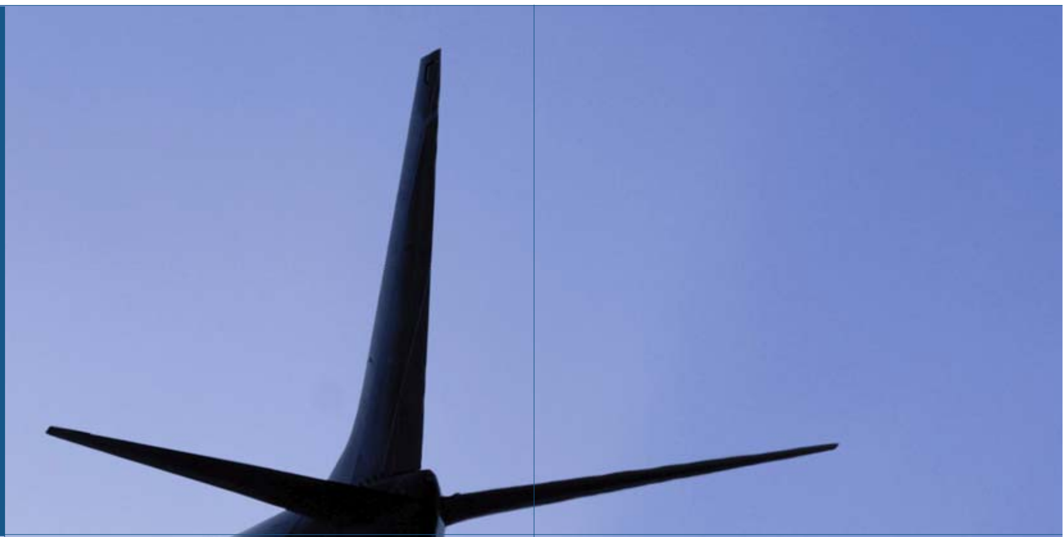
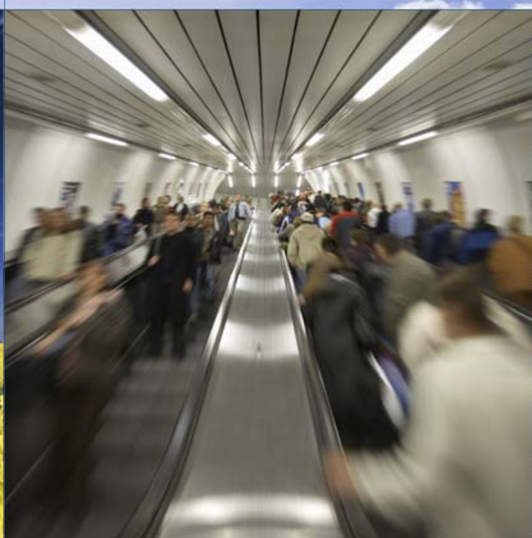
Transport Technologies and Policy Scenarios to 2050

World Energy Council 2007

Promoting the sustainable supply and use of energy for the greatest benefit of all





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Executive Summary

Transport is one of the major global consumers of energy and therefore has an important role in meeting the primary objective of the World Energy Council, sustainable energy for all. Transport is the only energy sector in which the energy itself is mobile during consumption, rather than being delivered for use at a fixed location. For this reason, energy for transport is dominated by petroleum, which is widely available, relatively inexpensive and from which easily transportable liquid fuels of high energy density such as gasoline and diesel are made.

The sustainability of petroleum and other fossil fuels within the timeframe of this study, to 2050, has been put into question by scientists, policymakers and other stakeholders. Sustainability is measured in terms of the 3 A's criteria of accessibility, availability and acceptability, differentiating between the relative importance of different regions. Sustainability of fuels brings into question the sustainability of the associated vehicle technologies. In this study, existing and potential fuel and vehicle technologies are assessed both qualitatively (by the 3 A's criteria) and quantitatively (by the contribution to reduced consumption) to determine a roadmap for technologies which can help meet the objective of sustainable energy. Other non-technical measures are also considered. The roadmap of technologies and measures is put into a practical context by considering the policies necessary to ensure that the objectives are met in the most efficient and effective way possible.

The following analysis and projections of technologies apply to both developed and developing countries. The penetration of technologies will in general occur first in developed countries and at a later time in developing countries, since their less wealthy economies are less able to absorb the technology cost. This delay will be greater for the more advanced and expensive technologies, but the market presence of new technologies in developed countries can be expected to enable early adoption in many developing countries. The analysis of policy options applies equally to all countries and regions, since the economic viability of technologies and measures in a functioning market is an essential condition for effective transport policy regardless of the stage of economic development.

Technologies for reducing consumption

Passenger vehicle technology is expected to remain dependent on petroleum fuels and internal combustion engines (ICE) for the foreseeable future. Enhancement of ICEs through clean diesels, hybrids and new combustion techniques will ensure increased efficiency. Hybridisation will increase in popularity, in particular in congested areas with stop-start driving.

Alternative fuels will also increase steadily in penetration, with second generation biofuels such as synthetic biomass-to-liquid (BTL) growing significantly by 2035 and synthetic gas-to-liquid (GTL) already expected to grow strongly in the coming decade. Hydrogen fuel and fuel cell vehicles are expected to gain a

BTL and cellulosic ethanol have the potential to reduce fossil and petroleum energy consumption (and GHG emissions) by up to 90%.

market foothold by 2035 and grow towards 2050. By 2050, gasoline and diesel fuels will still play a major role, but their biofuel portion will be significant. Electric power utilisation in transport will also increase, in particular in OECD and richer developing countries. This will be manifested as increased hybridisation with a potentially significant element of pure electric vehicles powered by batteries and/or fuel cells.

Commercial vehicles comprise over 40% of land transportation energy consumption. Improvements will likely remain based on the diesel engine, with innovations such as variable valve timing and new combustion techniques. Hybridisation may penetrate in certain applications, in particular in urban buses.

In aviation, engine and materials technologies and flight management measures will potentially be available, which can improve aircraft efficiency by over 30%. However, set against the expected 200% growth in air travel by 2050, efficiency improvements can serve only to dampen the increase in consumption. Aviation fuel presents a particular opportunity for alternative fuels, since aviation fuel (kerosene) can be, and is already, made using the synthetic Fischer-Tropsch process, which can use gas, coal or biomass as a feedstock (GTL, CTL, BTL CTL fuels).

The potential for reduction in energy consumption varies by technology. High penetration (50%) of diesel and hybrid passenger vehicles can contribute a reduction of several percent in global transportation energy demand, in comparison to the growing baseline. Estimated economic breakeven points (i.e. the point at which the incremental cost of technology is recovered through associated fuel savings, assuming 3 year payback) for these technologies in passenger vehicles are generally lower than the foreseeable technology cost. This indicates the lack of a consistent business case for the consumer. Higher oil prices, consumer acceptance of longer payback periods and complementary benefits of the technologies will and do increase the breakeven point (as in Europe with over 50% diesel penetration).

Assuming economically, environmentally and socially sustainable production, the highest potential for reduction in petroleum and fossil energy (and therefore greenhouse gases - GHGs) lies in biofuels, including BTL and cellulosic ethanol. Such biofuels have the potential to reduce fossil and petroleum energy consumption (and GHG emissions) by up to 90%. Their benefit in existing vehicles is immediate, is not limited by new infrastructure requirements and they can contribute in all transport sectors which consume liquid fuels (land passenger and freight as well as shipping and aviation).

The production of BTL and cellulosic ethanol is, however, accompanied by a significant increase in primary energy consumption due to the energy consumed in their production process. Other advanced biofuels are under development and may present viable long-term options. Conventional biofuels such as ethanol from sugar cane and biodiesel (or hydro-treated

For plug-in hybrid technology to become viable for the mass market, substantial reductions in the cost of the electric powertrain are essential.

vegetable oil) from oil plants can be expected to retain some market share even to 2050. In particular, to ensure the most efficient solutions prevail, it is important that biofuels are selected according to market forces and viable, consistently applied GHG intensity and sustainability standards, without discrimination.

Other synthetic fuels such as GTL and CTL increase accessibility and availability by diversifying the fuel supply base and, in particular with GTL, are already available and economically viable. On a life cycle basis, GHG emissions from GTL are comparable to conventional diesel, and for CTL without carbon capture and storage they are approximately double. CTL and GTL also contribute to technological experience and understanding of synthetic fuels in general, benefiting BTL development.

A number of measures are projected which can improve the efficiency of mobility systems. These include urban planning and alternative work scheduling to reduce commuting, improving the scope and attractiveness of public transport, driver behaviour, intelligent transport systems and innovative systems such as personal rapid transit. More efficient transport systems must be both convenient and economically beneficial if they are to contribute significantly to energy objectives. In building urban areas and transport systems and, in particular, in setting regulations and costs, policy should seek a balance between the energy objectives and mobility. In particular in developing countries, populations should not be prevented from participating in economic growth through increasing their level of mobility, which may include access to private vehicles.

Technology breakthrough

In order to make substantial improvements in sustainability of energy for transport, in the light of substantial projected economic growth over the next 43 years, breakthroughs in technology will be necessary by 2050. Hydrogen and fuel cells can contribute significantly in the passenger vehicle sector if the substantial challenges of fuel cell cost, hydrogen storage, hydrogen production and hydrogen delivery can be overcome.

Battery electric vehicles have a potentially greater energy savings potential, but battery technology and cost must improve substantially to provide the performance and range demanded by consumers. Electric powertrains are likely to make advances in small vehicles for city driving and a number of commercial companies are already offering vehicles to this niche and in the premium segment. Plug-in hybrid electric vehicles offer most of the benefits of electric vehicles, with the convenience of conventional internal combustion engines. The presence of two full powertrains in a plug-in hybrid vehicle means that for this technology to become viable for the mass market, substantial reductions in the cost of the electric powertrain are essential.

In order for BTL, cellulosic ethanol and other biofuels to make the maximum contribution to a

The integrated approach incorporates all relevant stakeholders in the chain of energy production and use in applying energy saving measures and technologies

reduction in petroleum consumption and GHG emissions by 2050, significant advances in technology are necessary. Continued cost reduction in biomass resource management and production processes is a prerequisite for these fuels to be an economically viable prospect at high volumes and thereby contribute to accessibility and availability. Cost reductions can be expected through economies of scale and optimisation of the technologies, as well as identification of new products.

In addition, breakthroughs in land yield and water management for biofuels crops are essential to ensure high volume sustainable production. Most studies project maximum global yields equivalent to between 25% and 40% of total fuel demand. To increase past this point, new agricultural techniques would be necessary, perhaps relying on further advances in genetically modified organisms.

The long term environmental acceptability of CTL will be enhanced by the economic viability of carbon capture and storage (CCS). Life cycle GHG emissions of CTL with CCS are approximately 30% higher than conventional diesel (c.f. 100% higher without CCS). Therefore, environmental acceptability of CTL will be difficult even if combined with CCS. CCS technology will need substantial improvements and more investment to realise its potential. If CCS becomes viable, additional potential lies in energy generation from fossil fuels (which may be used for electric powered transport) as well as for CTL production.

Rational policy – an integrated market-based approach

Policymakers must first agree on the overall objective, whether it be a reduction in energy consumption or greenhouse gas emissions. From there, technological development must be complemented by rational policy that will encourage and enable the technologies to emerge. The common thread in policymaking is that the market must be allowed to identify and advance the most efficient methods.

In order to meet the target, an integrated approach is the most efficient concept, rather than concentrating only on technologies. The integrated approach incorporates all relevant stakeholders in the chain of energy production and use in applying energy saving measures and technologies. This chain includes business, consumers and governments. The approach addresses the behaviour of business and private consumers in purchasing decisions and use of energy, of fuel suppliers in the energy content of their fuels, of equipment manufactures in the efficiency of their products and of governments in their responsibility for the transportation environment. It must be ensured that for all stakeholders a productive market is in place which financially rewards behaviour leading to higher efficiency.

Contents

1. Introduction

As a primary element of the Energy Policy Scenarios to 2050, the Transport Study must consider the relevant objectives of the World Energy Council relating to sustainable energy for all and in particular the 3 A's criteria.

The 3 A's

The 3 A's are defined as follows:

- **Accessibility**

The extent to which people have access to modern energy, as distinct from dependence on traditional energy forms.

- **Availability**

The reliability and security of energy supply systems, once access has been achieved.

- **Acceptability**

The environmental sustainability of energy supply and use.

Goals of the Transport Study

The goals of the Energy Scenarios to 2050 Transport Specialist Study are fourfold:

- To obtain a detailed appreciation of energy requirements for transport of goods and personnel over the planning period to 2050 (globally and regionally).
- To obtain a detailed appreciation of technology developments and options, which can increase energy-use efficiency and reduce reliance on hydrocarbon sources.
- To obtain a detailed appreciation of economic and social options and associated policies, which can increase energy use efficiency and reduce reliance on hydrocarbon sources.
- To produce a Position Paper on Transport Technology and Systems, which will serve as an effective support document for Scenarios development.

Elements of the Transport Study

The Transport Study will address the technical and behavioural aspects of energy use in transport and the associated policy elements which are necessary to enable those aspects to be beneficially employed.

Technical and behavioural elements

The measurable items which will result from this study can be clearly defined and relate to both qualitative and quantitative aspects.

Qualitative: the objective of this part of the study is to identify and rank efficiency and energy reduction technologies according to the 3 A's criteria: accessibility, availability and acceptability.

Figure 1-1 World Energy Consumption by End-Use Sector to 2030
Source: EIA, International Energy Outlook 2006

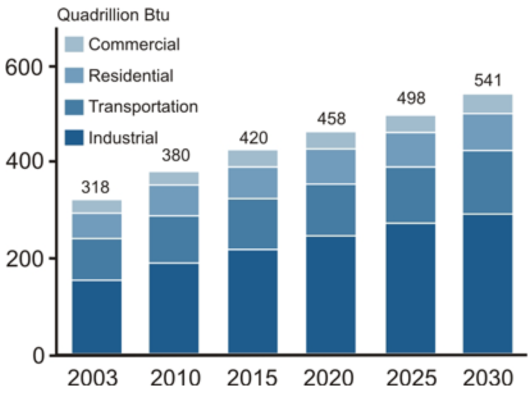
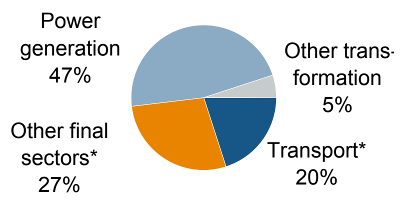


Figure 1-2 Incremental World Primary Energy Demand by Sector to 2030
Source: EIA, International Energy Outlook 2006



***Excluding electricity and heat**

Quantitative: this part of the study is intended to provide information on the magnitude of energy reduction potential and the marginal cost of implementing technologies and other measures to achieve the energy reduction endpoint. In this part of the analysis it is again worthwhile to consider what the objectives are: that is, in which parameters are we interested and the consumption of which “energy” would we want to reduce? There a many answers to this question:

- **Tank-to-wheel energy** is the energy used only to propel the vehicles themselves, which is an important parameter but does not consider the peripheral consumption of energy.
- **Well-to-wheel energy** considers all the energy inputs associated with the mobility, but does not consider the different sources of that energy.
- **Well-to-wheel petroleum energy** considers only that energy which is specifically from petroleum sources, and currently derives to a large extent from regions of the world considered potentially unstable or unreliable.
- **Well-to-wheel fossil energy** considers only that energy which is from fossil sources, which are by necessity exhaustible.
- **Greenhouse gas emissions** consider the net full cycle greenhouse gas effects of the use of fuels.

The quantitative analysis incorporates all of these parameters, allowing the reduction of any of them to be considered as an objective when assessing the numerical results. It is to be noted that CO_2 and other greenhouse gas emissions are not a primary focus of this study. Fossil fuel consumption is, however, a focus and can, to a large degree, be considered a surrogate for CO_2 emissions.

