Fuelling the future

Reducing the emissions of passenger cars in the UK by 2020

Workshop report 2007

RSC | Advancing the Chemical Sciences

About this Publication

This publication is based on a series of workshops that were held at the RSC in April and May 2007. It reflects a number of expert views from academia, research and technology organisations, the motor industry, the chemicals industry and other key stakeholders (see Appendix). This is a summary of those views alongside the King Review aims to spark debate and contribute towards a realistic low carbon transport innovation strategy.

Reducing the CO_2 emissions from passenger cars is an important part of a wider strategy to reduce emissions from the power generation, industrial, transport and domestic energy sectors. The RSC has been actively campaigning since 2005 to demonstrate the vital role the chemical sciences will play in the provision of safe, clean, affordable and secure energy. The RSC position is laid out in the report "Chemical science priorities for sustainable energy solutions".

http://www.rsc.org/ScienceAndTechnology/Policy/Documents/SustainableEnergySolutions.asp

The authors have aimed to present this material fairly. Nevertheless, the report should not be taken as representing the formal positions of any of the organisations participating at the workshops, nor of the RSC. Moreover, it may not include all the points raised in discussion.

About the RSC

Since 1841, the RSC has been the leading society and professional body for chemical scientists and we are committed to ensuring that an enthusiastic, innovative and thriving scientific community is in place to face the future. The RSC has a global membership of over 44,000 and is actively involved in the spheres of education, qualifications and professional conduct. It runs conferences and meetings for chemical scientists, industrialists and policy makers at both national and local level. It is a major publisher of scientific books and journals, the majority of which are held in the RSC Library and Information Centre. In all its work, the RSC is objective and impartial, and is recognised throughout the world as an authoritative voice of the chemical sciences.

Fuelling the Future
Reducing the emissions of passenger cars in the UK by 2020

The following four sections summarise the main outputs from a series of workshops held in April and May 2007.

1. Conventional engine technology and vehicle design

Car manufacturers and other OEMs are currently developing or bringing onto market a whole spectrum of products and technologies to improve fuel economy.

Oil derived liquids are at present the most cost effective transport fuels and the most efficient energy storage materials available to us.

Vehicle Design[1]

Changes in vehicle design such as better tyre design and use of lightweight composite materials could also have significant effect on the fuel efficiency of a vehicle and reduce CO_2 emissions. In 1997 there were 600 million vehicles on the world's roads, with engines operating at efficiencies of 10–25% for petrol and 15–35% for diesels. Transmission, road and other losses reduce efficiency significantly for the overall vehicle. Vehicle engineers around the world are currently chasing every lead with a view to achieving the goal of improved fuel efficiency coupled with reliability and affordability. It is generally accepted that the customer is unprepared to compromise his or her expectation of vehicle performance, reliability or cost, so technological improvements are necessary alongside environmental developments.

There is significant potential to improve gasoline engine efficiency using existing/developing technologies. Multidisciplinary teams including chemists and chemical engineers have already achieved significant improvements in the operation of the internal combustion engine by developing direct injection spark ignition systems and small diesels with more efficient turbo chargers. Efforts to improve engine efficiency by variable valve timing, cylinder deactivation, to reduce engine displacement during normal driving, reductions in engine friction and accessory loads, and sophisticated engine management systems all show promise. Significant improvements have already been made to the fuel and exhaust system by introducing unleaded petrol, detergent additives and oxygenated fuels (although oxygenated fuels such as MTBE will be worse for CO_2) and catalytic converters. Homogeneous Charge Compression Ignition (HCCI) offers the most radical development possibilities, but this is unlikely to enter the mainstream by 2020.

Vehicle performance can also be considerably improved by reducing weight through the use of lighter construction materials. The past 20 years has seen a steady decrease in the amount of iron and steel in a typical family car with a corresponding increase in the amount of polymer composites, aluminium and even magnesium. Increased attention to the various bulk, surface and compositional chemistry aspects of the forming, joining and recycling of these materials, to reduce manufacturing, design and assembly costs without compromising safety, will greatly enhance the use of lightweight materials in vehicle construction. This will require polymer and synthetic chemists to create new structural materials and designs to radically reduce vehicle weight without compromising safety.

[1] RSC 'Chemical Science Priorities in Sustainable Energy Solutions' report (March 2005)

In the past few years some vehicle manufacturers have introduced hybrid drive trains into the market place. Various arrangements are possible but the combination of a smaller gasoline or diesel engine coupled to electric batteries and electric drive motors, together with recovery of the vehicles momentum through regenerative braking, have led to dramatic increases in energy efficiency. Further improvements in this approach will require lightweight construction materials and technology, efficient low emission engines and improved battery or alternative energy storage technology.

A further fruitful area of research might be to consider personal mobility as a systems engineering problem consisting of the engine and fuel, the transmission system, the vehicle itself including the wheels, the road surface and construction, the refuelling infrastructure and the eventual recycling of the components. Much of this will require a deep understanding of the chemistry and chemical engineering aspects of the fuels, their combustion characteristics, the engine and vehicle shell materials, the control systems and sensors required, transmission and energy storage and the re-use of the component materials. The task of creating a sustainable transport system when 'cars will continue to be the preferred means of personal mobility in the urbanised regions of the developed world is considerable and will require the ingenuity of chemists as well as engineers.'

Overall technology was not viewed as posing a significant barrier. The proceeding sections of the report concentrate on three technologies which potentially can contribute to significant reduction in CO_2 emissions from 2020 and beyond: biofuels, hybrid and electric vehicle technologies and hydrogen power.

Improvements in lubricant additives

Legislation on the national level in the US, Japan and the EU in Europe are driving reductions in emissions from the road traffic fleet. In Europe the implementation of Euro V and subsequently Euro VI (and comparable schemes elsewhere) standards are forcing OEMs and lubricant manufacturers to improve efficiency of their engines and transmissions.

Improvements in machining are leading to smaller tolerances and higher quality, smoother surfaces on moving parts within modern engines. Having a smooth surface on contacting parts means that theoretically a thinner oil film is required to separate and effectively lubricate the engine's moving parts. Challenges remain however; a passenger car's engine has to cope with a wide variety of environments, and hence operating temperatures.

