impacts highlighted**	**Research topics and targets proposed to address environmental sustainability issues**
36 The Rail Industry - A Way Forward on Sustainable Development	Rail Safety and Standards Board February 2006	'Energy used by rail creates emissions which contribute to global warming.' 'Rail has higher SO2 emissions per passenger km or freight Tkm than road due to high Sulphur content of fuel.' 'Lower NOx and particulate emissions per passenger km or freight Tkm than road and air.'	Carbon emissions – 'grid distributed power technologies: power station efficiency, distribution loss, new materials technologies for power lines', Maglev trains. 'research on future power technology'. 'implementation of regenerative braking technology'. SO2 – 'Treasury address taxation issues currently preventing the uptake of low sulphur fuels'. NOx and particulates – 'Retrofitting exhaust treatment system to diesel engines'. No details or targets provided.
37 Rail21: Sustainable rail systems for a connected Europe	European Rail Research Advisory Council (ERRAC) March 2006	None highlighted	Propose research topics - 'Help improve and deliver achievable standards for noise, emissions, diesel engines, etc'; 'Develop new lightweight and low noise freight wagons; greening existing fleet'. No details or targets provided.
38 Railroad and Locomotive Technology Roadmap	Argonne National Laboratory, for the US Department of	Only indirect references - in the USA 'Locomotives currently emit over one million tons of NOx each year'. 'Diesel fuel for locomotives can	Potential research topics;- Train Systems – 'Aerodynamics, Wheel/Rail Friction, Rolling Resistance' Locomotive Systems – 'Idle Reduction, Energy Recovery, Motors and Drives' Locomotive Engines – 'High-Efficiency Turbo, Sensors and Controls, Fuel

	Energy December 2002	contain 10 times more sulphur than diesel fuel for trucks.'	Injection/Combustion, NOx Adsorber, PM [particulate matter] Trap' Advanced Powerplants and Fuels – 'HCCI [homogeneous-charge compression ignition], Alternative Fuels, Fuel Cells'. These are described in detail, but with no targets. Notes that 'Some of the technologies that could be employed to meet the emission standards may negatively affect fuel economy'.
39 Rail Technical Strategy supporting the "Delivering a Sustainable Railway" White Paper	Department for Transport, July 2007	Highlights need for the railway to reduce its environmental impact, but no specific issues.	Targets for increasing energy efficiency e.g. through regenerative braking, use of biofuels and in the medium term hybrid traction development. Longer term, decisions on electrification will depend on the rate at which the carbon footprint of electricity generation declines. Hydrogen technology should be pursued at an EU level with UK collaboration.
40 Strategic Rail Research Agenda 2020	European Rail Research Advisory Council, May 2007	The need to increase level of environmental protection is highlighted but no specific issues are identified.	Key research areas: potential for reducing dependence on fossil fuels e.g. eco-diesel and hydrogen (environmental benefits of "eco-fuels", deployment options and optimum conversion strategies). Reducing noise emissions; regenerative braking; research on new funding rules for environmentally friendly applications; use of recycled materials for vehicle constituents; energy efficiency of heating and air-conditioning technologies.