Policy

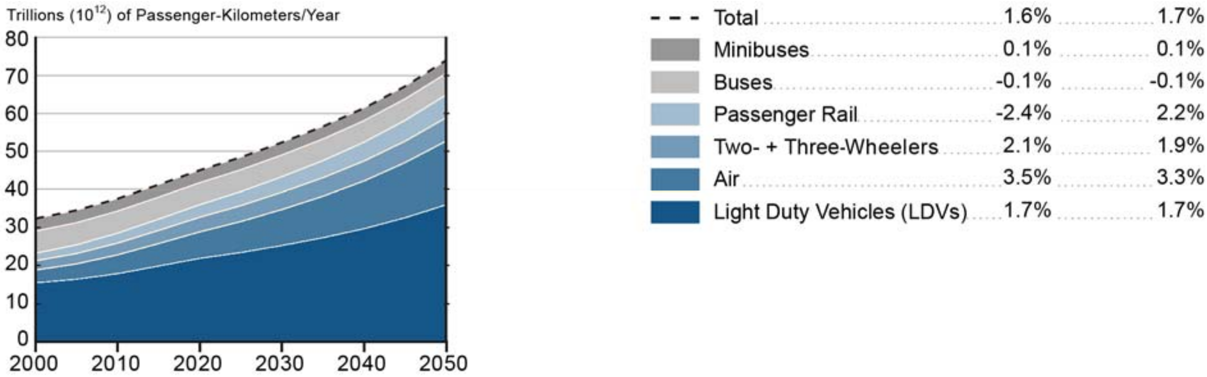
A full understanding of technology provides a useful platform for policy decisions. Those decisions themselves must, in the end, be based not on technology but on the processes necessary to enable appropriate technologies and other measures to be successful. Technology itself is therefore only part of the solution.

To put the mobility task into perspective, the data displaying global energy demand by sector to 2030 in Figure 1-1 and Figure 1-2 are informative. Whilst transportation is and is projected to, remain the second largest energy sector, it is dwarfed by the industrial sector, whose growth alone to 2030 equates approximately to total transportation demand.

Therefore, concentration on the transport sector’s consumption is an integral part of the energy future, but it must be considered holistically with other sources, in particular the industrial sector, in formulating energy policy.

In addition, it is not only technology that will be able to reduce consumption of fuel in

Figure 1-3 Data on personal transport activity
Source: Mobility 2030



transportation by 2050. Many other actors are responsible in the chain of consumption for automotive fuel, including fuel suppliers, governments who invest in infrastructure and transport systems and consumers who purchase and drive the vehicles. The behaviour of each of these actors can have an equally significant effect on overall consumption.

In this study, in order to link the different sectors involved in energy consumption and in particular the different actors involved in fuel consumption, in transport, policy will be addressed in terms of an “Integrated Approach” which reflects all the relevant elements.

Scope and data sources of the Transport Study

The transport study encompasses sectors, technologies and other measures relating to transport of passengers and freight until 2050 in all global regions. Figures 1-3 and 1-4 show the current projected energy demand in the passenger and freight transport sectors respectively, demonstrating the high overall growth rate and the particularly fast growth in all major passenger and freight modes.

The primary set of data selected as a basis for the transport study is the sustainable mobility dataset from the “Mobility 2030” report published by the World Business Council on Sustainable Development (WBCSD). This provides in-depth data and analysis on the transportation sectors in question and is in turn based upon data from the World Energy Outlook of the International Energy Agency (IEA).

Figures 1-3 and 1-4 represent energy and petroleum usage projections from the WBCSD data for the passenger and freight sectors, on which the mobility study will base its analysis.

The original data supplied by the Sustainable Mobility project will be used in this study as the base case, to be referred to as the “Business as Usual” or BAU case.

In addition to the numerical background data of the WBCSD, a number of further reports were used as sources of data, discussion and policy. These are listed in the bibliography in Appendix 1 and are referenced in the text of this report.

A further perspective is available through the fuels types used (Figure 1-5). Gasoline continues to dominate, with diesel and jet fuel both showing substantial growth. Residual fuel, mainly used for shipping, makes a clear contribution, but water transport will be considered in this report only in the context of diesel fuel substitution by alternative fuels.

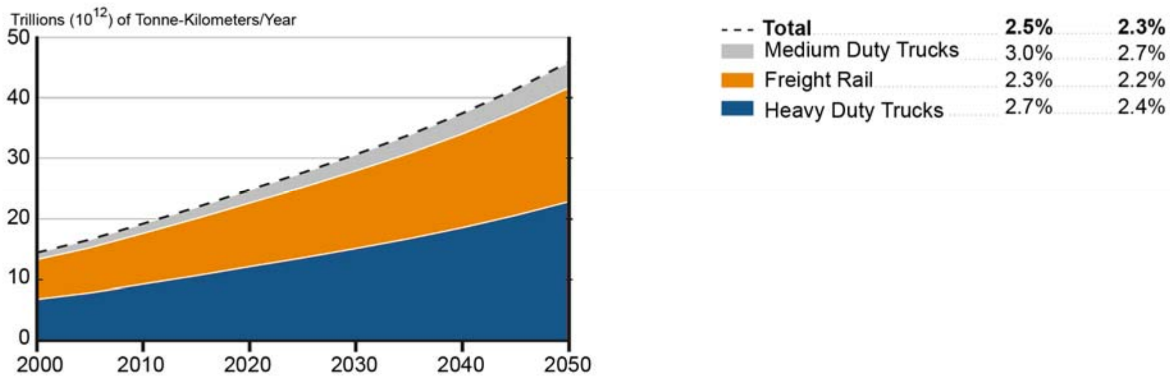
Sectors, technologies and other measures

Overview of sectors

Passenger transport includes but is not limited to:

- Light duty personal vehicles
- Air
- Other personal vehicles

Figure 1-4 Data on freight transport activity
Source: Mobility 2030

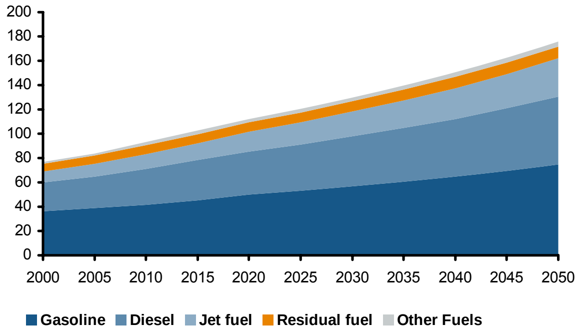


- Rail
- Buses and minibuses

Freight transport includes:

- Heavy duty trucks
- Rail
- Medium duty trucks

Figure 1-5 World fuel use by fuel type
Source: WBCSD Sustainable Mobility project



Overview of technologies and measures

Technologies to be considered are any which have a potential material effect upon primary energy consumption, petroleum consumption or greenhouse gas emissions.

"Hard" technologies are those which involve the application of hardware of vehicles or of transportation systems and infrastructure, or indeed of fuel and energy technologies. This may therefore include any of the following:

- Powertrain efficiency technologies
- Vehicle efficiency technologies
- Alternative fuels technologies
- Aero engine efficiency technologies
- Infrastructure implementation and technologies

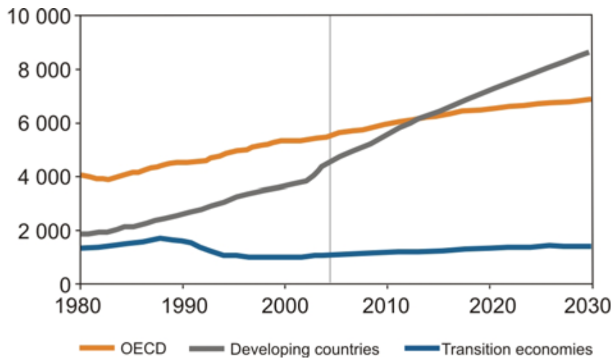
"Soft" technologies and measures are those which influence or relate to behaviour, including:

- Mobility system efficiency enhancements, affecting both demand and traffic flow
- Intelligent transport systems (ITS)
- Aircraft management measures
- Vehicles usage and lifestyle measures, including telecommuting and avoiding unnecessary journeys

Policy measures

The aforementioned technologies and measures are to be implemented by the responsible stakeholders – industrial companies, consumers, governments. In order for such changes to take place, a policy framework must be in place to inform on, encourage and incentivise the appropriate measures. With the aim of meeting the stated energy objectives, policy measures will be identified, which will influence decision making by stakeholders in regards to applying the appropriate technologies and measures.

Figure 1-6 World Primary Energy Demand by Region
Source: EIA, International Energy Outlook 2006



Timeframe and regions

For the analysis, three points in time will be discussed, in order to present a progression of technology implementation over time, with increasing uncertainty at each successive point:

2020 → **2035** → **2050**

The period from 2005 to 2050 is therefore split into three equal segments.

The global picture for energy is split into the following eleven regions:

OECD North America	Eastern Europe	Middle East
OECD Europe	China	Latin America
OECD Pacific	Other Asia	Africa
FSU	India	

Data is available to analyse each of these regions separately. In order to reduce the complexity and focus on the main areas of interest, analysis will be performed according to the following regional categories:

- Global.
- OECD countries and non-OECD (developing) countries.
- Where appropriate, further categorisation by individual region or country, also considering high-growth developing countries which by 2050 will approach the level of developed countries.

Potential developed regions

The analysis in this report will differentiate roughly between OECD and non-OECD countries. It is reasonable to make a further distinction, since over the 50-year period of the study, the lines between OECD and non-OECD are likely to become blurred. According to WBCSD figures, in 2005, the GDP per head of all non-OECD regions is less than 25% of the GDP per head of the OECD North America region. By 2050 it is predicted that FSU, Eastern Europe and China will all be within the region of 52% to 63% of the GDP per head of the USA, implying significant real growth in national wealth whilst quickly catching up with the currently developed world. Some Latin American countries may also achieve similar status although the average is projected to be 34% in that region. These countries and regions can be considered to be “developed” to a certain extent and are to be referred to as the “potential developed regions” in this study.

This leaves the remainder of Latin America, India, Asia the Middle East and in particular Africa, with a GDP per head in 2050 between 8% and 25% that of OECD NA, as the remaining developing regions and countries. Even in these regions, there are likely to be some parts that could belong, from an income perspective, to the potential developed regions, for example South Africa and certain regions of India.

2. Qualitative analysis of technologies

Mobility technologies

In order to select appropriate technologies for in-depth analysis, a master list of technologies was compiled in three categories: for vehicle/powertrain, fuel and mobility system efficiency.

Vehicle and engine technologies – *passenger vehicles*

These technologies include those primary technologies which have the potential to reduce energy and fossil fuel consumption. They include only those expected to have a potential material influence on consumption, therefore certain well known technologies are not included in the list.

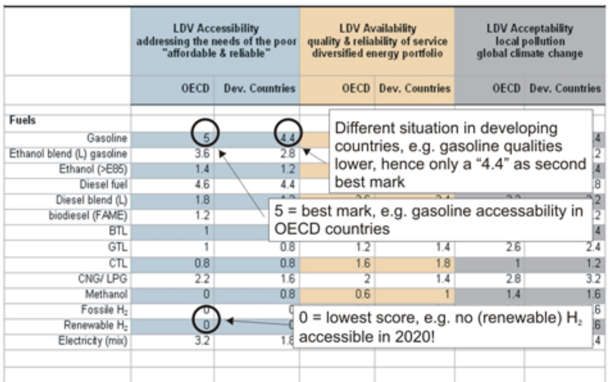
PISI	Internal Combustion Engine (ICE) using Port Injection Spark Ignition.
DISI	ICE using Direct Injection Spark Ignition.
DICI	ICE using the Direct Injection Compression Ignition technology.
HEV	Hybrid electric vehicle (e.g. ICE plus electric motor).
PHEV	Plug-in hybrid electric vehicle.
FC	Fuel Cell Vehicle.
Ref.-FC	Fuel Cell with fuel reformer on board.
BEV	Pure Battery Electric Vehicle.
CNG	Compressed Natural Gas Vehicle.

Vehicle and engine technologies – *heavy duty vehicles*

Heavy duty on-road vehicles and non-road vehicles, including rail locomotives and ships, primarily run on diesel fuel. The following list includes alternative primary technologies, potentially appropriate for heavy duty applications.

DICI	ICE using the Direct Injection Compression Ignition technology.
HD-HEV	Heavy duty hybrid electric vehicle (e.g., ICE plus electric motor).
FC	Fuel Cell Vehicle.
BEV	Pure Battery Electric Vehicle.
CNG	Compressed Natural Gas Vehicle.

Figure 2-1 3 A's voting method



Aviation engine and craft technologies

In addition to the potential for alternative methods of producing aviation fuel (kerosene), the following aero engine efficiency technologies are under investigation:

Unducted propulsors with reduced flight speed

Advanced combustors, zero bleed engines, advanced engine cycles (e.g. ACR)

Laminar flow control

Lightweight materials

New configurations

In-flight refuelling

Fuels

The following list include those fuels which have the potential to reduce energy and fossil fuel consumption. Again, certain fuels have been excluded from the list due to the lack of potential for material influence on consumption.

GTL	Gas To Liquid (naphtha, diesel or kerosene)
CTL	Coal To Liquid (naphtha, diesel or kerosene)
BTL	Biomass to Liquid (naphtha, diesel or kerosene)
EtOH	Ethanol
FAME	Fatty acid methyl ester (biodiesel)
Others	Emerging biofuels such as bio-butanol and hydro-treated vegetable oil
ME	Methanol
DME	DME
CH2	Compressed Hydrogen
LH2	Liquefied Hydrogen

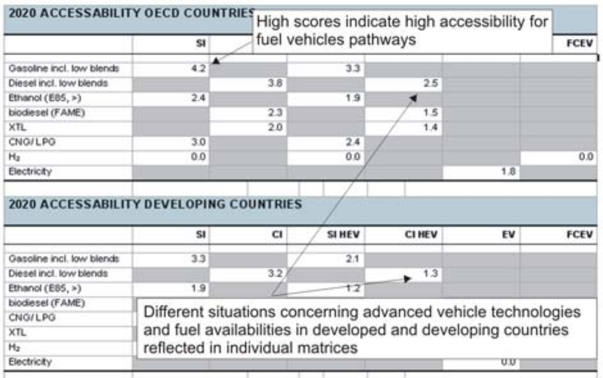
Analysis method

This analysis is conducted in three steps, resulting in a numerical evaluation of each technology in regards to each of the 3 A's.

Step 1: Independently assess vehicles & fuels

"Grades" for each fuel / vehicle technology for each "A-criteria", to be selected by expert members of Mobility Specialist Study Group

Figure 2-2 3 A's evaluation method



2020 ACCESSABILITY OECD COUNTRIES

	SI					FCEV
Gasoline incl. low blends	4.2		3.3			
Diesel incl. low blends		3.8		2.5		
Ethanol (E85, >)	2.4		1.9			
biodiesel (FAME)		2.3		1.5		
XTL		2.0		1.4		
CNG/LPG	3.0		2.4			
H_2	0.0		0.0			0.0
Electricity					1.8	

2020 ACCESSABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	3.3		2.1			
Diesel incl. low blends		3.2		1.3		
Ethanol (E85, >)	1.9		1.2			
biodiesel (FAME)						
CNG/LPG						
XTL						
H_2						
Electricity					0.0	

New combustion concepts such as HCCI will support continued improvement of conventional powertrains.

Step 2: Vehicles & fuel integration

Assumptions:

- Fuels reduced to „qualities at the pump“ (e.g. gasoline including low blends)
- Besides gasoline & diesel only E85, biodiesel, x-TL and H_2 treated separately
- Vehicle classes reduced to "Spark Ignition", "Compressed Ignition", Hybrids (SI + CI), FCV and EV
- One Matrix fuel/ vehicle per "A-criterion" and Region (developed or developing countries)

Step 3: Assessment of Fuels & Vehicle Technologies

- Voting of step 1 (fuels and vehicles separately) by every WG member
- Deduce group voting (average of individual voting) and perform fuel / vehicle integration
- Issue results

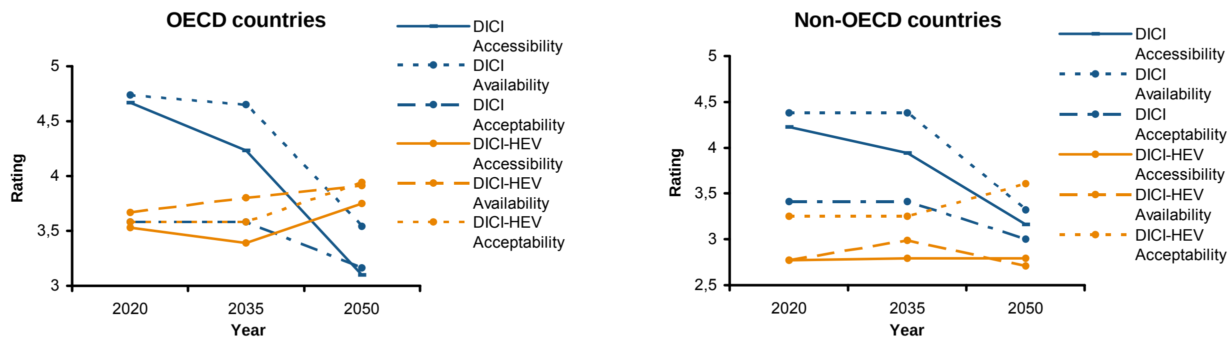
Results, passenger vehicle technologies

The full set of results is listed in Appendix 2 and Appendix 3.