Since the viscosity of the oil is inversely related to temperature, it follows that if the oil is allowed to become too hot, it will thin to a level where it can no longer effectively lubricate, leading to lower efficiency and increased wear. In practice a lubricant formulation has to maintain adequate high temperature viscosity, at the cost of low temperature viscosity being higher than necessary, consequentially increasing friction.

Improved lubricant formulations, including additives known as viscosity modifiers limit the amount that a lubricant thins at high temperature, which means that low temperature performance can be more readily optimised. In the industry, oils which thin little at high temperatures are known as high VI (viscosity index) lubricants, whilst lubricants that thin excessively are known as low VI lubricants.

The lubricant's ability to 'stay in grade' i.e. not to thicken as it becomes degraded over its lifetime is also improving with time. This has been achieved by using carefully optimised detergents and dispersants which keep surfaces clean, and suspend undesirable sludge in the oil. Antioxidants are also present to inhibit the destructive oxidation process which leads to thickening and the formation of corrosive acids.

Another factor influencing engine lubricant is that the OEMs are demanding fluids with ever increasing drain intervals. In the 1950s, lubricants were only lightly formulated, and made from low quality base oils, and even with the low specific power outputs of the engines, the lubricant would need changing typically every 2000 miles. Now however, a typical drain interval for a lubricant is in the order of 15,000 miles in Europe (and increasing) and to cope with this engine oil manufacturers are able to charge premium prices for their products because of their extended drain intervals, higher quality base oils and finely balanced additive packages.

A consequence of improving technology is that additives known as friction modifiers can be added to lubricants to improve their frictional characteristics and lead to improved efficiency. As the specific power output of cars continues to increase (in terms of bhp per litre) then the lubricant quality needs to improve in line with this in order to maintain drain intervals and engine protection. Estimates vary as to how much lubricants can contribute to fuel economy benefit, but the difference between using a low quality oil and a high quality oil are believed to be between a 1-3% saving, which equates to a substantial amount of CO_2.

Fuel suppliers are also investigating adding friction modifiers directly to the fuel in order to reduce friction and increase efficiency with promising results. Shell claims to use this technology today in their V-Power fuel.

2. Biofuels

The current EU vision

The EU transport sector is heavily dependent on fossil fuels (in the UK it is 99.97% of private motor vehicles are powered by fossil fuels, according to the DfT vehicle licensing statistics report 2005). EU oil reserves are depleting, particularly those from the North Sea continental shelf, thus an increasing proportion of imported oil will be required in the future to meet demand. Reliance upon imported oil raises issues of energy security as supply can be affected by external influences with significant market impacts. Deriving power, heat and fuels from locally sourced renewable resources has been recognised in the UK and Europe as a mechanism for both reducing CO_2 emissions and improving energy security. This has been recognised at the EU level; the EU Commission (EC) is currently agreeing the final format of a draft energy policy for Europe. Key measures in the EC energy policy[2] are that by 2020, 20% of all energy (not just electricity) should be derived from renewables and that the use of biofuels should be increased to 10% of all road fuels. As an intermediate target biofuels should contribute 5.75% to transport fuels by 2010. Beyond 2020, the Biofuels Advisory Council has advised the EC that biofuels could meet 25% of the EU transport fuels needs[3]. Biofuels contributed less than 1 % of total European transport fuel consumption in 2004, but this contribution has been rising progressively over the past decade[4].

In comparison, the US Department of Energy's Biofuels Initiative strategy aims for biofuels to provide a 30% contribution to transport fuels by 2030.

Science and technology

In the EU biofuels are typically dispensed as a blend of 5% biofuel and 95% conventional fuel at petrol stations. There is a limit to the proportion of biofuel (particularly bioethanol) that can be blended with conventional fuels without the need for engine modification; increasing biofuel usage needs to be integrated with vehicle design. Biodiesel use generally requires fewer engine modifications than bioethanol, however, the changes required even for compliance with high ethanol concentrations are simple and cheap to implement if carried out during the vehicle manufacture.

There are also issues with the supply infrastructure for biofuels. For example ethanol is hygroscopic and can cause separation from gasoline if transported together (often the components are delivered separately and mixed at the petrol station). With biodiesel there are problems with long-term stability as it is prone to oxidation, it is also hygroscopic, leading to possible corrosion and filter clogging.

1st generation biofuels are more expensive to produce compared to conventional fuels and need to be subsidised by government. 1st generation biofuels provide CO_2 emission reductions compared with conventional fuels but currently in Europe this is limited to around a 50% reduction (i.e. they are not carbon neutral). Currently, the best practice in 1st generation biofuel production is exhibited in Brazil where bioethanol is efficiently produced from sugarcane on a massive scale. However, there are widespread ecological concerns relating to deforestation and habitat destruction (see 'Society and the public' section).

2nd generation biofuels (derived from lignocellulosic biomass) have more potential than 1st generation biofuels (derived from food crops). However, it was recognised that 1st

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[2] ec.europa.eu/energy/energy_policy/index_en.htm
[3] ec.europa.eu/research/energy/pdf/biofuels_vision_2030_en.pdf
[4] ec.europa.eu/energy/res/publications/doc/2004_brochure_biofuels_en.pdf

generation biofuels are a key milestone in establishing the market and infrastructure for biofuels, because the technology is readily available. The advantages of 2nd generation biofuels (compared to 1st generation) are that they:

- Do not necessarily compete with food crops for arable land
- Have greater potential CO_2 emissions reductions (source Well to Wheels report[5])
- Have greater potential yields per hectare and a greater potential global yield
- Are potentially cheaper (than 1st generation biofuels)
- Offer the potential to co-produce numerous chemical products (the biorefinery concept)

However, there are several significant technical challenges to overcome before 2nd generation biofuels are realised. For example a fermentation process requires:

- Development of energy efficient processes to convert biomass into a fermentable solution
- Development of enzymes that are tolerant to C5 and C6 sugars
- Development of energy efficient processes for separating alcohol from water

Lignocellulosic biomass can also be converted to biofuels via a Biomass To Liquid (BTL) process. In this process biomass is first gasified to produce hydrogen and carbon monoxide. These gases are cleaned and conditioned before undergoing a Fischer-Tropsch (FT) reaction to produce paraffinic hydrocarbons, which can be further upgraded. The FT reaction is catalytic. BTL fuels can offer significant CO_2 emission reductions compared to conventional fuels and, in the best case, compared to other biofuels (source: Well to Wheels report[6]). Key challenges are increasing selectivity for the desired product and operating the process at an economically viable scale. Plant oil hydrogenation processes, as NExBTL (Next Generation Biomass to Liquid) second generation biodiesel process, could be incorporated into existing petroleum refining facilities. These processes convert plant oils (triglycerides) into high cetane number hydrocarbon diesel fuel, thereby providing possibility to utilize other refinery streams for production of diesel fuel.