In 2020 gasoline and diesel powered vehicles will still be by far the majority worldwide. In some regions/countries, first generation biofuels (ethanol from sugar beet, FAME) play an important role, but especially in OECD countries the usage of FAME will be limited to low blends into diesel due to engine compatibility restrictions. Other alternative fuels such as CNG and LPG will be mainly used in captive fleets and hence the overall impact is quite low. This is the case for hydrogen in 2020, which may begin to develop a market presence in some OECD regions on very limited scale. The vehicle development will be shaped by the further optimisation of combustion engine technologies (DISI, clean Diesel technologies) and a further progressing of hybridisation in OECD countries. New combustion concepts such as homogeneous charge compression ignition (HCCI) and combined homogeneous heterogeneous combustion (CHHC) will support continued improvement of conventional powertrains. Hybrids will be a factor especially in mega-cities with slow traffic conditions where hybridised powertrains offer highest efficiency improvements.

By 2035 the share of biofuels will have grown significantly due to a large scale supply of second generation biofuels (including ethanol from cellulose, BTL and hydro treated vegetable oil). GTL will be a cost-effective alternative fuel option and will become available in increasing volumes in the next decade. GTL will encourage development of BTL, as it shares the synthesis technology and has identical fuel properties. Due to expected shortages in the oil supply in

Figure 2-3 3 A's results for heavy duty diesel and diesel hybrid electric technology



some regions with low CO_2 concerns, synthetic fuel from coal (CTL) will also be produced in large industrial scale. It is expected that CTL will be available in China earlier than 2035 due to the country's large coal reserves and projected future transportation demand. In many OECD countries a limited hydrogen infrastructure may be in place at that time, supported by a corresponding growing availability of fuel cell cars and, to a lesser extent in the transition phase, of hybridised hydrogen combustion engine powered cars.

In 2050 the energy and fuel landscape will strongly differ from today's, with high importance of second generation biofuels and possibly hydrogen mainly from CO_2-free sources. Gasoline and diesel blends will still be in place but the share of oil based fuels is steadily decreasing, being replaced either by renewables or coal (e.g. China). As a consequence, vehicle technology has shifted very much to (partially) electric powered vehicles, either as hybridised ICEs or as fuel cell or pure electric vehicles. Electric hybrid ICE vehicles themselves can be further categorised into mild, full and plug-in versions, to be analysed further in Chapter 5. Production of conventional SI or DICI vehicles will migrate to developing countries, with the more advanced technology dominating in developed countries.

Heavy duty vehicle technologies

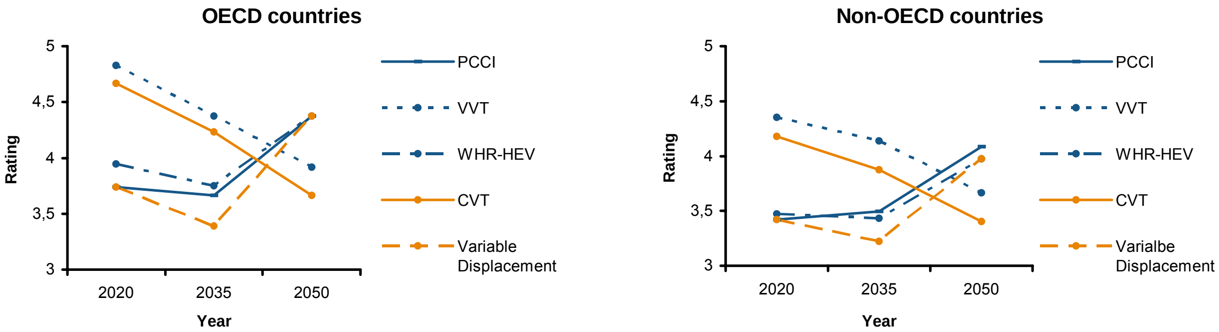
The full set of results for heavy duty vehicle technologies is to be found in Appendix 4. The scope of these technologies is much narrower than for passenger vehicles. Diesel technology is already widespread and is therefore not available as an efficiency measure. It is not expected that that fuel cell technology will play a significant role as a primary heavy duty powertrain even by 2050. The technologies under analysis include hybrid electric systems and measures which improve the efficiency of conventional heavy duty diesel engines.

The 3 A's analysis indicates the following trends to 2050:

Conventional diesel engine technology remains dominant until at least 2035. By 2050 diesel hybrid electric powertrains are expected to emerge in terms of accessibility and availability, to reflect their inherent higher level of acceptability due to environmental characteristics. The take up will be significantly slower than for passenger vehicles for two reasons. Firstly, the incremental improvement through a hybrid electric drive is diminished if the underlying powertrain is a diesel engine, compared to gasoline engine. Secondly, the majority of fuel consumed by heavy duty vehicles is in freight transport, in which stop-start driving is normally a relatively small proportion of the vehicle miles travelled, lessening the hybrid advantage and reducing its economic business case. However, absolute saving for commercial vehicles can be large due to their size and high consumption.

The 3 A's results in figure 2-3 confirm this opinion. Hybrid powertrains are likely to achieve

Figure 2-4 Average 3 A's results for diesel engine technologies



earlier penetration on urban buses and other heavy duty applications in which a high proportion of stop-start driving is to be expected.

The 3 A's results confirm the above statement for OECD countries, for which diesel hybrid electric technology overtakes diesel engine technology in each of the 3 A's by 2050. However, in non-OECD countries, accessibility and availability of the hybrid technology is expected to lag behind the conventional engine even in 2050, due to its cost premium. Whether the hybrid, or indeed any other heavy duty engine technology, can gain penetration in developing countries will depend heavily on the actual cost premium and the price of oil, thereby altering the potential economic savings for the consumer (in this case the truck driver).

In addition, the following engine technologies have been analysed, each representing improvements on the conventional diesel engine:

- **PCCI:** premixed charge compression ignition
- **VVT:** variable valve timing
- **WHR-HEV:** waste heat recovery hybrid
- **CVT:** continuously variable timing
- **Variable displacement**

In order to reduce complexity, a single average 3 A's value has been calculated for each of the technologies at each of the time points, providing an overview of the potential for each technology.

The VVT and CVT technologies are expected to figure even before 2020 but may be overtaken by the other available technologies after 2035. By 2050, the PCCI, WHR and variable displacement technologies are expected to emerge as their development matures. These results apply similarly to OECD and non-OECD countries.

Hybrid drives also offer potential for heavy duty vehicles with diesel engines. In certain applications with a high proportion of stop-start driving, this option may provide substantial absolute consumption savings. Hybridisation may even prove economically beneficial in highway trucks due to the high overall consumption rates per vehicle. In addition to powertrain technologies, the energy advantages of alternative fuels are experienced through their use in heavy duty vehicles. Since the great majority of heavy duty vehicles are diesel powered and expected to remain so, the alternative fuel of choice for high future penetration is likely to be x-TL type or hydro-treated vegetable oil, as discussed above and further analysed below. In fact, the continuing future presence of the heavy duty vehicle demand for diesel fuel provides a level of certainty in the future demand for alternative diesel fuels such as x-TL. This is in contrast to light duty vehicles, for which the type of future fuel cannot yet be accurately predicted, thereby providing less certainty in the future demand for gasoline type alternative fuels.

Air travel is projected to grow significantly faster than all other personal travel modes between 2000 and 2050.

Aviation

Air travel is projected to grow significantly faster than all other personal travel modes between 2000 and 2050, at 3.3% p.a. in passenger-km terms compared to 1.7% for all modes. Its proportion of global transportation energy consumption is predicted to rise from 12% to 18% in that time. Any effort to reduce either total transport energy growth or the total transport energy consumption must therefore take aviation into account.

Technologies

The Advisory Council for Aerospace Research in Europe (ACARE) has been tasked by European governments to investigate technologies to reduce aircraft fuel consumption by 50% relative to 2000. Potential contributions are projected from engine design (20%), airframe design (30%) and air traffic management and operations (10%). Specific technologies are the following:

Currently viable technologies – not economic:

- Unducted propulsors with reduced flight speed (20 – 30%)
- Laminar flow control (10 – 20%)
- High span configurations (10%)
- Operations (e.g. in-flight refuelling) (10 – 40%)

Other research has indicated potential future technologies:

- Advanced combustors
- Zero bleed engines
- Advanced engine cycles (ICR)
- Lightweight materials and structure
- New aircraft configurations

The topical nature of this subject has been highlighted through the public call by Richard Branson, Chairman of Virgin Atlantic, to introduce measures reducing CO_2 emissions from aviation by 25%, spurring other companies to consider similar measures. Much of the improvement would be gained through ground and flight management techniques. The measures include:

- Starting grids for departure to allow more aircraft towing, reducing on-the-ground consumption by over 50%
- Continuous descent approach, involving a longer and smoother descent, reducing fuel burn
- Air traffic control consolidation in Europe to coordinate efficient air movements
- Reduced weight of peripheral items.

As with automotive powertrains, new generations of aircraft and engines are built to be more efficient than the previous generation. For example, the new Boeing 787 midsized airliner is claimed to be up to 20% more efficient than existing aircraft of the same class, through more efficient engines, improved aerodynamics, lightweight materials and its electric architecture.

With air travel projected to quadruple between now and 2050, these technical solutions appear able only to dampen the growth in aviation energy demand. Depending on the regulatory situation, it appears likely that only those technologies which are economically viable will be implemented, therefore depending very strongly once again on the price of petroleum.

In addition to efficiency improvements, there is potential for the use of aviation fuel with low full-cycle CO_2 emissions. For aviation fuel (kerosene) this specifically relates to Fischer-Tropsch type x-TL fuel. Since aviation fuel conforms to a single global standard and kerosene's long-chain molecules are ideal for the Fischer-Tropsch process, the potential is clear. In fact, both CTL and GTL aviation fuel are being tested in the USA and South Africa, where a 50% CTL mix is already permitted. Each of these offer potential for reduction in petroleum consumption and lower exhaust emissions. With the introduction of BTL, the potential for fossil energy and full-cycle greenhouse gas reduction also exists. The same implications are present for x-TL kerosene as for x-TL diesel fuel, which is studied further in Chapters 3 and 5.

Regional analysis

A more detailed graphical analysis for OECD and developing countries over the 3 time periods 2020, 2035 and 2050 shows the different technological development and speed of progress. For this purpose, the individual 3 A scores for selected fuel/powertrain combinations have been displayed in Figure 2-5 for the three time periods for OECD and developing countries. The gasoline SI car has been chosen as reference (marked in blue) and the two most promising alternatives biofuels (shown: E85 in SI HEV) and hydrogen (shown: FCV) have been highlighted as well in dashed orange and grey.

A comparison of OECD and developing countries shows that by 2020 the accessibility and availability of the conventional fuels, gasoline and diesel, including low blends of biofuels, is to some extent lower than in OECD countries. Concerning alternative fuels there is, apart from CNG and LPG, a big difference between developed and developing countries:

- Biofuels will penetrate faster in developed countries; however, there is chance to minimise the gap by 2050 if sufficient investments in biofuel production facilities are made in developing countries.
- Hydrogen can achieve a significant fuel market share (greater than about 5%) by 2050 only in OECD countries. Due to the more complex process chain from well to wheel, it is unlikely that hydrogen and fuel cells will gain such a market position in developing countries. For fleet users in developing countries, hydrogen fuelled

Figure 2-5 Regional 3 A's analysis results for selected fuel/powertrain combinations

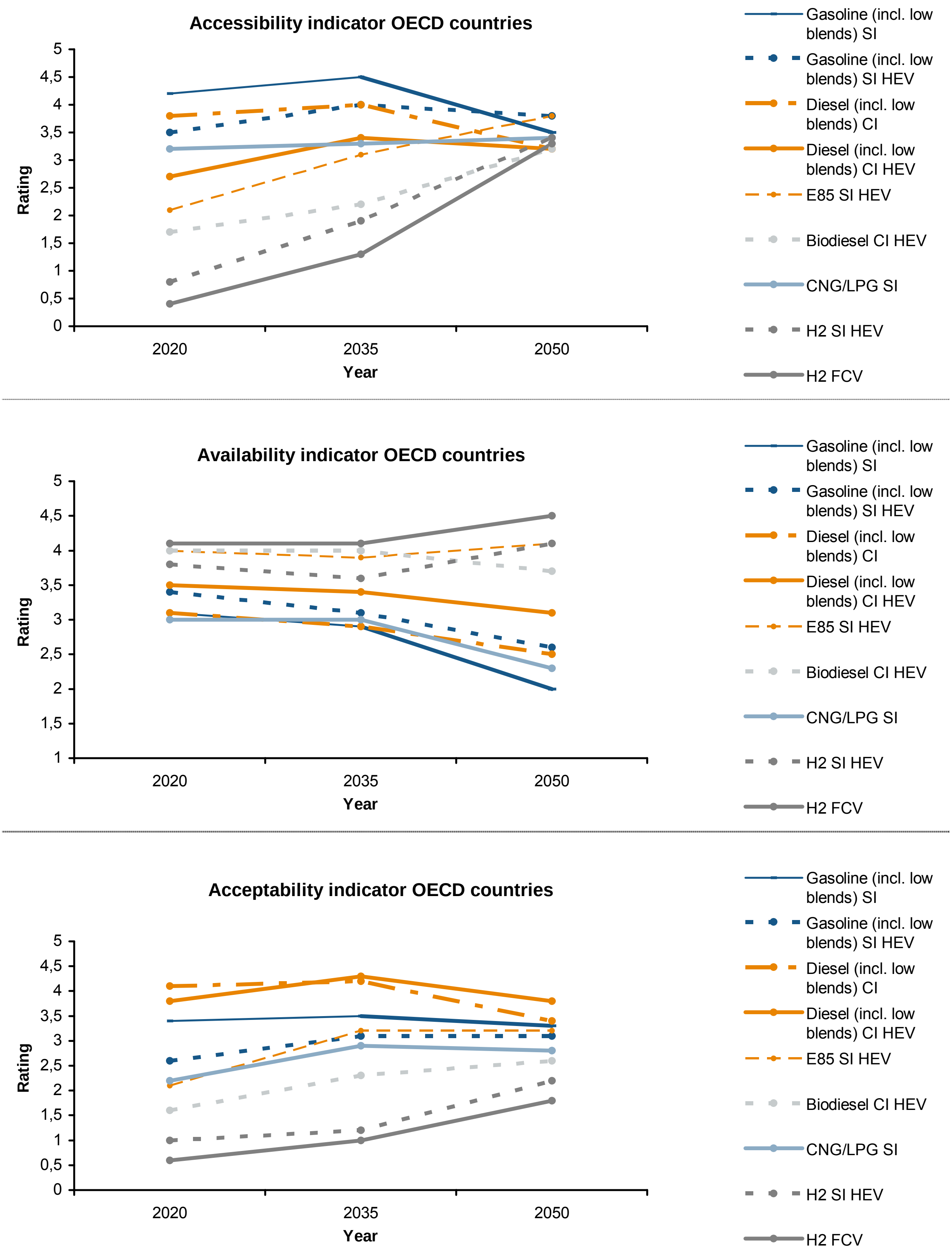
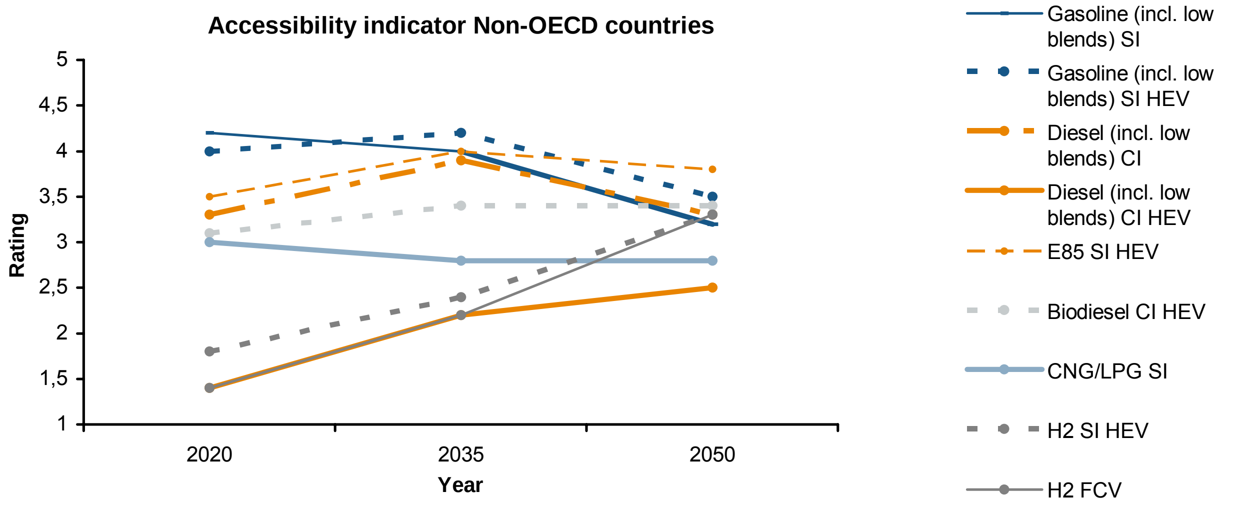
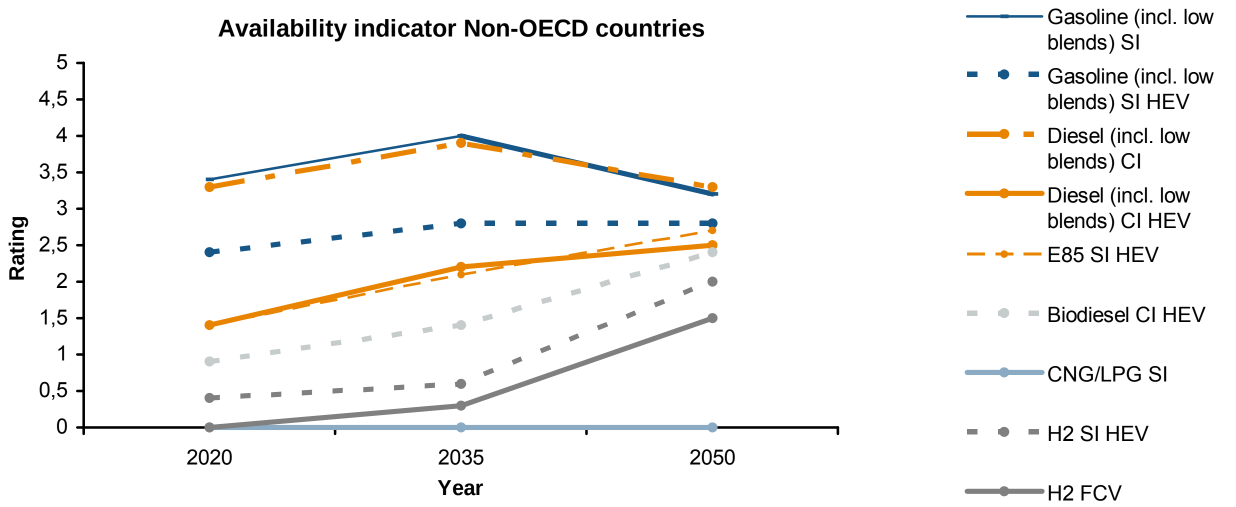
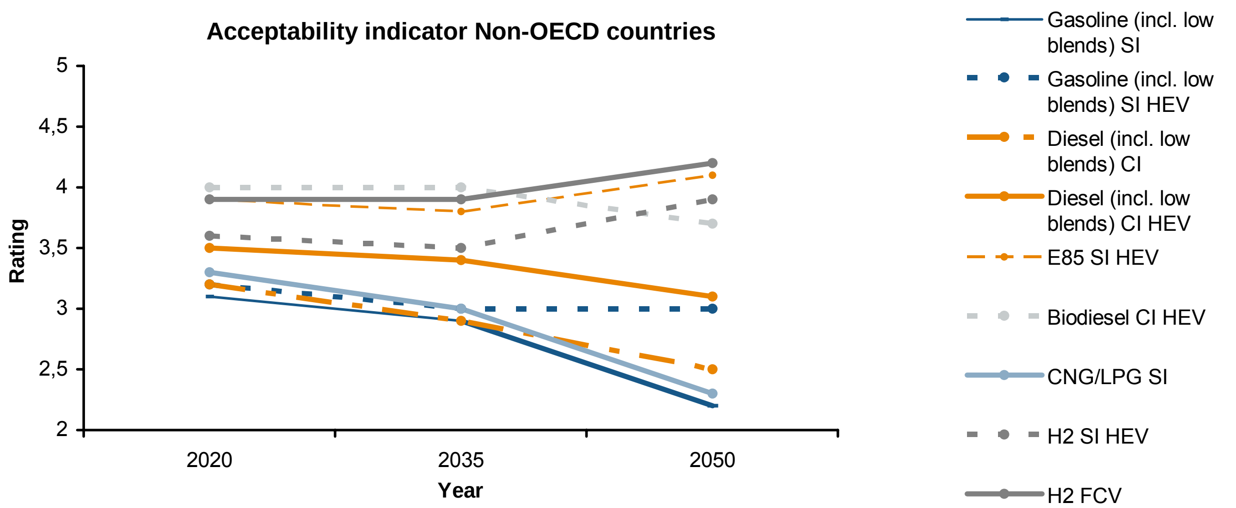


Figure 2-5 ***(continued)*** Regional 3 A's analysis results for selected fuel/powertrain combinations







combustion engines could lower the hurdles concerning accessibility and availability however, this technology strongly competes with CNG and LPG both of which are already in use with a further growth perspective.

- Powertrain technology development differs strongly, too. The shift towards electric assisted (hybrids) and fully electric powered vehicles (FCV, BEV) is starting in developed countries, while conventional technology is likely to remain the dominant driver in personal transportation in developing countries out to 2050.
- Adoption of alternative fuels is likely to begin earlier in those potential developed countries which will emerge as middle income regions by 2050, such as China and Eastern Europe, in particular in their more advanced countries and subregions.

Conclusion

Alternative fuels will and must play an important role in the future of transportation. While the predictions of the peak of oil production differ widely between now and 2050 (IEA, ASPO, oil industry), it is feasible that growing demand for transportation energy could not be comfortably met by oil around 2035 and beyond, affecting, therefore, both accessibility and availability.

Therefore, we will need to develop more efficient transport options and as many clean alternatives as possible. Under the assumption that climate concerns remain, and even intensify, in the meantime, biofuels will be necessary to address acceptability as well.

Among the multitude of alternative fuels, the 3 A analysis has identified the two most promising solutions:

- Second generation biofuels (ethanol (or butanol) from cellulose, BTL and hydro-treated vegetable oil)
- Hydrogen

These are likely to figure alongside continuing optimisation of conventional fuels and powertrains as well the introduction of new powertrain technologies. Among the technologies outlined in Chapter 4, the following powertrain technologies are assumed to play a major role:

- Optimised gasoline DI and diesel engines
- Hybridised ICE powertrains (gasoline in OECD and potential developed regions, diesel hybrid and eventually hydrogen hybrid also in Europe)
- Hydrogen Fuel Cell (OECD, requires a complete new infrastructure and technical breakthroughs which are discussed in Chapter 8)

In addition to these technologies, which are well established in technology roadmaps of manufacturers and governments, in certain regions other technologies such as plug-in-hybrids or electric vehicles could penetrate the market in significant magnitudes. Penetration depends on regional energy prices and availability as well as on the achievement of required breakthroughs (see Chapter 8 for detailed analysis).

Due to high greenhouse gas emissions, coal based fuels such as CTL are not deemed as viable alternatives on large scale, even if some regions with low CO_2 concerns are already preparing a step into CTL production today. Carbon Capture and Sequestration (CCS) technologies could limit the negative impact on greenhouse gas emissions, however, the large-scale utilisation of CCS has not yet been fully proven. Further insight into CCS for CTL and GTL production is given the frame of the "breakthrough analysis" in Chapter 8.

For the later period beyond 2035, a competition for liquid fuels between road and air transport is likely. This could be a supporting argument for hydrogen as vehicle fuel at least in developed countries, since a hydrogen fuelled aeroplane is significantly more technically challenging, and therefore less economically competitive, than a hydrogen fuelled car and less likely to develop into a viable technology.

Technologies which increase the energy efficiency of passenger and freight automobiles can be expected to achieve significant market penetration in both OECD and non-OECD countries by 2050. In particular for passenger vehicles, these include the diesel and hybrid electric technologies, with OECD countries leading the way. At a later date (by 2050) fuel cell vehicle technology is projected to achieve significant penetration in OECD countries, but not yet in non-OECD countries.

In heavy duty vehicles, improvements to the diesel engine through enabling technologies such as variable valve timing are expected through 2050 in all regions. Extensive application of hybrid electric powertrains can be expected on heavy duty vehicles in OECD countries by 2050.

The conclusions of this section are similarly supported by the consumer expectation of convenience in personal transport. A number of factors contribute to the convenience factor of transport, including:

- Owning a personal vehicle where other alternatives (such as public transport) offer insufficient service and flexibility
- Range of vehicle between refuelling stops
- Widespread availability of the appropriate fuel
- Physical comfort

These are factors, which citizens in OECD countries mostly take for granted, in that their comfortable vehicles need be refuelled every 500 – 800 km at filling stations which are located conveniently for most of the population. They are the reasons why conventional technology is still considered suitable and will remain so until that conventional technology becomes inaccessible through pricing or regulation. In considering new technology, for consumer demand to merit high penetration rates, those technologies must continue to offer these convenience factors.

Alternative fuels such as BTL and GTL are able to use existing vehicles and refuelling infrastructure, maximising the convenience of this technology and supporting its breakthrough should it become economically viable. Ethanol achieves this to a lesser extent, since it requires dedicated vehicles and a separate refuelling infrastructure, but still offers a high level of convenience.

When considering advanced powertrain technologies such as hydrogen fuel cells and battery electric vehicles, those convenience factors which relate to range and refuelling are not automatically achieved, due to the need for a completely new infrastructure. When considering these technologies and their required refuelling infrastructure, convenience to the customer must be considered alongside the economic cost, in order to understand the entire demand-side picture.

These arguments may apply somewhat differently in developing countries, where cost issues dominate and convenience is likely to be secondary until national wealth approaches that of OECD countries. However, since the likely barriers for the most advanced automotive technologies are both convenience and cost, the distinction is not yet relevant.

3. Quantitative analysis of technologies

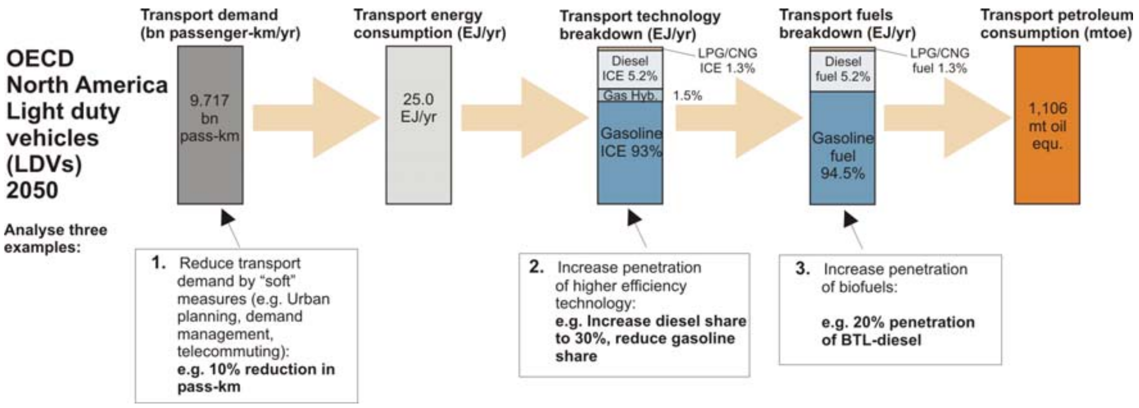
Analysis method

The quantitative analysis portion focuses on a subset of the technologies studied in the 3 A's analysis portion. The calculations are based on two premises

- The chain of calculation from mobility demand through to energy & petroleum consumption, with the base case being the regional and transport mode results of the WBCSD dataset.
- The point in this calculation chain at which a technology has its primary influence

The following example, based on the OECD North America light duty vehicle sector, illustrates the calculation premises:

Figure 3-1 Energy chain
Source: WBCSD Sustainable mobility project



Of the five measures of energy listed in Chapter 1, the following two are to be analysed here:

- Total well-to-wheel energy consumption
- Total well-to-wheel fossil energy consumption

Further analysis will be performed on the other measures of energy, for example GHG emissions, as appropriate.

Scenarios for analysis

The full list of analysis parameters is listed in Appendix 5. The table below is a summary of the scenarios to be analysed.

Table 3-1 List of scenarios

#	Fuel	Vehicle
0	-	Base
1a	BTL share of diesel fuel 25% in 2050	Base very optimistic for a base case!
1b	-	OECD diesel penetration = 50% in 2050
1c	BTL share of diesel fuel 25% in 2050	OECD diesel penetration = 50% in 2050
1d	-	Non-OECD diesel penetration = 50% in 2050
1e	BTL share of diesel fuel 25% in 2050	Non-OECD diesel penetration = 50% in 2050
2a	Cellulosic ethanol share of gasoline 25% in 2050	Base
2b	-	OECD hybrid penetration = 50% in 2050
2c	Cellulosic ethanol share of gasoline 25% in 2050	OECD hybrid penetration = 50% in 2050
2d	-	Non-OECD hybrid penetration = 50% in 2050
2e	Cellulosic ethanol share of gasoline 25% in 2050	Non-OECD hybrid penetration = 50% in 2050
3	H_2 availability secured	OECD H_2-FCEV penetration 25% by 2050 (non-OECD not considered)
4a	Switch 30% of OECD passenger-km demand from personal vehicle to rail in 2050	
4b	Switch 30% of non-OECD passenger-km demand from personal vehicle to rail in 2050	

* although high penetration of FCEVs in non-OECD countries is reasonably considered highly unlikely, the comparison of magnitude is informative. In addition, if China and India continue rapid economic growth, their technological advancement may indeed promote faster adoption of advanced technologies from OECD countries and begin to approach the penetration implied in this scenario.

In this analysis, the following assumptions are made:

- Costs of technology are approximately consistent globally.
- Estimates of future technology costs are well documented and can be applied to analyse cost benefit.
- Costs of future fuels are approximately consistent globally – to the extent this is not the case, governments absorb differences through taxes and subsidies.
- Improvements in vehicle efficiency are employed to reduce fuel consumption.

The following tables detail the standard energy input and outputs used in the calculations and the assumed fuel economy for each automotive technology.

Table 3-2 Volume energy input density for gasoline and diesel fuels, tank-to-wheel and well-to-wheel
Source: EPA, CONCAWE

Energy MJ/L	Diesel	Biodiesel	BTL	CTL	GTL	Gasoline	Ethanol-corn	Ethanol-cane	Ethanol-cell
Tank-to-wheel	38.7	35.4	36.1	36.1	36.1	34.8	23.0	23.0	23.0
Well-to-wheel	45.4	56.6	84.1	76.4	64.4	40.0	62.9	97.2	80.7
Petroleum-to-wheel	45.4	17.9	3.1	0.0	0.0	40.0	4.8	0.8	3.5
Fossil well-to-wheel	45.4	17.9	4.0	76.4	64.4	40.0	30.3	0.9	8.3

Table 3-3 Assumed 2000 average fuel consumption in different regions and relative fuel consumption of automotive technologies
Source: WBCSD

Region	2000 average fuel consumption (l/100km)
OECD North America	9.6
OECD Europe	6.6
OECD Pacific	8.4
FSU	8.4
Eastern Europe	8.0
China	9.4
Other Asia	8.8
India	8.7
Middle East	8.7
Latin America	8.7
Africa	10.3

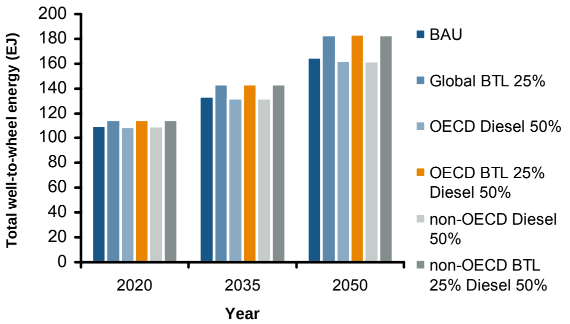
Powertrain technology	Relative fuel economy (energy)
Gasoline vehicles	1.00
Gasoline Hybrid – Mild	0.83
Gasoline Hybrid – Full	0.70
Diesel	0.82
Diesel Hybrid – Mild	0.76
Diesel Hybrid – Full	0.64
CNG/LPG	1.05
BEV	0.20
Hydrogen Fuel cell	0.55

Results

The full results are to be found in Appendix 5.