Marine biomass offers another alternative, with micro-algae potentially becoming a significant source of biomass. It is possible that 3rd generation biofuels, produced from dedicated energy crops (possibly GM crops), may also be developed successfully.

Participants believed that existing chemical and biochemical industries will enable developments. There are already some chemical plants suitable for processing lignocellulosic material but these are sub-optimal. When designing chemical plants there are many technical challenges to be overcome, and many new facilities will be required.

Biofuels have a major advantage over hydrogen technology in that they are liquid rather than gas. This makes them intrinsically easier to develop and be used by customers. They have much higher energy densities than gaseous fuels and can be carried in existing vehicle fuel systems. Because they are miscible with existing fossil fuels they provide a cheaper route for vehicle and infrastructure changes.

There are also issues that need to be explored regarding the interactions of biofuels with engine lubricants, causing excessive sludge, deposits and shortened lubricant lifespan.

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[5] http://ies.jrc.cec.eu.int/wtw.html
[6] http://ies.jrc.cec.eu.int/wtw.html

Biofuels policy and economics

Targets for biofuels are set by governments, but there is lack of cohesive, coordinated supporting strategies and regulations. These are needed to drive changes and encourage the adoption of biofuel technologies. In Europe biofuels are typically financially supported by a reduction in fuel duty (in some cases to zero). These incentives are required to make biofuels competitive, if not cheaper, compared to conventional fuels and enable businesses to make investment decisions. However, participants were concerned that fiscal incentives were stifling the development of 2nd generation biofuels by removing impetus to deliver lower cost technologies. It was also noted that when subsidies were withdrawn in Germany the biodiesel market collapsed as the technologies cannot compete economically.

Funding for research, development and demonstration is available through the EU FP7 programme. Furthermore, the EU Strategic Energy Technology (SET) Plan that is soon to be open for consultation aims to provide strategic funding for technology platforms such as biofuels. The Renewable Transport Fuel Obligation is also currently in place in the UK as mentioned earlier.

A joined-up regulatory EU strategy is needed, based on the advice provided by key stakeholders such as those organisations represented at the workshop. Communication with politicians and decision-makers is vital, as is information exchange and collaboration with environmental bodies.

With an increasing focus on biofuels and the associated technologies, there is a need for a thorough and comprehensive definition of what is and is not a biofuel. For example it is unclear whether BTL derived fuels can be classified as biofuels. Clarification would have obvious benefits when constructing regulatory frameworks.

As the UK and Europe rely on imports from outside the EU, consideration must be given to creating and maintaining good international relations. Imported biofuels/biomass could have the same potential security of supply issues as petrochemicals.

Society and the public perception of biofuels

Public perceptions of biofuel technology have an important role to play in achieving targets. This is true of most scientific and technological developments but is of particular importance with transport fuels, as the ultimate successes and uptake will be consumer-driven. However, the public may realise the difference when using biofuel blended with conventional fuels unless attention is drawn to the issue. Using high concentration bioethanol fuels consumers will notice a significant increase in volumetric fuel consumption. Lack of a suitable pricing and taxation system will be a disincentive to use these fuels. Workshop participants did not reach a consensus on what the level of public acceptance would be.

Currently public opinion is not unfavourable, although more recent interest by the media may have highlighted negative implications. Examples include deforestation and habitat destruction, competition with food crops, the rise in tortilla flour prices in Mexico, threats posed by diseases such as black stem rust and the use of Genetic Modification (GM) technology. The visual impact upon the land may also become an issue; fields of bright-yellow rapeseed crops have already generated comments from the public. These predominantly environmental issues can have significant societal impacts.

Influencing the public may not be within the remit of the scientific community, as many of the negative implications are already reasonably fact-based. The key stakeholders in government, industry and academia will need to ensure care and integrated approaches are taken when assessing the impacts of biofuel production, and that this information is effectively disseminated to the public. The needs of supply chain stakeholders will need to be met, particularly farmers, who may need convincing of the advantages of switching land-use to biocrops (such as long-term demand and profit). A focus on the need for self-sufficiency and energy security may be good selling points.

Environmental impacts of biofuels

There are many issues to consider when assessing the environmental influences on, and the impacts of, biofuels. The best approach is to consider the full Life Cycle Analysis (LCA). LCAs must be calculated on the same basis for all fuels (including fossil fuels). Ideally the agricultural structure and supply chain must be optimised in order for biofuels to have maximal CO_2 emission reductions. For example, there is a need to monitor the emissions produced by growing and transporting biomass.

The global biomass resource is not unlimited, for example the UK currently produces around 70% of its own food. Land availability is a key issue, as is water management. Large parts of Eastern Europe are under-cultivated and could be utilised, simultaneously boosting local farming communities and reducing the need for non-EU imports. Ecosystem studies are required to assess the full impacts of biocrop cultivation and processing, and long term sustainability issues must also be considered. Reliable data regarding the climate impacts of increased use of fertilisers (which release N_2O, a potent CO_2) is urgently required.

The proliferation of crop diseases has already been mentioned, and was discussed in the context of diversity and GM technology. A diversity of biomass sources is needed for security of supply against pests and diseases. GM technology has many benefits in the engineering of pest or pesticide resistant crop varieties, but may not necessarily promote ecological diversity. Diseases (such as the recent Ug99 strain of black stem rust fungus) could therefore have a potentially more devastating impact on biofuel supply (as well as food crops). However, 2nd generation (lignocellulosic) processes should be more tolerant of a wide range of feedstocks, and therefore alleviate this potential diversity problem.

As well as the effects of biofuel production on climate change, we must also evaluate the impact of climate change on biofuel production. The climate is already changing, and this will have strong influence on the feasibility of biocrop cultivation in different parts of the world.