The following graphs provide a summary of the results, from which the main conclusions can be drawn. Each graph shows global transport energy requirements at the three study time points for business as usual (BAU) and stated scenarios.

Figure 3-2 Global well-to-wheel transport energy for Diesel & BTL scenarios 1a – 1e



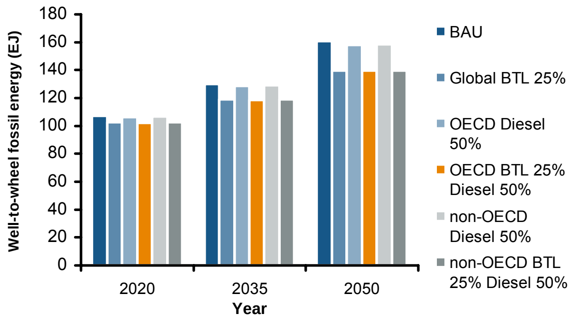


Figure 3-3 Global well-to-wheel transport energy for Hybrid & Cellulosic Ethanol scenarios 2a – 2e

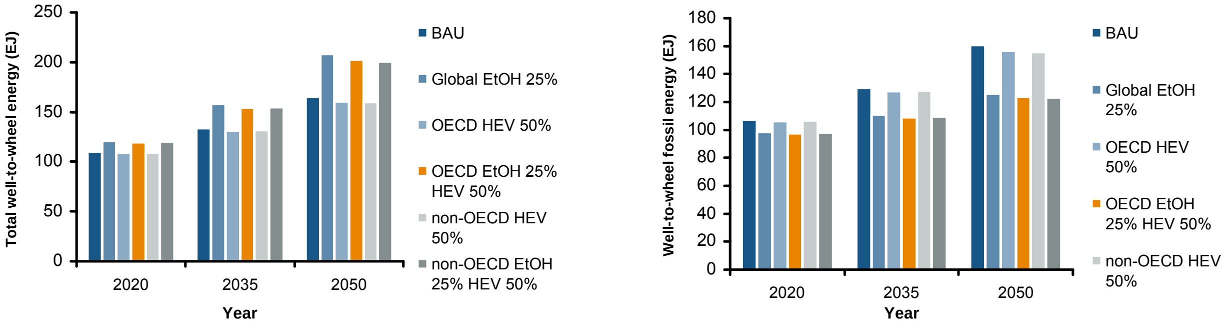


Figure 3-4 Global well-to-wheel transport energy for FCEV scenario 3

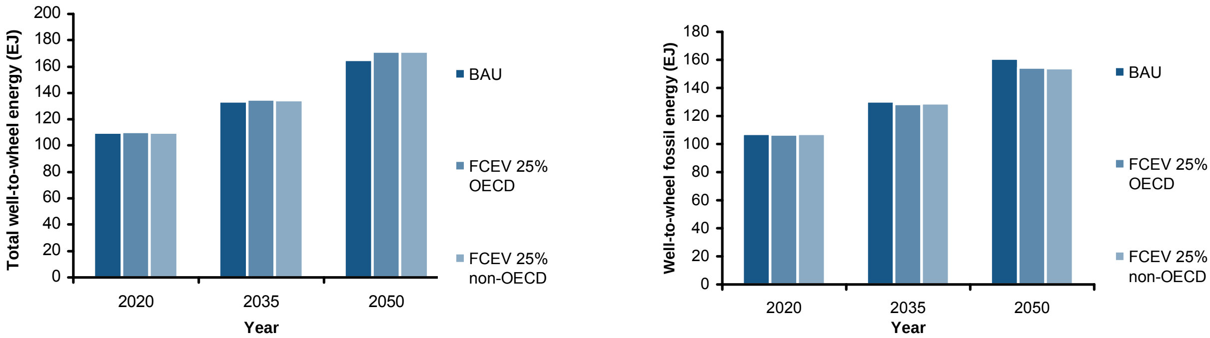
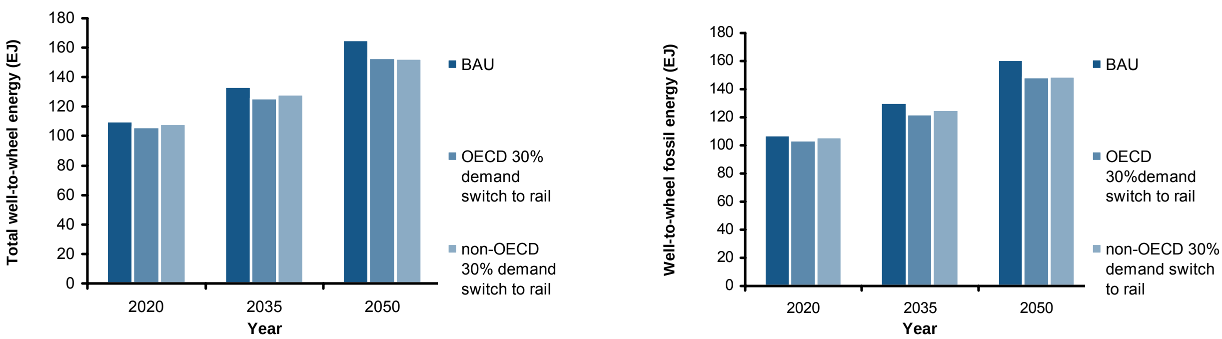


Figure 3-5 Global well-to-wheel transport energy for mobility efficiency scenarios 4a & 4b



The following points can be directly extracted from the numerical results:

- With each of the technology options: diesel, hybrid electric and hydrogen fuel cell, measurable incremental reductions in global well-to-wheel and fossil energy can be achieved.
- The use of second generation biofuels, BTL and cellulosic ethanol, with high penetration, significantly increases primary well-to-wheel energy consumption using known technology and significantly decreases fossil energy consumption (and therefore GHG emissions).
- The energy effects of BTL use are leveraged by higher diesel passenger vehicle penetration and by the use of diesel fuel in commercial vehicle operations.
- In each case, the technology measures individually act to dampen total and fossil growth over the analysis period, against the background of massive predicted energy growth. It is therefore clear that absolute reduction requires much higher penetration and widespread application of the most effective energy-reduction technologies.

Cost & demand analysis

Vehicle technology

Figures 3-6 and 3-7 demonstrate under which conditions the individual vehicle and fuel technologies present a beneficial economic case to the customer. The following assumptions were made in this analysis:

- Percentage fuel economy benefits are consistent in different markets.
- Three year payback period with zero discount rate taken into account by consumer (equivalent to 2001 National Academy of Sciences study).
- Midsize sedan type vehicle is assumed in the numerical analysis.
- The breakeven area is considered for the highest (USA) and lowest (OECD Pacific) annual mileage regions (measured in vehicle miles travelled per year).
- No account is taken of driving mode – likely to be more effective for hybrids in, for example, Japan.
- Only initial cost to the consumer is considered – resale values and maintenance are not included.
- Gasoline and diesel have equal per-gallon price (approximately correct in most regions).

Figure 3-6 Consumer breakeven analysis for diesel vehicles (July 2006 fuel prices, plus examples with consumer price premium)
Source: 2006 fuel prices: EIA, CNNMoney.com, WEC Transport Study Group calculations, vehicle prices from company price lists

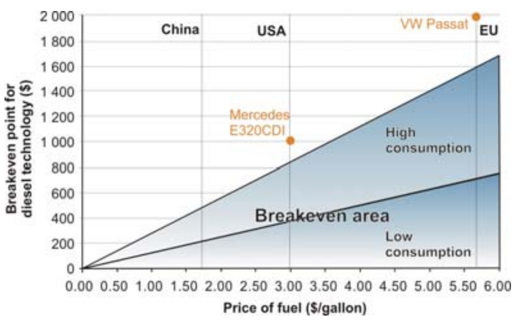
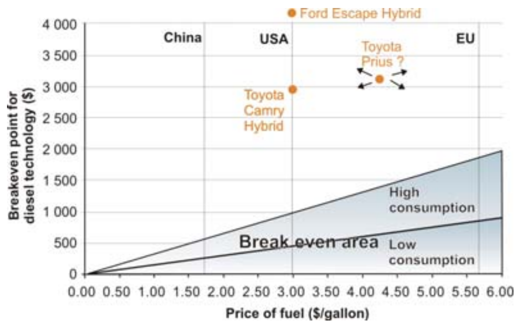


Figure 3-7 Consumer breakeven analysis for hybrid vehicles (July 2006 fuel prices, plus examples with consumer price premium)
Source: 2006 fuel prices: EIA, CNNMoney.com, WEC Transport Study Group calculations, vehicle prices from company price lists



- The cost of technologies is equivalent in all regions.
- Differences in performance, and therefore consumer demand, between new technologies and conventional vehicles are not fully taken into account.
- No account is taken of government policies to regulate fuel economy.

Current fuel prices in $/gallon in China, USA and the EU have been indicated on Figures 3-6 and 3-7. Technology costs have not been included on the graphs, since there is too much uncertainty and debate even about the current costs of these technologies. Some points of reference are assumed from current consumer pricing:

- It cannot be assumed that consumer prices for advanced powertrain technologies consistently represent incremental manufacturing costs, due to factors such as differences in regulatory requirements between regions and marketing factors.
- Incremental prices for light diesel vehicles are currently as high as $6 000 for a heavy pickup (e.g. $5 300 for Ford F-250) and in the region of $1 600 for a midsize sedan in the E.U. (e.g. VW Passat). This indicates the range of consumer prices to be considered. Each is a mature high volume product for which the premium is likely to reflect manufacturing costs and profit margin, as well as other market influences such as performance (F-250 in US) and manufacturers' CO_2 commitments (Passat in Europe).
- Manufacturing costs of diesels are initially likely to increase above current levels due to requirements to meet increasingly stringent emissions standards in the U.S. and the E.U. By 2050, through expected higher production volumes and advances in technology, diesel engine costs may be expected to decrease.
- It is assumed in the analysis below that the incremental manufacturing cost of hybrid electric vehicles is significantly higher (by a factor of 2-3) than for diesel vehicles and will remain so for the foreseeable future.

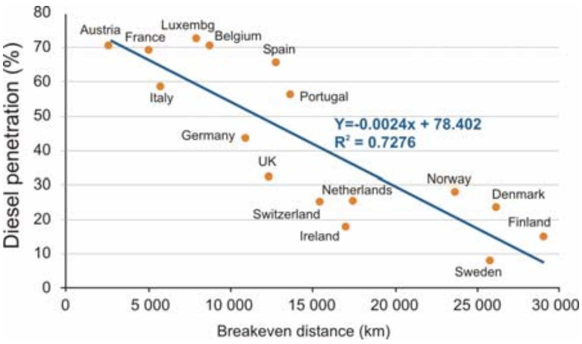
Whilst taking into account the uncertainty in both current and future costs, it is informative to observe the cost estimates for diesel and hybrid vehicles from the EIA's 2006 Energy Technology Perspectives, which takes account of advances in all technologies.

The short-term premium for diesel does not appear to take into account the likely increased costs for exhaust aftertreatment (particulate and NO_x emissions), in particular with expected advances in regulations in both the US and Europe. With the large uncertainties in the costs

Table 3-4 Average technology cost estimates for a midsize light duty vehicle with gasoline, diesel and hybrid
Source: EIA's 2006 Energy Technology Perspectives

Technology	Vehicle cost (+ increment over gasoline, without inflation)		
	2003-2015	2015-2030	2030-2050
Gasoline	$16 100	$16 200	$16 300
Diesel	$17 400 (+$1 300)	$17 500 (+$1 300)	$17 400 (+$1 100)
Gasoline hybrid	$19 250 (+$3 150)	$18 650 (+$2 450)	$18 200 (+$1 900)

Figure 3-8 Diesel penetration vs. breakeven distance in European countries
Source: J.D. Power 2003



of hybrids in such an immature market, it also cannot be assumed with great confidence that the figures for hybrids are representative. However, these figures indicate a trend for the long term with hybrid cost premium settling to approximately double the diesel premium, which is consistent with other industry estimates.

Due to the assumptions and uncertainties noted above and the timeframe being studied, any conclusions from this analysis will necessarily be of a directional nature.

The following points are noted from these results:

- Even with the conservative payoff period of three years, both diesel and hybrid technology can present a positive business case for consumers.
- For each region, the breakeven point is determined as a direct function of fuel price.
- Even in low per-vehicle consumption regions such as OECD Pacific, a positive payoff from a diesel vehicle may be achieved assuming fuel prices over $2.00 per gallon and technology costs towards the lower end of the range described above.
- In low per-vehicle consumption regions, a positive payoff for a hybrid vehicle can be expected in 2020 at fuel prices above $2.50 per gallon if the technology costs reach $5 000 or less. Since the low consumption in such regions is to a certain extent due to dense population and therefore a significant proportion of stop-start city driving, the payoff for hybrids is likely to be more positive than indicated by the above data.
- Differentials between regions may be caused by emissions regulations, which are likely to affect the cost and acceptability of diesel vehicles.
- The acceptability of diesel vehicles may affect their image and therefore consumers' willingness to buy.
- Only by fully taking into account driving characteristics can it be determined which technology has greatest benefit in each region.

It is also informative in analysing technology take-up, to use the example of Europe, in which the penetration of diesel vehicles in the passenger car fleet has risen from 22% in 1996 to 50% in 2006. The following graph shows the relationship between breakeven distance – how many kilometres must be driven to recoup the initial extra outlay for the diesel – and penetration of the technology in different markets. The breakeven distance differs in European countries due to tax treatment of vehicles and fuel as illustrated in Figure 3-8.

Figure 3-9 Payoff for fungible fuels
Source: 2006 fuel prices: EIA, CNNMoney.com, alternative fuel cost as per pump prices and industry estimates

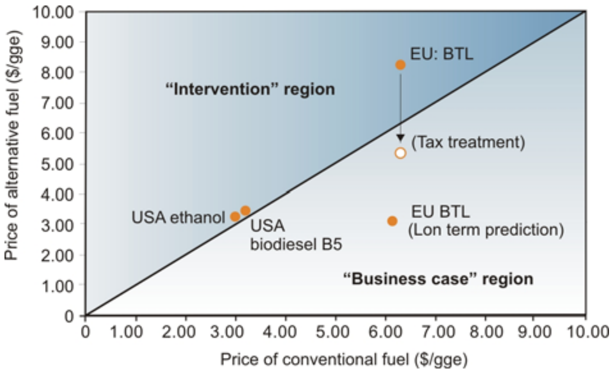
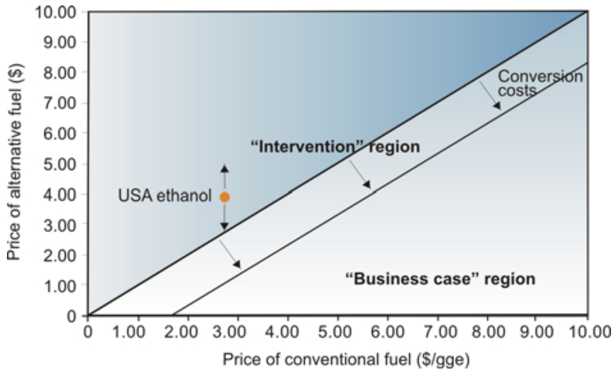


Figure 3-10 Payoff for non-fungible fuels
Source: 2006 fuel prices: EIA, CNNMoney.com



There is a clear, yet imperfect, correlation between breakeven distance and diesel penetration, indicating that consumers are to a certain extent economically rational, but also that other factors exist in the decision to purchase fuel consumption reducing technology.

Alternative fuels

Whilst this report will concentrate on advanced biofuels, in particular BTL and cellulosic ethanol, due to their non-food feedstock flexibility and low fossil energy inputs, all alternative fuels must be assessed according to the same criteria without prejudice. These criteria include:

- Well-to-wheel (full cycle) fossil energy consumption (and GHG emissions)
- Yield per unit land space
- Water requirements
- Biodiversity
- Environmental sustainability
- Agricultural sustainability
- Social sustainability

Such criteria are being considered in current policy frameworks such as the European Union's Fuel Quality Directive and the Low Carbon Fuel Standard in the Federal U.S. and California. In general, these criteria point in the long term towards second generation biofuels, which derive from non-food plants and therefore do not compete directly with food production. However, if first generation biofuels with high yields and low fossil energy input can also be produced in a way that ensures biodiversity and sustainability, these should be fairly and objectively assessed and considered.

In particular, the above criteria do not rule out the continued widespread production and use of fuels from food crops, as long as their production complies with the sustainability criteria listed above. Since, for example, ethanol from sugar cane and biodiesel (or hydro-treated vegetable oil) from palm oil have high land yields, they should be objectively considered alongside all competing products.

Alternative fuel breakeven

Figures 3-9 and 3-10 demonstrate the payoff region for alternative fuels. Alternative fuels have been classified here by their degree of fungibility. Fungible fuels are those which can be blended almost universally into the existing fuel stock, for example x-TL diesel fuel and aviation fuel or low blend ethanol into gasoline. Non-fungible fuels are those which require vehicle modifications or even a new powertrain type and a separate delivery system, such as E85 ethanol, high blend biodiesel or hydrogen.

Fungible fuels (e.g. x-TL, low blend ethanol, low blend biodiesel) and non-fungible fuels (E85, high blend biodiesel)

For fungible fuels, the payoff equation is quite simple. If the end cost of the fuel to the consumer is higher than the cost of conventional

For long term viability, alternative fuels would need to be of a similar or lower retail cost in comparison to petroleum fuels.

fuel, it requires either goodwill from the customer or intervention to gain market share. Goodwill may be achieved by presenting, for example, x-TL as a high quality alternative to petroleum diesel. However, for long term viability, such fuels would need to be of a similar or lower retail cost in comparison to petroleum fuels.

This depends on four factors:

- The global price of crude oil. This is an uncertain factor affecting the viability of alternatives, which therefore reduces the incentive to invest in those alternatives.
- Taxes imposed by governments on petroleum fuels. Taxes on fuel are very high in certain regions, providing opportunity for incentivising alternatives by introducing tax credits (as in the U.S.) or reduction in rates (E.U.).
- The cost of producing the alternative fuel. The cost of low blend ethanol is similar to that of gasoline. The cost of BTL and CTL production is currently significantly higher than conventional fuel, even at the currently high oil prices of mid 2007 (whereas GTL production is commercially competitive).
- Cost of using the alternative fuel, such as infrastructure investments and engine modifications and ease of use.

Additionally, intervention can have the effect of increasing penetration of fungible fuels. For example, in the U.S. the renewable fuel standard calls for increases in the total volume of ethanol blended into gasoline. In Germany, beneficial tax treatment for biofuels has made BTL diesel economically viable in the short term, leveraging its long term potential, although this benefit is now being withdrawn.

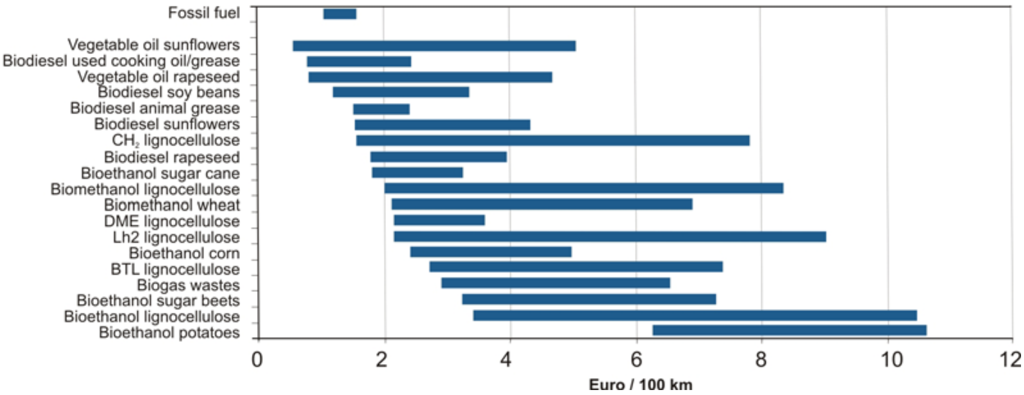
Choren, the company which is researching and producing a BTL diesel fuel in Germany, recently presented projections of future production cost of BTL at €0.5/L, equivalent to $2.50 per gallon. At this cost level, and assuming beneficial tax treatment, BTL would become economically viable particularly in Europe. With sufficiently high long-term petroleum prices, this would extend potentially to other world markets with lower retail fuel prices, including the U.S.

Similarly, cellulosic ethanol may become economically viable as a blend stock, but less information is available about the potential production cost of this fuel production method.

When considering non-fungible fuels, the breakeven calculation is similar, but there is a barrier to be overcome in applying the fuel to vehicles. This cannot easily be calculated as a fuel cost, since it is non-proportional to the production volume of the fuel. Examples of such barrier costs include:

- Flexible fuel vehicle (FFV) production costs for gasoline and E85 use.

Figure 3-11 Relative production costs of biofuels options
Source: IFEU, 2004



- Hydrogen fuel cell vehicle development and production costs.
- Hydrogen ICE vehicle development and production costs.
- E85 fuel availability.
- Hydrogen fuel infrastructure.

In many cases, such barriers are overcome by government policies and goodwill. For example, in the case of E85 in the U.S., sale of a certain proportion of the fleet as FFVs provides a regulatory benefit for auto manufacturers through the corporate average fuel economy regulation. In addition, U.S. based manufacturers are producing more FFVs than are necessary to gain the maximum benefit, thereby assisting in the creation of greater demand for E85, with the intention of supporting the U.S. government's energy policy. Current US policy is going even further, with mandates of E85 flexible fuel vehicles up to 80% of the automotive fleet being considered in Congressional legislation.

In California, the state government has embarked upon a scheme to install a hydrogen infrastructure across the state to provide the necessary convenience factor supporting consumer purchase of hydrogen fuel cell and hydrogen ICE vehicles.

Whether these policies prove to be effective depends on the long term economic viability of the alternative fuels and automotive technologies in question. The data represented in Figure 3-11 demonstrates that there is potential for biofuels to present a positive business case in comparison to fossil fuels, although the calculation is more favourable for biodiesel types than for fungible fuels such as BTL. This reiterates the point that the economic viability of these fuels is heavily dependent on petroleum fuel cost and price (including taxes).

Regional analysis of results

In principle, if a technology is economically viable for consumers in one market, it will be equally so in other markets. This assumes globally consistent pricing, which in turn assumes an extremely high level of global cooperation with tariffs, a harmonising of taxes and with a reduction of other barriers to insignificance. That this is unlikely under even a high cooperation scenario is clear. In order to perform a regional analysis, fixed points are therefore required. The fixed points that are in existence are the current prices of petroleum fuel in each region, from which future movements could be projected. Table 3-5 shows the December 2006 price of gasoline fuel in each of the eleven regions and the corresponding breakeven point for both diesel and hybrid vehicles in that region at that fuel price.

Assumptions:

- The breakeven point is the consumer price premium for the technology in question below which the average consumer would make a financial gain from the investment due to decreased fuel costs.

- Breakeven calculated over three years.
- Average annual mileage in each region is considered – using WBCSD data.
- Projected fuel economy in each region is considered – using WBCSD data.
- Fuel economy benefit of diesel and hybrid vehicles – using WBCSD data.

Table 3-5 Regional breakeven analysis for automotive technologies
Source: 2006 prices: EIA, CNNMoney.com

Region (country)	Gasoline price (per gallon)	Diesel price (per gallon)	Breakeven point diesel	Breakeven point hybrid
OECD North America (USA)	$2.84	$2.68	$814	$1 027
OECD Europe (Germany)	$6.12	$5.25	$1 029	$1 110
OECD Pacific (Japan)	$4.35	$3.59	$776	$803
FSU (Russia)	$2.68	$2.46	$538	$672
Eastern Europe (Croatia)	$4.69	$4.50	$638	$945
China	$1.81	N/A	N/A	$383
Other Asia (Thailand)	$2.91	$2.68	$439	$582
India	$4.12	$3.36	$691	$651
Middle East (Saudi Arabia)	$0.91	$0.38	$514	$232
Latin America (Brazil)	$4.42	$3.25	$1 360	$1 049
Latin America (Venezuela)	$0.12	N/A	N/A ($small)	$28
Africa (South Africa)	$2.62	N/A	N/A	$606
Africa (Nigeria)	$0.38	N/A	N/A ($small)	$88

The results of this analysis are highly dependent on a number of factors, in particular the assumption about how consumers value future savings in fuel purchasing. Doubling the payoff period to six years doubles the breakeven point

At this level of fuel price, the breakeven point for diesel technology is lower than the currently estimated cost in all regions ($1 300 in 2015, $1 100 in 2050). The fact that in certain regions, especially Europe, diesel has a very high penetration demonstrates that other factors come into play. These include higher range and performance and, potentially, consideration by some consumers of a longer payoff period.

The breakeven point for hybrid is in all regions substantially lower than the projected cost ($3 450 in 2015, $1 900 in 2050). Again other factors come into play in current markets, including performance, environmental image and novelty factor.

Additionally, it can be assumed that hybrid electric vehicle use is, on average, more economically viable in Japan than the above figure suggests, which is proven by Japan's already high uptake of hybrid vehicles and explained by its high density cities and stop-start driving. Depending on the precise structure of growth and development in developing countries, the same conditions of high city density may have an effect on the actual economic payoff of hybrid electric vehicles in those countries. This point will be discussed further in Chapter 4.

For the hybrid, and to a lesser extent the diesel, in certain regions (China, Middle East, Africa, South America) significant penetration is economically viable only if petroleum prices increase substantially.

The analysis for the fuel cell vehicle has not been performed numerically, due to the greater uncertainties in the future consumer price of price of hydrogen fuel.

Assuming a seamless global market for fuels, the economic payoff of alternative fuels, including x-TL diesel and cellulosic ethanol will be determined in direct competition with petroleum fuels as indicated in Figure 3-9 and Figure 3-10 above. Government support and taxation will have an effect on the short term viability of these fuels and may be sufficient to "kick-start" their development. This intervention is more likely to be forthcoming in OECD countries and large developing countries which have the resources to fund the initial investment.

Production of such fuels should be particularly attractive to those developed and developing countries, which have little or no access to petroleum reserves and abundant sources of coal, natural gas or suitable biomass. BTL farming in a world of increasing oil price may prove to be a substantial opportunity for poorer developing countries with large biomass resources, in particular if richer nations can assist with initial investment. In addition, open trade markets for biofuels are essential if the full benefits are to be realised.

In each of the technology options discussed, the economic payoff of energy reducing technologies, and therefore the likelihood of the projected reduction in energy consumption being realised, increases with high price of petroleum fuel. It is not a recommendation of this analysis that fuel prices be raised either through manipulation of the market or government taxes, since, particularly in developing countries, high fuel prices can dampen growth and deny citizens the capacity for greater personal mobility. However, two policy points can be made in this respect:

- To the extent that the price of crude oil does increase through the market forces of limited supply and increasing demand until 2050, there are expected to be automotive and fuels technologies available to substitute for it and secure mobility.

- If governments decide to intervene by changing tax rates on petroleum and alternative fuels, there is scope to leverage the uptake of certain technologies with even small changes in gross fuel prices. For example, an increase in the fuel price in China by 20% increases the breakeven point for diesel vehicles close to the projected incremental cost of diesel vehicles. It can also be expected that this would begin to increase demand for such vehicles, initially amongst those individuals who consider a longer economic payoff period than the 3 years assumed here.

Conclusion

The following conclusions can be drawn:

- BTL diesel fuel has a high fossil energy (and GHG) reduction potential. Its fungibility with petroleum diesel fuel and its reliance on existing automotive technology ensure the barriers to entry are relatively low. The cost of manufacturing BTL fuel compared to petroleum and the total available yield remain barriers which create uncertainty. The high primary energy content in producing BTL must also be considered – there may be uses for the biomass energy that are more efficient overall. The relative cost factor will in the long-term drive consumption towards the more efficient process.
- GTL and CTL diesel are also fungible fuels which expand the supply base and reduce petroleum consumption. GTL is already commercially viable and can be expected to increase penetration and provide the technological basis for other synthetic fuels (BTL and CTL). CTL is associated with a significant increase in greenhouse gas emissions, constraining its future acceptability.
- The increase in penetration of diesel vehicles replacing conventional gasoline

Production of BTL and cellulosic ethanol fuels may represent an excellent opportunity to developing countries

vehicles presents, in some regions, a positive consumer business case assuming current petroleum prices, and is a relatively cost efficient method to reduce energy consumption. The overall energy potential with high penetrations represents a few percent of global transport energy consumption. Higher diesel penetration enables higher synthetic fuel use and thereby leverages reduction in fossil energy consumption.

- Cellulosic ethanol has a similarly high fossil energy and GHG reduction potential to BTL fuel. Since ethanol is not fully fungible with gasoline and currently requires vehicle conversion if used in high concentration (E85), further progress in vehicle adaptation or absorption of conversion costs is necessary to increase the share of ethanol in gasoline to achieve the stated energy potential.
- An increase in penetration of gasoline hybrid electric vehicles presents a positive consumer business case in some regions, again achieving a modest reduction in global transport energy consumption.
- By 2050, hydrogen fuel cell vehicles may be able to compete with diesel and electric hybrid vehicles in terms of cost efficiency of reduction in energy consumption, but this depends strongly on the source of the fuel. Using natural gas as a source for hydrogen can currently help to reduce fossil energy consumption by about 50%. Hydrogen by electrolysis has high primary energy content but, dependent on the electrical energy generation mix, its production and use in fuel cell vehicles may contribute to a significant reduction in fossil energy consumption. The cost of the hydrogen fuel is the second major factor in determining consumer demand and will be heavily dependent on the cost of the primary energy used to produce the hydrogen.

The above conclusions are non-regional in nature, however regional conclusions can be derived.

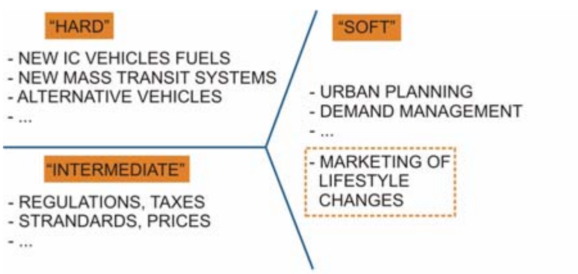
- The absolute energy savings potential in 2050 of each technology assessed is of a similar magnitude in both OECD and non-OECD regions, due to the projected economic growth and associated energy demand growth in developing countries in that timeframe.
- Production of BTL and cellulosic ethanol fuels may represent an excellent opportunity to developing countries for production and export. Open trade markets for biofuels are an essential prerequisite.

- The regional use of biofuels will depend on the consumer price in comparison to the local price of petroleum fuels. Those countries with higher petroleum fuel prices, whether OECD or non-OECD will likely exhibit greater penetration of the biofuels in question. These biofuels may therefore gain similar penetration levels in developing and developed countries.
- To the extent that consumers in developing countries can afford the initial outlay for new vehicle technologies, those technologies will gain penetration. The main determining factor will be the economic payoff potential of the technology, according to the local price of petroleum fuel.
- In the case of hydrogen FCVs, positive action by governments relating to infrastructure would be necessary to allow for a growing market. This may be forthcoming in those countries which reach mid- or high-income levels by 2050 and whose populations therefore demand developed world products such as FCVs (this result assumes significant FCV penetration in OECD countries as a benchmark).

4. Transport system efficiency technologies and measures

Measures to reduce transport energy demand take a number of different forms. The figure below summarises three main types of measures for reducing transport energy demand. "Hard" technologies including engine and vehicle measures are the starting point for discussion in this study. "Intermediate" measures, including regulations, taxes and pricing measures, are to be addressed in the policy discussion and recommendations. The third category of measures are so called "soft" technologies, which include those measures that can affect demand for mobility, thereby reducing total travel and therefore energy consumption.

Figure 4-1 Schematic of available demand management measures



It has been determined in a number of studies that the intermediate and soft technologies can individually, or in combination, result in decreased travel measured in passenger-kilometres. Such measures include the following:

- Urban planning in existing or growing urban areas
- Demand management through offering viable transport alternatives
- Utilising modern communications technology to reduce vehicle miles travelled per vehicle (e.g. telecommuting).
- Utilising modern communications technology to improve driving efficiency (e.g. telematics, traffic control).
- Offering mass transit systems
- Pricing strategies to encourage less driving or switching to more efficient modes.
- Government regulations, which encourage or enforce the use of certain technologies or modes of transport.