Recommendations for biofuels

The EC energy policy’s target of a 5.75% biofuel contribution to transport by 2010 is unlikely to be achieved, but with significant changes in policy and investment in research the 2020 target of 10% may be reached.

The following recommendations were made:

- Research, development and demonstration of 2nd generation biofuels technology is a priority
- Economic and fiscal incentives are necessary to encourage development
- Whilst organisations in the EU exist that deal with aspects of biofuels (e.g. EuropaBio, Biofuel Technology Platform, etc) there is a need for a joined-up approach across the whole supply chain
- Public acceptance must be considered a priority
- Life-cycle assessments must be carried out to ensure that biofuel production and use minimises CO_2 emissions

- Research into ecosystem studies and diversity will provide important information on the impacts of biofuels, and will help predict impacts.

While it is important to consider replacement of petroleum-based fuels in road transport, we must also consider aviation and maritime fuel usage. Ignoring these contributors to carbon emissions may ultimately negate the positive changes incurred by using biofuels.

3. Hybrid and electric vehicles

Urgent and substantial reductions in CO_2 emissions are needed to minimise the impact of climate change and progress will need to be significant towards this end by 2020. Given this timeframe emphasis must be on technologies that are already advanced in development that offer CO_2 emission reductions in the short term: hybrid and electric vehicles are commercially available today and offer promising CO_2 savings, although life cycle analyses which should include producing the batteries should be further explored.

Vehicle definitions and readiness

- *Hybrid electric vehicles (HEVs)* are powered by two energy/power sources; electricity (stored in batteries or supercapacitors) and liquid fuel (via an internal combustion engine [ICE]). Batteries onboard are charged through alternators driven by the ICE and by capturing energy through regenerative braking. HEVs are commercially available with varying degrees of hybridisation. These are comparable in function, durability and reliability to conventional vehicles and reduce CO_2 emissions by around 30% in urban driving conditions.
- *Plug-in hybrid electric vehicles (PHEVs)*. PHEVs are similar to HEVs but have the ability to recharge their energy storage system via an external source (for example through the national grid). Ideally this would provide sufficient energy to complete a daily commute without the need to operate the ICE.
- *Electric vehicles (EVs)* are powered solely by batteries. Batteries are recharged via external electricity sources and by capturing energy through regenerative braking. An array of EVs are commercially available but all suffer from a limited range (around 50 miles) and long charging times (1 to 6 hours depending on battery type and battery size). Significant reductions are possible if electricity is generated from dedicated low CO_2 emission resources (such as wind power).

Market penetration of HEVs and EVs

The environmental merits of HEVs and EVs are clear. However, despite being commercial availability for several years neither HEVs nor EVs have achieved significant market penetration: currently 0.03% of the UK's vehicle fleet are composed of HEVs and EVs[7]. For EVs this is attributed to the limited vehicle range and long charging times; battery technology restricts EVs to niche urban applications. Although this category encompasses most daily commutes, customer expectations, lengthy charging times and the lack of a recharging infrastructure have delayed adoption of EVs. For HEVs the reasons for low uptake are different; HEVs are comparable in function to conventional vehicles and a refuelling infrastructure already exists. HEVs are more expensive than comparable conventional vehicles. Public uncertainty concerning the environmental and fuel economy benefits of these vehicles is likely to have contributed to their low uptake. For electrically-powered vehicles to have a substantial impact on CO_2 emissions a greater targeted market penetration is essential; this is achievable if decisive action is taken to overcome existing social, political and technical obstacles.

Technological barriers for HEVs and EVs

[7] Figures from DfT National vehicle licensing statistics 2005 - http://www.dft.gov.uk/pgr/statistics/datatablespublications/vehicles/licensing/coll_vehiclelicensingstatistics2/vehiclelicensingstatistics2005a

Energy storage is the key underlying issue for all electrically-powered vehicles. The energy, power, efficiency, lifetime, rate of battery charging and cost of energy storage systems will directly impact upon the function, price and therefore adoption of electrically-powered vehicles.

Batteries

Commercial mass-market HEVs and EVs use lead-acid and nickel metal hydride battery technologies. These are inadequate; EVs cannot currently compete with existing conventional vehicles. The specific energy of the storage system directly impacts on the function of the vehicle. For EVs low specific energy results in limited vehicle range (typically ~50 to 100 miles); this is a major concern. Recently, battery development has focussed on lithium ion (Li-ion) technology. These battery systems, currently in widespread use in mobile phones and laptops, exhibit two or three times greater specific energy and energy density than conventional battery technologies allowing Li-ion batteries to be smaller, lighter and more powerful.

Table 1: Specific energy and energy density of various portable energy storage strategies[8]

Energy storage strategy	Specific energy [MJ/kg]	Energy density [MJ/L]	Storage mass [kg][a]	Storage volume [L][a]
Petrol and tank	30	30	16	16
Ethanol and tank	19	20	25	24
CNG and tank[b]	11	11	44	44
Hydrogen storage strategies	2 – 6	2 – 3.5	40 – 120	70 – 120
Pb-Acid battery module	0.1	0.3	1500	500
NiMH battery module	0.2	0.5	750	300
$LiCoO_2$ cathode Li-ion battery module	0.5	1.0	300	150

[a]Sufficient to provide 120 MJ mechanical work on an advanced light duty vehicle with regenerative breaking; Assumed conversion efficiencies to mechanical work: Petrol, ethanol, CNG 25%; Hydrogen PEM 50%; Batteries 80%.
[b]25 MPa

Converting Li-ion battery technology from current small scale applications to batteries capable of powering EVs or HEVs is challenging. It is not simply a case of 'scaling-up' the current technology: innovative materials chemistry is required; for example the application of nanotechnology to anodes and cathodes. A recently developed prototype Li-ion-powered EV, the Tesla Roadster, is now available in the US[9]. This car has a range of over 200 miles and represents a vital step for EVs. However, the vehicle is currently too expensive. Moreover, Li-ion batteries for vehicles are comprised of hundreds of cells, if any of these fails the whole system is compromised. Future HEVs will use Li-ion batteries that are composed of larger cells. However, other concerns also remain:

Charging - Customer expectations of refuelling are high; conventional vehicles can be refuelled in minutes. Lithium batteries, like all currently available battery technologies, require hours to recharge. If these batteries could be charged at the maximum sustained battery power charging times could be significantly reduced.

[8] http://gcep.stanford.edu/pdfs/assessments/ev_battery_assessment.pdf
[9] http://www.teslamotors.com/performance/electric_power.php

Costs - In order for EVs and HEVs to be successful, the cost of the battery must not govern the overall cost of the vehicle. Currently battery technology is expensive; lithium ion vehicle battery packs cost around £6,500. This is far greater than the price of the drive train for conventional vehicles. The high cost of lithium ion battery packs is largely attributed to the active materials (or their precursors). As such, mass production will not necessarily reduce costs substantially.

Strategic materials - Cobalt oxide is a key material for producing lithium ion batteries. The world estimated cobalt reserves are relatively small; less than a tenth of that of nickel and just over a hundredth of that of copper. Cobalt accounts for a quarter of the mass of lithium ion batteries. If 30 million battery packs capable of powering EVs were made annually the world cobalt reserves would be depleted in six years (provided the global estimates are accurate). The majority of cobalt reserves are located in politically unstable regions - the top three sources of cobalt are Congo, Cuba and Zambia. This could raise a major security of supply issue. To address this electrodes based on cheaper more abundant materials must be synthesised or cobalt would have to be recycled.

Safety – Lithium ion batteries can suffer from 'thermal runway' effects, reaching temperatures hot enough to melt aluminium and explode batteries.

Key challenges:

- *develop a battery with a 200 mile range and acceptable power range capabilities which is light, inexpensive to produce and not dependent on strategic materials.*
- *reduce or replace the cobalt oxide needed in battery electrodes*
- *develop 'fast charge' technology which can recharge within minutes*

Other technical barriers

In addition to batteries, improvements in supercapacitors, flywheel capacitors and power electronics will influence the function of battery-powered vehicles.

Supercapacitors, like batteries, are electrochemical devices, but they differ from batteries in that supercapacitors are optimised for rapid power transfer, rather than bulk energy storage. Conventional supercapacitors employ high surface area carbon electrodes and aqueous based electrolytes. However, recent innovations have included the replacement of one carbon electrode with a lithium intercalation compound such as $Li_4Ti_5O_{12}$, the use of non-aqueous electrolytes allowing higher voltages and the use of nanomaterials.

These devices can act as important power buffers, absorbing energy at a high rate, and then transferring it to devices such as batteries or flywheels. They are particularly attractive technologies in hybrid vehicles or direct electric traction. However, the technology is currently expensive, largely due to low production volumes.

Chemical science challenges need to address:

- new electrode materials;
- new non-aqueous electrolytes;
- better understanding of fundamental mechanisms.

Flywheels store energy kinetically in a rotating mass. Flywheels are capable of delivering very high power, with a response time of milliseconds. As such, flywheels can store energy for short term peak loads. The efficiency of power management electronics remains a challenge to minimise losses in the circuits.

Power electronics controls the power flow between the internal combustion engine, battery/supercapacitor/flywheel and electric motor. In the past automotive power electronics used technologies mainly issued from industrial applications or railway applications. Although, power electronics has seen some improvements in recent years, new innovative solutions are needed to fit the technical and high volume production constraints of the automotive industry. Main topics are high operating temperatures, packaging, limiting failure mechanisms and robustness and new cost-effective power drive train topologies. These key issues need to be addressed in the future.

Infrastructure for using HEVs and EVs

Electricity is already a universal currency for energy, and a comprehensive distribution network exists. The technical challenges involved in recharging EVs from the national grid are in some perspective manageable: the current system can support the recharge demands of low volume EV or PHEV deployment. Research into accommodating large-scale recharging is essential. Safe, convenient public recharging stations will be required in the mid- to long-term. However, since charging is a lengthy process this does not offer an appealing solution to the user - an alternative option is to exchange batteries at charging stations.

Steps should be taken to encourage off-peak charging, helping to lessen the need to increase the capacity of the national grid beyond current projections. It is currently unclear whether investment for recharging infrastructure will come from government or industry. La Rochelle in France developed an EV recharging infrastructure for around 130 vehicles; this may act as a useful case study.

Economic issues for HEVs and EVs

At present, the cost of hybrid and electric battery technology is high. Tax incentives are used to make these vehicles cost competitive with conventional vehicle options. For electrically-powered vehicles to achieve significant market penetration these incentives must continue. In addition the full cost of owning and maintaining HEV and EV must be made transparent to customers – for example, the battery lifetime and costs of replacing batteries must be made clear.

Political issues for HEVs and EVs

European governments are committed to reducing CO_2 emissions significantly by 2020. To achieve these targets authorities must prioritise currently available low-carbon technologies; this is the prime driver for electric technologies. Support should be provided at European, national and local levels, through clear, targeted, outcome-driven policies. A spectrum of incentives and mandates will be required to accelerate market penetration and industrial investment in relevant technologies. These policies should form part of an integrated approach which tackles the transport system as a whole. An additional driver for EV/PHEV may be increased energy security, however, this is currently under debate; while electricity can be generated from a diverse range of resources, and materials required for batteries may be strategic. This issue must be addressed. In parallel to setting clear policies the governments should also act as trusted sources of information, providing clear and transparent advice about environmental benefits and lifetime ownership costs of new vehicles.

Environmental issues for HEVs and EVs

The environmental merits of HEVs are clear. HEVs improve fuel economy and therefore reduce emissions; most HEVs reduce CO_2 emissions by around 30% during urban driving cycles. These fuel economy benefits are greatest for urban driving cycles. Fuelling HEVs with biofuels could further increase the environmental benefits.

PHEVs and EVs are primarily powered by electricity from an external source. The source of this electricity determines the CO_2 savings. EVs powered by electricity from the national grid can significantly reduce CO_2 emissions. This 'saving' may be increased by generating electricity from alternative resources; for example solar, wind, biomass and nuclear. Well-to-wheel analyses are required to determine the most effective generation method - these analyses compare the energy input, emissions and cost of the full cycle of a fuel from the fuel source to conversion into vehicle kilometres in a car. In the long term electricity must be generated from sustainable low-carbon sources. Full life cycle analyses are required for HEV, EV and PHEVs to allow the full impacts of the technologies to be compared in a consistent and comprehensive manner.