A more comprehensive list of options published by the Victoria Transport Policy Institute is to be found in Appendix 7. Some of these options will be further analysed below. There are also clearly challenges which must be overcome, both in devising suitable measures and also in the social and economic consequences of implementing them, also discussed further below.

By necessity, much of this chapter will deal with issues related to cities. This year the global population living in cities reached 50% of the total population. People, commerce, wealth, congestion and many related elements of transport are highly concentrated in cities, which therefore must be a primary focus of any transportation policy study.

A relevant policy activity which confirms this importance is the preparation of a Green Book on Urban Transport by the European Commission. This is currently a consultation document which will be compiled over a number of years with input from individuals, European member states, European union officials and politicians in order to provide a comprehensive insight into long-term policy for cities and urban areas. It's greatest focus will be on the reduction of fuel consumption and GHG emissions.

Potential categories of measures to be studied include urban planning, demand management, alternative transportation and intelligent transport systems. These categories are likely to be strongly interdependent; for example, urban planning can be geared towards optimising the potential for mass transit links, the mass transit infrastructure itself must be funded and constructed and government agencies may introduce road pricing or other financial incentives to encourage travellers into mass transit. However, initially they will be categorised and analysed separately and combined in the final analysis.

An assessment of elasticity is then performed and finally a sensitivity analysis of mode switching.

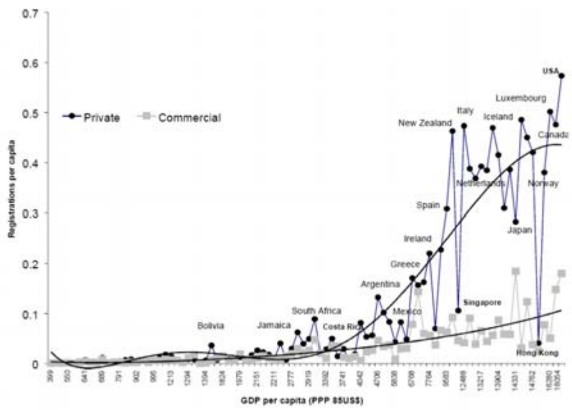
Urban planning

Urban planning policies which may have a beneficial effect on demand for transportation, and therefore energy, are well established. In the U.S.A., for example they are coordinated by the Smart Growth Network: a partnership between the U.S. Environmental Protection Agency and a number of independent organisations with interest in efficient growth. Smart Growth is based upon ten principles:

1. Mix Land Uses
2. Take Advantage of Compact Building Design
3. Create a Range of Housing Opportunities and Choices
4. Create Walkable Neighbourhoods
5. Foster Distinctive, Attractive Communities with a Strong Sense of Place
6. Preserve Open Space, Farmland, Natural Beauty, and Critical Environmental Areas
7. Strengthen and Direct Development Towards Existing Communities
8. Provide a Variety of Transportation Choices

Figure 4-2 Vehicles per capita vs. GDP per capita

Source: Bauer & Mar, World Energy Congress 2004, data provided by R. Medlock, University of Houston



9. Make Development Decisions Predictable, Fair, and Cost Effective
10. Encourage Community and Stakeholder Collaboration in Development Decisions

Under each of these principles, specific measures can be identified and, 200 specific measures have been documented in Smart Growth publications (publications from Smart Growth Network, ICMA). An example includes the use of innovative zoning tools to encourage mixed use communities and buildings. Mixed use zones increase the likelihood that dwellings, businesses and shopping locations are located close together, thereby encouraging shorter commutes or even walking to work and shopping. Conventional zoning often requires land uses to be separated. Two specific examples of success in this area are quoted. The Kentlands development in Gaithersburg, Maryland was one of the first generation mixed use zones; it was built using a planned unit development (PUD) and its success along with similar early developments has encouraged further innovations in other areas. San Diego has established an “urban village overlay zone” encouraging mixed use development, successful in at least one district in creating a pedestrian-oriented neighbourhood with all facilities nearby.

Such measures can clearly have beneficial effects on a local scale. The difficulty in assessing their potential for transport demand reduction is in quantifying the effect. Even if individually such zones reduce local traffic, when assessing the aggregate result of many such zones there may be confounding effects such as the encouragement for people to move further from the city in which they work, attracted by the superior lifestyle, thereby lengthening their commute. As yet, very little quantifiable data is available.

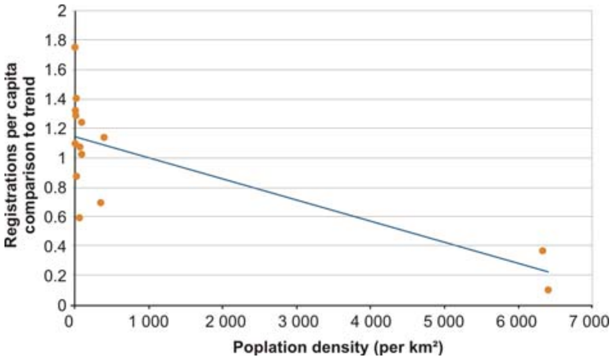
In addition, such measures will, by necessity, have a political element, since many of them require intervention by government in the form of zoning regulations, public planning and constructing transportation systems. This creates uncertainty both in the ability to implement systems and in their effectiveness if they are implemented.

What can be determined, both anecdotally and quantitatively, is the relationship between population density and vehicle registrations. Figure 4-2 demonstrates the relationship between personal vehicle ownership (registrations per capita) and wealth (GDP per capita), with higher wealth in general indicating high personal vehicle ownership.

Taking the rough trend line as an indicator of average expectations, there are countries which have higher than average number of vehicles per capita, including the USA, Italy and New Zealand, and some which have significantly lower. Table 4-1 lists a number of the countries shown according to population density.

It might be expected that there would be a clear correlation between the two parameters. However, the only positive conclusion from the data is that those countries with the highest

Figure 4-3 Registrations per capita in relation to population density
Source: Bauer & Mar, World Energy Congress 2004, data provided by R. Medlock, University of Houston



Japan’s vehicle ownership per capita is 30% below average and the Netherlands’ 14% above.

population density, namely Hong Kong and Singapore, have vehicle registrations much lower than predicted by GDP per capita. This is unsurprising, since the high density of population and associated congestion is a strong deterrent in itself against owning and using a vehicle. In addition, in Hong Kong parking is exorbitantly expensive and there are excellent and inexpensive public transport links. In Singapore, strict government policies including the Vehicle Quota System and Electronic Road Pricing make owning a vehicle extremely expensive.

Table 4-1 Registrations per capita in relation to population density
Source: Bauer & Mar, World Energy Congress 2004, data provided by R. Medlock, University of Houston

Country	Population density (per km^2)	Relation to GDP trend
New Zealand	14.9	1.75
Argentina	13.9	1.40
USA	31.0	1.32
Iceland	2.9	1.29
Spain	85.1	1.25
Netherlands	392.5	1.14
Canada	3.2	1.10
Ireland	59.0	1.07
Greece	84.3	1.02
Norway	12.0	0.88
Japan	339.0	0.70
Mexico	54.7	0.59
Singapore	6 333.8	0.37
Hong Kong	6 406.7	0.10

At lower population densities there appears to be little or no systematic relation between personal vehicle ownership and the population density of the country in question. For example, Japan and the Netherlands have similar population densities, but Japan’s vehicle ownership per capita is 30% below average and the Netherlands’ 14% above. There are factors which can help to explain this specific anomaly, including:

- Japan’s cities are very dense, giving them a character approaching that of Hong Kong, with congestion, expensive parking and excellent public transport.
- The Netherlands is very well connected to neighbouring European countries, which increases the space in which the population can travel.
- Luxembourg, much smaller than The Netherlands, is perhaps a more striking example of small space but very high cars per capita.

In addition, Canada, Iceland and Norway have low population densities but relatively low vehicle ownership per capita. In these countries the population is highly concentrated in certain regions and large parts of these countries are inaccessible. Taking this into account would increase their effective population density and likely increase the correlation between population density and car ownership in relation to GDP.

The U.S.A. exhibits a high vehicle ownership relative to the trend despite a relatively high population density. Since the U.S.A.'s 20th century development and culture was based to a large extent on the automobile, this is not a surprising outcome.

It is, therefore, also clear that many interrelated factors play a role in determining per capita vehicle ownership. The questions that arises is: can these factors be considered in the development of large fast growing countries, especially China and India, with the objective of dampening transport energy consumption? The most obvious measure would be to ensure that cities and urban regions in these fast growing countries develop towards being high density conurbations with characteristics like Hong Kong or, as a less extreme example, Japanese cities such as Tokyo. It would, however, be reasonable for the governments and citizens of these countries to consider such development goals to be undesirable. In the absence of such extreme planning measures, national and city governments still have the opportunity to plan the growth of their cities with energy efficiency in mind, using established smart growth measures as discussed above.

Demand management

Contrary to large scale measures such as urban planning, there are many measures that can be implemented at an individual company, business or public sector office level. These can have a substantial effect if widely adopted. An example of a demand management measure is alternative work scheduling. The following information on Alternative Work Schedules (also called Variable Work Hours) is extracted from the TDM (Transportation Demand Management) Encyclopedia:

- **Flextime**. This means that employees are allowed some flexibility in their daily work schedules. For example, rather than all employees working 8:00 to 4:30, some might work 7:30 to 4:00, and others 9:00 to 5:30.
- **Compressed Workweek (CWW).** This means that employees work fewer but longer days, such as four 10-hour days each week (4/40), or 9-hour days with one day off every two weeks (9/80).
- **Staggered Shifts.** This means that shifts are staggered to reduce the number of employees arriving and leaving a worksite at one time. For example, some shifts may be 8:00 to 4:30, others 8:30 to 5:00, and others 9:00 to 5:30. This has a similar effect on traffic as flextime, but does not give individual employees as much control over their schedules.

Some evidence of the potential of these measures is available. Several papers dating from 1986 surveyed the mobility requirements of the population in the Metropolitan Area of Mexico City, their transport modes and the resulting fuel consumption. The effect of a CWW on the transport demand in Mexico City was estimated to be at least a 10 percent reduction of the 16 million litre of fuels (gasoline and diesel) consumed daily at the

Table 4-2 Assessment of demand management measures

Objective	Flextime rating	CWW rating	Comments
Reduces total traffic.	1	2	Flextime supports ridesharing
Reduces peak period traffic.	3	2	
Shifts peak to off-peak periods.	3	3	
Shifts automobile travel to alternative modes.	1	-1	CWW may reduce ridesharing
Improves access, reduces the need for travel.	0	-1	CWW may encourage longer commutes and sprawl
Increased ridesharing.	1	-1	CWW may reduce ridesharing
Increased public transit.	1	0	CWW may reduce transit use
Increased cycling.	0	0	
Increased walking.	0	0	
Increased Telework.	0	0	
Reduced freight traffic.	0	0	

Rating: 3 (very beneficial) to -3 (very harmful). 0 (zero) indicates no impact or mixed impacts

time (currently it is about 20 million litre per day). (J.Quintanilla, P.Mulás, R.I.Guevara, B.Navarro and M.Bauer, “Modified urban labor week for energy saving and pollution reduction in the transport sector”. Proceedings of the WEC 17th World Congress, Houston, USA (1998). Paper 3.3.08, Vol.5, pp. 483-492)

Unfortunately, although this would benefit a large proportion of the workforce that spends over 3 hours daily commuting in public transport at a significant expense, this has not been implemented in Mexico because it involves changing the labour laws, which is a very sensitive political question. It has, however, been taken up in other countries. In the TDM Encyclopaedia, in addition to many references, the following is informative:

Commuter Challenge Programme (www.CommuterChallenge.org)

“The Commuter Challenge website has detailed descriptions of more than two-dozen Puget Sound area (around Seattle, Washington) employers that offer alternative work schedules. The programme is partly a response to local commuter trip reduction laws (CTR) and annual awards are provided to those employers which exhibit the best performance in reducing commuter journeys. Each case study describes the type of employer, the policies and resources they offer, the programme’s effectiveness, and feedback from administrators who manage the programmes.”

Alternative Transportation

Mass transit systems, including city underground railways, light rail and buses are in existence in many world cities in both developed and developing countries and are popular. A simple calculation would determine that the lack of such a system in those cities, for example New York, would imply a greatly increased energy demand

Table 4-3 China transportation energy challenge
Source: WBCSD calculations

	Now	2050	Increase
China population (millions)	1 272	1 472	11%
WTW China pass transport demand (bn pass-km)	427	5342	12.5-fold
WTW China pass transport energy demand (EJ)	1.8	12.8	7.0-fold

In China by 2050, with only 11% increase in population, travel demand is projected to increase 12-fold and travel energy demand 7-fold.

through personal transportation and result in unimaginable congestion and even economic hardship.

However, there are many massive conurbations which have no or limited mass transit and therefore rely on personal mobility but continue to thrive. This includes many cities in the U.S.A., such as Los Angeles or Detroit, which are very large but relatively low density cities. The lack of a popular transit system is a direct function of the structure of the cities and it appears unlikely that any amount of urban planning in such cities would be sufficient to create the conditions necessary for mass transit to be either financially viable or in sufficient demand to warrant public funding.

The greatest potential with mass transit may lie in those regions which are still to be developed: for example, as yet undeveloped zones around American cities and particularly in large developing countries such as China and India.

In certain American suburbs, a combination of smart growth policies focussed on mass transit infrastructure (light rail or bus) could dampen transport demand growth measurably.

In large, rapidly growing developing countries there likely exists still greater potential for reducing transport energy demand compared to the business as usual baseline. As, for example, China's income per head rises, there is likely to be a significant increase in demand for personal transportation as occurred previously in the U.S.A., Europe and Japan. If low density growth of cities continues as it did in the U.S. over the last 60 years, it is very likely that an ever more affluent population will choose personal mobility, i.e. passenger vehicles, over mass transit.

The scale of the challenge in China itself can be estimated (see table 4-3, data WBCSD calculations). With only 11% increase in population, travel demand is projected to increase 12-fold and travel energy demand 7-fold. The multiplication effect is due to higher personal vehicle penetration rates as GDP per head increases. In fact, with China's GDP per head projected to approach that of current developed countries (58% of US GDP per head in 2050 compared to 17% in 2005), the mobility demand for its huge population is indeed likely to be massive.

Potential may exist to dampen the increase in passenger-km demand through urban planning measures which encourage compact city urban design and mass transit rather than long commutes from low density suburbs. The available data is not sufficient to quantify the potential effect, but the figures do provide an insight into the upper and lower boundaries.

The increase in Chinese transport energy demand quantified above represents fully 24% of the global increase from 2005 to 2050 and 11.5% of the 2050 total demand. Projected growth in other large likely high-growth regions the Former Soviet Union, India, the rest of non-OECD Asia and Latin America add a further 23% of the total 2050 energy demand. Thus over 34% of global passenger transport energy demand by 2050, approximately 32 EJ, is accounted for by growth in these five regions. In these regions, growth in energy demand is 250% with total population increase of only 36%.

It is reasonable to conclude that the difference in the growth of energy demand compared to growth in population cannot be fully offset, since economic growth combined with increasing globalisation will, as indicated by historical precedent, result in a significant increase in personal vehicle ownership and actual travel demand. Therefore the upper boundary to the demand reduction potential compared to the calculated baseline is somewhat less than 100% of this 32 EJ in energy demand growth. Whether dampening of this growth by as much as 50%, 30%, 20% or even less is viable, is debateable.

Based on these rough estimates, let us assume that as much as 50% dampening of energy demand growth is possible with appropriate measures. In that case, the energy potential is 16 EJ, which according to the business as usual figures is equal to 17% of the 2050 global passenger travel demand or 10% of the total transport demand. That appears to be a result worth considering and one for which appropriate policies can still be implemented in those developing countries with high growth potential, China being the primary focus due its size and current economic dynamism.

Personal public transportation

The management of transport demand appears to imply a reduction in personal mobility, either through dampening of the demand for personal vehicles or shifting to public transport. Public transport has a number of disadvantages in terms of comfort and utility:

- Lack of privacy.
- Frequent stops.
- Waiting times.
- Fixed routes.
- Inconveniently located stops.

One development shows potential for avoiding at least some of these disadvantages and overcoming the growth/mobility dilemma, that of personal rapid transit (PRT).