Social issues for HEVs and EVs

Air pollution and health hazards

Urban air quality may become a powerful driver for PHEV/EVs as when powered by electricity they do not produce harmful NOx and SOx emissions. HEVs also reduce these harmful emissions by improving fuel economy. With the number of cars rising air pollution may become a powerful driver for electrically-powered vehicles.

Customer expectations

For most travel days (>75%) the current EV range fulfils the requirements. However personal automobile customers are accustomed to the function of conventional vehicles. As such, limited travel ranges will delay adoption of EVs significantly as most mass market customers consider these limits 'unacceptable'. If battery technologies do not significantly improve charging issues could be overcome by altering customer expectations – for example, in the future car batteries could be exchanged instead of recharged at refuelling stations, or separate vehicles could be hired for long distance travel. However changing behaviour may be a lengthy process.

Perception

Misrepresentations in the media of HEV fuel economy benefits must be addressed. The urban benefits of HEVs need to be widely promoted. In addition, social attitudes will play an important role encouraging the adoption of HEV/PHEV/EV. Social emphasis on 'going green' will be important. The media will therefore play a key role in HEV/EV adoption.

Education

The public needs information on how to drive and maintain vehicles more efficiently. This is relatively easy to achieve with HEVs/EVs; by displaying the driving efficiency of the last half hour segment drivers are encouraged to continually improve the efficiency of their driving. Education is also necessary to encourage behavioural shifts towards public transport and car sharing.

Driving trends

Driving/recharging cycles will impact the systems design and battery life. Behavioural studies are required to understand the motivation of the mass market customers. The impact of shallow discharges and intermittent recharging must be fully investigated to allow battery configurations and control strategies to be adapted to maximise performance.

Training facilities

Electric drive trains differ significantly from mechanical drive trains. As such, mechanics will require extra training.

Other considerations

A large fleet of battery powered vehicles may allow vehicle-to-grid (V2G) applications. In this system the national grid can draw power from plugged in vehicles in order to cope with peak demand. Understanding the large scale implementation requires further study.

Fuel cell powered vehicles require advances in battery technology. HEV and EVs may act as a bridging technology for fuel cell powered cars.

4. Hydrogen

Hydrogen as a transport energy solution

A future hydrogen economy could offer close to carbon-neutral transport from secure, renewable energy sources. Widespread adoption of hydrogen vehicles may ease political and environmental concerns, reducing air pollution, global climate change and dependence on fossil fuel imports. However while theoretically promising, hydrogen vehicles and the infrastructure they require must overcome major hurdles if they are to be regarded as any sort of transport solution.

A scenario for replacing carbon-based fuels with hydrogen

The replacement of carbon-based fuels by hydrogen will take many decades, requiring massive changes to supply, distribution and delivery infrastructure in the entire energy network. The introduction and subsequent expansion of hydrogen into an additional energy vector, as well as a more widely used transport fuel, in the global energy market will thus be a gradual and incremental process. At each stage in the process there will be significant challenges and issues to be overcome. The nature and scale of these issues will change during the transition decades and appropriate solutions to them may also change over time.

Vehicle Design

Introduction Phase (Current–2015)

At first, it is likely that hydrogen production will be demand led, as requirements for initial supplies are driven by demand for hydrogen as a transport fuel, mainly for fuel-cell vehicles but also for hydrogen powered internal combustion engines. Fuel cells will initially be trialled in buses and fleet vehicles, but penetration is likely to grow with the development of hydrogen fuelling infrastructure. Development of better on-board hydrogen storage systems and further cost reductions in fuel cells could result in their uptake for use in passenger cars, taking advantage of the higher efficiency and enhanced driveability of this new technology.

Establishing a cost effective hydrogen distribution network and identifying better hydrogen storage solutions will therefore be key projects in this phase. Whilst the initial distribution network will be mainly an investment issue (with the development of a full refuelling infrastructure occurring in phases over twenty years or more) the necessary advances in hydrogen storage materials, as well as in improved materials for fuel cell construction, are important current challenges for the chemical sciences community.

Given the low absolute demand for hydrogen (relative to conventional hydrocarbon fuels) the energy efficiency of the production pathway will initially be of secondary importance. Even the most optimistic scenarios for hydrogen fuel forecast that demand in the early years can be satisfied from existing, centralised production capacity. Reforming of hydrocarbons is thus likely to satisfy most demand for hydrogen in the early years. The higher conversion efficiencies make hydrogen, when used in fuel cells, a greener option than petrol or diesel internal combustion engines, even when produced from non-renewable sources.

Continued development of effective renewable or carbon-neutral processes on a production scale will, however, remain an important objective so that these new pathways are ready for later years.

Early Transition Phase (2015–2035)

As intermittent renewable, and potentially nuclear, power generation increases, a need for energy storage using hydrogen is likely to develop. Hydrogen production, *via* electrolysis or thermochemical routes (using heat from nuclear reactors), could start to become more supply driven as hydrogen develops into a true energy vector, as well as being used as a transport fuel.
It is likely that there will be a greater focus on the efficiency and emissions generated during hydrogen production and throughout the energy cycle as growing volumes of hydrogen are produced and demand for hydrogen as a transport fuel increases. Reforming of hydrocarbons, without carbon capture, may become less attractive as other production routes based on renewables or carbon-neutral pathways are introduced.

For the same reasons, the high energy consumption of compression or liquefaction will focus attention on alternatives to these storage methods in the distribution of growing amounts of hydrogen. Large-scale, solid-state hydrogen stores using similar materials to on-board stores may provide a solution. Development of processes using materials that can be reversibly hydrogenated (e.g. the reversible conversion of benzene to cyclohexane) offer a further option for hydrogen transport. Catalysis and material stability will be important factors in any such process. Distributed generation of hydrogen, in smaller 'forecourt reformers' or through improved electrolysers, will increase should demand grow and if further production capacity is required. Although neither of these offer zero-carbon, or carbon-neutral hydrogen, the energy and costs involved in transporting hydrogen may make these processes attractive in some cases.

Late Transition Phase (2035–onwards)

In later decades the focus of activity is likely to move towards the replacement of hydrocarbon based production processes by new pathways to hydrogen. Advances in photochemical, enzymatic and high temperature thermochemical cycles may bring costs down to levels that are competitive with increasing oil and gas prices. Hydrogen production from coal, coupled with carbon capture, may also become an important route. These processes are in the early stages of development and much work will be required to provide feasible production processes.

Technological barriers

Today's personal automobile customers are uncompromising in their demand for performance, reliability and value for money. New vehicles must compete with existing models in terms of function, safety and durability. For hydrogen propulsion systems to reach these standards major technical breakthroughs are required.

Hydrogen Storage

Safe and efficient storage of hydrogen is critical for developing vehicles which meet customer expectations in terms of vehicle range and refuelling procedures. The goal is to produce a low-cost, light-weight system capable of holding enough on-board hydrogen to travel for 200 miles without compromising vehicle design or passenger comfort. Advanced conventional storage concepts, which use either compressed gas or liquefied hydrogen, can only achieve sufficient volume density to meet this mileage target with some compromises (although demonstration fuel cell vehicles can achieve a 200 mile range).

Storage technologies are often compared on their system weight-to-fuel capacity. The ultimate goal is to create a 10 weight percent system (in which hydrogen accounts for 10% of the total storage system weight) that costs no more than 10% of the value of the car. Current systems fall far short of this benchmark, reaching no more than 5 weight percent.

Additional problems also remain: liquid hydrogen technologies, for example, suffer from 'boil-off' rates of around 1 to 3% per day despite sophisticated passive cooling systems. Efficient on-board storage therefore remains a major challenge and although alternative high-density storage mechanisms have been investigated (including chemical hydrides, complex hydrides, hydrogen adsorbents) none currently offer a suitable storage alternative. To tackle this problem innovative research and development efforts will be required: storage systems must be a key research priority.

Key challenge: create a system which costs no more than 10% of the value of the car, in which hydrogen accounts for 10% of the total storage system weight.

Hydrogen Production

Hydrogen can be derived from a variety of renewable and non-renewable sources. To minimise the contribution to global warming, hydrogen must be manufactured without generating significant CO_2 emissions. Current techniques are based on fossil fuels: hydrogen is produced by steam reforming of compressed natural gas, or via the gasification of coal. Renewable technologies can be used to generate hydrogen but it is clear that these methods are unlikely, in the medium-term, to allow sufficient and cost-competitive volumes to be produced. Producing hydrogen from energy generated via nuclear fission is another possibility; this is likely to be the long term option, although it is still unclear whether electrochemical (using electricity to split water) or thermochemical (using heat to split water) production poses the most feasible strategy.

Renewable hydrogen can also be produced from biomass or organic wastes, either via gasification or anaerobic digestion; production from organic waste is a particularly attractive option as it also contributes to the management of waste and reduces methane emissions from landfill. An alternative option is to produce hydrogen within vehicles: hydrogen in methanol or ethanol can be released by alcoholysis with lightweight metal hydrides in the presence of a suitable catalyst (platinum or noble metal based). However, with current technology the car industry deems this method too complex for commercialisation.

In summary, despite progress large-scale hydrogen production remains uncertain. Financial support for research into efficient production has been overlooked by many funding bodies; this needs to be addressed. Particular attention should be paid to the conversion of biomass into hydrogen and the production from renewable energy sources. An additional consideration for hydrogen manufacturing is the purity level; this should be fit-for-purpose (fuel cells require a higher level of purity than internal combustion technologies). The purity level of hydrogen production required should be factored in when comparing the life cycle energy requirements of hydrogen technologies.

Fuel cells vs. internal combustion engines

Hydrogen energy conversion has focused on two fundamentally different approaches; internal combustion engine (ICE) and fuel cells. Fuel cell vehicles are the 'end game' for hydrogen-powered transport, but currently fall short of requirements; cell lifetimes are too short, costs are too high and technical problems remain. Hydrogen-powered ICE vehicles are closer to commercialisation than fuel cell technologies. Advances in hydrogen ICE vehicles may help create a viable economic path to fuel cell vehicles, as on-board hydrogen storage, refuelling, sensors and instruments are common between the two technologies. Several prototypes of fuel cell and ICE vehicles are available, but these vehicles fail to compete in real terms with existing technologies. Early assumptions about the technological readiness of both fuel cell and ICE hydrogen propulsion systems were overly optimistic. Although substantial developments have occurred in the past decade, it seems unlikely that hydrogen-powered vehicles will have any significant market penetration by 2020 (except in niche markets, such as buses and forklift trucks). A more achievable target for commercial hydrogen transport is 2030, but this will depend on major technological leaps forward and overcoming additional obstacles.

Key challenge: develop a cost and performance competitive hydrogen-powered vehicle with a 300+ mile range

Economic and political obstacles for the hydrogen economy

Infrastructure for using hydrogen powered vehicles

Until there is a macro-level consensus on the feasibility of hydrogen cars major investment is not realistic. However, establishing a widespread hydrogen refuelling infrastructure is a prerequisite for the commercial introduction of hydrogen cars. This will be a major challenge which should not be underestimated. Substantial market intervention is likely to be required in early years of transition when demand is dispersed; whether this investment will come from government or industry remains unclear. However, the refuelling infrastructure requirements for vehicles that fuel at a central depot are much less onerous; as such, buses and other fleet vehicles, which require refuelling just once a day, are likely to achieve significant penetration earlier than cars. There are additional issues which must also be resolved: it is not currently known, for example, whether gaseous or liquid hydrogen will be used in the transport sector (although currently 700 bar compressed gaseous hydrogen is favoured by the car industry), or whether hydrogen will be produced locally, regionally or on a much wider scale. From the car manufacturers' viewpoint, lack of a coherent refuelling infrastructure will slow commercial commitment and delay progress. In Norway, work to develop a demonstration hydrogen refuelling infrastructure is well underway. The 'HyNor' project, which covers 360 miles of road between Oslo and Stavanger, is due to be completed next year[10]. Similar projects are underway in Canada[11] and California[12]. These may act as a useful templates for implementing hydrogen infrastructures.

Economic issues for using hydrogen powered vehicles

The *price* paid by consumer for hydrogen-powered vehicles depends on a variety of factors, including government subsidies and fiscal intervention. At present the manufacturing costs of fuel cells are at least an order of magnitude too high whilst for internal combustion engines the additional technology cost is more manageable. Fuel tank costs for both liquid and compressed gaseous storage will remain an issue until volume production has been achieved. The running costs for hydrogen-powered transport will depend on the cost of manufacturing hydrogen.

The ultimate goal, to match the cost-to-power ratios of current technologies ($50/kW), is a long way off – the most efficient hydrogen systems quote $1500/kW. Emerging hydrogen technologies will inherently be more expensive initially than established transport energy sources. However, automobile and related industries are fully capable of investing and innovating to overcome this, if clear, stable, outcome-driven policies or incentives are in place to encourage them. Large companies should be involved in the development of, and investment into, a sustainable hydrogen-based transport system.

At present the key economic priority is developing competitive hydrogen-powered vehicles in parallel to developing hydrogen refuelling infrastructure, and funding opportunities and

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[10] www.hynor.no/english
[11] www.hydrogenhighway.ca
[12] www.hydrogenhighway.ca.gov/

policies should reflect this. In the early stages, considerable investment will also be required for demonstration exercises.

Further down the line, when technologies have advanced beyond the research stage, incentives will also be needed to encourage end-users to purchase hydrogen-powered vehicles (e.g. tax cuts or CO_2/km limits) and industries to increase the volume of hydrogen vehicles produced (reducing production costs).

Key challenge: fuel cell with $50/kW at large production volumes

Political issues

The prime political drivers for hydrogen-powered transport are climate change, energy security and air quality; the emphasis on each of these varies geographically, with energy security being more important in the US and environmental benefits being key in Europe. Diversity in production methods will reduce dependence on imported fossil fuels from politically unstable regions of the world. Europe is currently lagging behind the US and Japan; both have invested heavily in hydrogen transport research and development, and this is driving industrial activity. To compete on a global scale Europe must create a similarly favourable business environment through clear, targeted and appropriate outcome driven policies. Policies must have measurable goals, supporting the sustained transition to hydrogen transport with both short-term and longer-term targets. These policies must form part of a consistent and integrated transport directive, which considers the transport system as a whole.

Environmental issues

Urgent and substantial reductions in CO_2 emissions are required within 15 years. For example, in the recent UK draft Climate Change Bill it is suggested that carbon emissions will need to be reduced by 26-32% by 2020. Given this timeframe, hydrogen technologies will not initially have an impact on mediating climate change. As such, technologies which provide short term reductions should be prioritised and investments in developing long term strategies rationalised.

The benefits of hydrogen are uncertain

The large-scale environmental benefits of hydrogen technologies are yet to be proven: there is uncertainty concerning the volume of hydrogen which can be produced from renewable energy sources. Currently the most promising options are production from organic wastes, and also photolytic and electrolytic (via wind) production, but problems remain. Unless the CO_2 is captured and stored, producing hydrogen from natural gas significantly reduces the environmental 'savings', while production from coal increases overall emissions. Dedicated production from nuclear energy remains in the developmental stages. As such, Well-to-Wheel (WtW) and full Life Cycle Analyses (LCA) are essential, so the impact of hydrogen technologies can be compared with alternative low-carbon transport options in a consistent and comprehensive manner. Such a study has been undertaken, and recently updated, by Concawe et al. http://ies.jrc.cec.eu.int/wtw.html

Main challenge: determine real environmental benefit of hydrogen on a WtW basis and compare on a like for like basis to alternatives

Renewables

The use of renewable electricity technologies for hydrogen fuel production has been debated. On one hand, hydrogen offers a route for renewable technologies to enter the transport market (with the exception of biofuels, which are already in the market). On the other hand, renewable technologies can be used more efficiently in stationary applications; these therefore offer far greater saving in terms of CO_2 emissions and may be a more appropriate use of renewable electricity. However with society unwilling to give up its mobility, the demand for transport is estimated to increase, work to introduce renewable technologies into the transport sector should begin now. It may be possible to avoid this problem by using non-electricity renewable resources, such as biomass and organic wastes; these offer renewable hydrogen, while also allowing renewable electricity resources to be used most efficiently. The environmental benefits of hydrogen technologies must be fully understood to allow rational decisions to be made on its future.

Social obstacles

Air pollution and health hazards

Urban Air Quality in the EU under existing and proposed legislation is judged to be adequate to avoid health problems. Urban air quality may become a driver for hydrogen technologies if health problems associated with vehicle emissions increase. This may become particularly important in emerging economies, such as India and China, where deaths associated with air pollution are increasing.

Perception

While hydrogen vehicles are proven in the laboratory to be as safe as petrol-powered cars, there are currently insufficient vehicles in the fleet to assess the 'real world' safety. Although no safety issues are anticipated, perception is often more important than reality. To ensure hydrogen technologies are welcomed by the public greater consumer awareness of hydrogen as a transport energy vector is required. Hydrogen-powered buses, which are now operating in selected cities worldwide, are helping to build public confidence. In the long term, understanding should be increased by including information about hydrogen-powered low-carbon transport in the national curriculum.

Other obstacles

Electric vehicles might be thought to be closer to commercialisation than hydrogen technologies, in terms of cost, efficiency and vehicle performance. Electricity can be produced relatively 'cleanly' from secure, renewable energy sources. However, battery technology limits electric vehicle range and the expectations of a better battery have not yet materialised. Nevertheless, improving electric energy storage and drive train technologies also benefit future hybrid and fuel cell vehicles.

Appendix: List of organisations participating in the Fuelling the Future – Transport 2007 workshops

Auriga Energy Limited
Baker Petrolite
Bioscience 4 Business KTN
BMW
BP International
British Sugar
Centre for process innovation
Delphi
DTI
e4tech
Ford
FPT Powertrain
Germany
Imperial College London
Infineum
Innospec
Jaguar
London Hydrogen Partnership / Energy Centre for Sustainable
Lotus Engineering
Lubrizol
MAHLE Powertrain Ltd.
Miller-Kleine associates
National Non Food Crop Centre
Potenza Technology Limited
Queen Mary University of London
Kings College London
SusChem
UK Energy Research Centre
University of Cardiff
University of Leeds
University of Manchester
University of Newcastle upon Tyne
University of Nottingham
University of Reading
University of St Andrews
University of Strathclyde
University of York
Warwick Manufacturing Group