Personal Rapid Transit

PRT is a transport system, normally in a city location on a small-gauge rail, on which passengers ride in small driverless vehicles, thereby overcoming the concern over lack of privacy. Stations and stops would be located on a branch from the main line, at which passengers can disembark and embark. This would ensure less frequent stops for each

Figure 4-4 West Virginia University's PRT system in operation
Source: West Virginia University

traveller and no waiting time (assuming a vehicle is immediately available). In addition, each passenger would be free to program his desired route. Thus four of the five disadvantages of public transport above can be removed.

Further advantages can be identified:

- Lighter vehicles (than trains and buses) require less robust and less expensive infrastructure.
- Vehicles operate on demand, avoiding redundancy of empty carriages.
- Automated operation allows high density travel.

There are examples of PRT in operation and planning. Thus far most examples of PRT are provided by companies with blueprints, rather than concrete plans. However, one or two operational examples can be quoted.

Heathrow Airport is planning a 2008 opening of a PRT between 2 of its terminals, with an option to extend the system if successful. It is in partnership with an engineering company, ARUP and a PRT start up, Advanced Transport Systems. A PRT-like scheme is in operation at Schipol Airport in Amsterdam, which however runs on road instead of rails. The only successful on-rail PRT system in operation is at West Virginia University in Morgantown, carrying passengers since 1975 (Figure 4-4).

Further progress will initially depend on the vision and finances of local & city governments.

The systems being implemented will demonstrate the potential as well as some of the problems of PRT. The problems can be expected to be of the following nature.

1. Cost: despite the potential for lower costs than other transport systems, the WVU system saw spiralling costs. These can arise from land acquisition, ensuring safety and building elevated tracks. Controlling costs is essential to ensure a sustainable concept and may be enhanced with new technology.
2. Space: even with narrow gauge rails, sufficient space will be difficult to secure, especially on city roads. Elevated tracks may help solve this problem but would cause new concerns about safety and looks.
3. Optics: in particular elevated tracks would likely bring opposition from residents, whose support would be necessary in gaining political support for such systems.
4. Safety: ground-level PRT's would create a host of safety concerns, since passenger would by definition have no or little control over their vehicles and would not be able to react to traffic dangers. The vehicles, by necessity small, would be vulnerable. Elevated PRT's would avoid these problems but there would still

be the danger of accidents involving the track supports. Terrorist attacks could conceivably be a concern for what would likely be a highly visible transport system, although this has not manifested itself in cities such as Chicago with highly visible elevated light rail.

With these concerns, it is likely that PRT's would initially penetrate in locations where they are isolated from other traffic, such as in airports. Uptake in cities or other residential areas would depend on the urban structure, whether there is space for an at least partially isolated system or acceptance for elevated tracks. Thus gaining a foothold, PRT may at a later stage be ready for higher penetration in densely congested cities.

The potential for PRT clearly depends on overcoming initial barriers to implementation and then proving itself as a long-term economically viable system. If this can be achieved a more ambitious long-term vision can be imagined. Consider a large city whose transport system is dominated by a PRT, in which safety is assured, public support is given and the economics are viable for both users and provider. The system would be relatively easy to expand as new branch lines could be added in a modular manner.

Seamless Transit

The greatest innovation, however would be to allow seamless transition between road and PRT. If passengers can use the same vehicle to drive away from their residence and onto the PRT track, it would mean a convenient and efficient method of travel. The technology to achieve this requires a method to transfer contact of the vehicle from the rail system to the road and vice-versa and a method to switch power source (e.g. power lines to battery for an electric vehicle or to an ICE). If the trend to electrification of vehicles continues, the personal electric vehicle and the electrically propelled PRT vehicle would be one and the same. Ultimately long-distance links between conurbations could be installed, thereby assuring efficient and sustainable mobility on a large scale whilst assuring personal mobility, freedom and growth.

Intelligent Transportation Systems

Intelligent Transport Systems (ITS) represent the integration of information and communications technology with transport infrastructure, vehicles and users. The objective of ITS is to increase the efficiency and effectiveness of transport networks, improving safety and reducing environmental impacts.

Specifically, ITS aims to reduce road congestion and increase the efficiency of traffic by dissemination of real-time traffic information and improving the attractiveness of alternative forms of transportation. The activities relate to personal and freight transit. The vision is of a transport system in which infrastructure and vehicles communicate with each other constantly, providing real time information to systems and people to improve the functioning of the entire system.

The potential reduction in congestion through ITS has been estimated at 40%, according to the European Union's White Paper on Sustainable Mobility. In the same document, savings in road fuel consumption through reduced congestion and improved driver behaviour are estimated at 50%. Systems such as coordinated traffic control, ramp metering, variable message signs, and traffic and incident detection systems have already been implemented across Europe. The scope of these can be increased and the sophistication of systems can improve their effectiveness. Research and education on ITS is proceeding through representative bodies, including ERTICO in Europe and ITS America in the U.S.

A main pillar of ITS involves providing real-time communication of information between traffic stakeholders – drivers, vehicles and infrastructure. There are already systems in existence which inform drivers of bottlenecks and congestion through satellite navigation. To reach optimum performance of such a system, a high coverage rate of all stakeholders would be necessary, for which continued research, education and outreach are essential. The information provided would inform of bottlenecks en-route, recommend alternative routes, advise on driving behaviour and provide detailed information on expected waiting times and reasons for delays.

A vision of fully integrated ITS in the future could include elements of drive-by-wire technology. Such technology is in operation today in a limited fashion – for example the Distronic system of Mercedes which retains a constant cruising distance from the car in front, even at variable speeds. Integrated into ITS, future evolutions could control "banks" of vehicles all travelling at the same speed close together, with real time information ensuring safety by anticipating heavy traffic or changes in road conditions.

Such systems comprise mainly information technology, with some vehicle and infrastructure hardware also necessary. In comparison to advanced powertrain technologies, this is low cost and therefore has the potential for early penetration in both OECD and non-OECD countries, especially potentially developed countries (consider the example of fast penetration of mobile telephones in developing countries).

Whilst such technology will likely make driving easier and reduce congestion, it will reduce transport energy consumption only if part of a transport strategy which includes reduced energy consumption as an explicit target. Potentially ITS could substantially increase road capacity and therefore traffic, even without requiring new roads to be built. ITS will reduce transport energy consumption in congested locations where, as part of a comprehensive traffic management system, it contributes to reducing congestion, ensuring efficient flow and retaining control of the volume of traffic.

Transportation elasticity

In order to determine how economic factors affect transport demand, transportation elasticity

Table 4-4 Demand elasticities relating to personal mobility
Source: VTPI

Estimated Component	Fuel Price	Income	Taxation (Other than fuel)	Population Density
Car Stock (vehicle ownership)	-0.20 to 0.0 (-0.1)	0.75 to 1.25 (1.0)	-0.08 to -0.04 (-0.06)	-0.7 to -0.2 (-0.4)
Mean Fuel Intensity (fuel efficiency)	-0.45 to -0.35 (-0.4)	-0.6 to 0.0 (0.0)	-0.12 to -0.10 (-0.11)	-0.3 to -0.1 (-0.2)
Mean Driving Distance (per car per year)	-0.35 to -0.05 (-0.2)	-0.1 to 0.35 (0.2)	0.04 to 0.12 (0.06)	-0.75 to 0.0 (-0.4)
Car Fuel Demand	-1.0 to -0.4 (-0.7)	0.05 to 1.6 (1.2)	-0.16 to -0.02 (-0.11)	-1.75 to -0.3 (-1.0)
Car Travel Demand	-0.55 to -0.05 (-0.3)	0.65 to 1.25 (1.2)	-0.04 to 0.08 (0.0)	-1.45 to -0.2 (-0.8)

Summarises various studies. Numbers in parenthesis indicate original authors' "best guess" values.

data is of value. The tables above and below, published in the 2006 Victoria Transport Policy Institute study, are a summary of a number of long- and short-run elasticities from various studies.

Table 4-5 Demand elasticities relating to further transport modes
Source: VTPI

	Short-Run	Long-Run	Not Defined
Petrol consumption WRT petrol price	-0.27	-0.71	-0.53
Traffic levels WRT petrol price	-0.16	-0.33	
Bus demand WRT fare cost	-0.28	-0.55	
Railway demand WRT fare cost	-0.65	-1.08	
Public transport WRT petrol price			0.34
Car ownership WRT general public transport costs			0.1 to 0.3

Summarises various studies of long-run price effects.
("WRT" = With respect to).

or the purposes of this study, the elasticity of car fuel demand is most informative, in particular in relation to fuel price, which is a parameter over which policymakers, in theory, have some control through taxation. It is interesting that the elasticity of car fuel demand (-0.7) comprises two approximately equal factors – car travel demand (-0.3) and mean fuel intensity (-0.4), indicating that increases in fuel prices result to similar extents, in both less driving and to migration to more fuel efficient vehicles.

In order to relate these elasticities to the above calculations regarding mode switching, it is necessary to assume that reduction in car travel demand is associated with a switch to mass transit (rail) travel.

The situation in mid 2006 of increasing fuel prices in the U.S. can be treated as an experiment to test the elasticity figure above. The price of gasoline in the U.S. increased by about 30% from its long term average in 2000 and nearly doubled between 2003 and summer 2006. Under these circumstances it might be expected to see evidence of a corresponding reduction in car travel demand in those years. Using the short-run elasticity figure for vehicle fuel consumption with the price of fuel of 0.27, the more than doubling of the fuel price between 2000 and 2006 might be expected to result in a 17% decrease in driving demand. In fact, driving demand in the U.S., as measured by the vehicle miles travelled (VMT), has increased since 2000. This indicates either that the prediction is inaccurate or, more likely, that any decrease in demand has occurred against a rapidly growing baseline of growth. Calculating that baseline is a much more complicated and inexact process. From the higher long-term elasticity figure of 0.7, a sustained fuel price at the high 2006 level could be expected to result in larger reductions in demand, compared to the baseline, over time and potentially result in absolute reductions in

Table 4-6 Aggregate effect of fuel price increases
Source: GasBuddy.com, China Daily, CNN.com, WBCSD consumption figures

Scenario	Fuel price ($/gallon)	Fuel price increment 21.4% (/gallon)	Aggregate price increment	Aggregate change in consumption	Total price / unit energy (/EJ)
1. OECD N.A.	3.01	$0.64	$32 bn	-1.6 EJ	$20.6bn
2. China	1.81	$0.39	$8 bn	-0.7 EJ	$11.7bn
3. non OECD	2.00 (est)	$0.43	$41 bn	-3.2 EJ	$12.9bn

car travel demand, despite the underlying growth.

In the U.S. in particular, it is necessary to analyse whether these effects would in fact result in a switch from personal vehicle travel to mass transit. Over the short term this is unlikely in those areas which do not have access to mass transit, where the dampening of travel demand would only have the effect of reducing total miles travelled. In those areas with ready access to existing mass transit, the elasticity would likely result in a switch to the mass transit mode. Only in the long term could sustained higher fuel prices be expected to result in a switch to mass transit in more regions, as the demand for mass transit encourages the build up of the necessary infrastructure.

For each of the mode switching scenarios above, the increase in fuel price to achieve a long term 15% mode switch by 2050 can be calculated and the resulting increase in total consumer costs through that increased fuel price. The long term 15% decrease in car fuel demand could by this calculation be brought about by a 15%/0.7 = 21.4% increase in fuel price. The only baseline fuel price currently available is the current price in each of the respective regions. This higher fuel price is therefore applied to the remaining petroleum consumption, available from the numerical databases from Chapter 3. The information is summarised for three regions in Table 4-6.

A further question to be addressed is the mechanism by which the fuel price is increased. If the price increase occurs through an increase in the price of crude oil, the proceeds from the incremental consumer costs go to funding the profits of oil companies and oil producing nations. In either case, this is also a parameter which cannot be predicted with any certainty.

If, however, the fuel price increase is brought about by government intervention through increased fuel taxes, the proceeds go to the government and are in principle available to be spent on programmes that directly benefit those who are disadvantaged by higher fuel prices or indeed to assist in the build up of, for example, mass transit infrastructure. This general trend can be seen when comparing Europe, with high fuel taxes, relatively compact cities and in general excellent public transport, to the U.S.A., in which the personal vehicle dominates in most regions and fuel prices are significantly lower.

Sensitivity analysis of mode switching

Mode switching from personal vehicles to mass transit is likely to play a major part in any Smart Growth or other urban planning scheme. For commuters into city centres the issue of “park & ride” is also an interesting option, allowing the use of the public transport network. Requisite is the provision of parking lots at key stations at the outskirts of big cities, where commuters from the country side can park their cars (mode split).

Having determined above what the projected transport energy demand growth is, an estimate for the energy demand reductions through mode

Table 4-7 Mode switching scenario description

No.	Scenario description	2020	2035	2050
1	OECD NA: percentage switch from personal vehicle travel to light rail/ underground rail	5%	10%	15%
2.	China: percentage switch from projected personal vehicle to light rail/ underground rail	5%	10%	15%
3.	Non-OECD countries: percentage switch from projected personal vehicle travel to light rail/ underground rail	5%	10%	15%

Table 4-8 Mode switching scenario results summary

Scenario	Total reduction in WTW energy consumption 2050	Percentage of projected global transport energy 2050
1. OECD N.A.	3.9 EJ	2.5%
2. China	1.5 EJ	1.0%
3. non OECD	6.0 EJ	3.7%
4. OECD N.A. Hybrid 50%	0.8 EJ	0.5%

switching can made by analysing specific scenarios.

The following scenarios are to be analysed numerically. The penetration rates have been selected to be challenging, considering the well-documented drive to more personal mobility as GDP per head increases and the likely social resistance to enforced increases in mass transit usage (Table 4-7)

The resulting energy outputs from these scenarios, demonstrating the potential effect on total well-to-wheel energy consumption in the respective regions, are to be found in Appendix 8 including a side-by-side comparison to two of the technology scenarios from Chapter 6. A summary is shown in Table 4-8.

The results demonstrate that, assuming mode switching and mode split were feasible at these levels, there exists potential to reduce energy demand by an amount significantly greater than that through even high penetration of certain hard technologies, such as hybrid vehicles.

A full comparison of these two types of energy reduction measures requires an assessment of their relative costs. Vehicle technologies have quantifiable costs due to extra componentry and engineering investment. The costs of mode switching are not immediately quantifiable and include:

- Consumer costs of higher fuel prices, if fuel taxes are the chosen method to encourage mass transit use.
- The public financial investment and potentially ongoing financial support for transit projects which may not present a profitable business case.
- Economic costs (or indeed benefits) to consumers dependent on fare levels in public transport.
- The political costs of financial, urban planning or other measures to encourage mass transit use.
- The social costs (weighed against the benefits) of using rapid transit as opposed to personal vehicles.
- The perception of reduced personal freedom, in particular if onerous measures are imposed.

Of these, the easiest to quantify directly are the costs of higher fuel prices, which will be dealt with below in the discussion of transportation elasticity.

In assessing the other costs listed above, it is informative to differentiate between the United States and the non-OECD countries including China. Table 4-9 differentiates between the conditions in OECD North America and non-OECD countries.

The aggregate GDP of current non-OECD countries is projected to be about 80% higher than that of OECD countries by 2050, whereas today it is about 20% lower. This projected growth of transport energy demand in

Table 4-9 Development comparison of North America and China
Source: Data from WBCSD sustainable mobility project

OECD North America	Non-OECD
Developed cities and infrastructure	Many cities and infrastructure in early stages of development
2005 - 2050 projected energy growth = 41%	2005 - 2050 projected energy growth = 220%
Vehicle ownership already near saturation (626 per 1 000)	Vehicle ownership at low level (17 per 1 000)

developing countries from 2006 to 2050 will indeed represent the majority of the global demand in 2050. Therefore any serious effort to reduce demand growth and absolute demand by 2050 would have to act on the effects of this developing country growth. In the first order, this would imply measures to dampen personal mobility demand and/or switch to mass transit on a large scale. In turn this implies limiting the developing world's accessibility to such developed world conveniences as personal vehicles.

Since increase in such accessibility, especially in developing countries, is one of the main policy objectives we are targeting, this would be an unacceptable outcome and no more acceptable than severely limiting access to personal transport in developed countries, where personal mobility has become a convenience treated almost as a fundamental right. The conclusion here may be to state a principle: that any measures to dampen transport energy demand significantly should be neither coercive nor excessive, with the interpretation of these terms to be discussed further on a regional level.

It is interesting to note that in the European Union's recent mid term review of its 2001 White Paper on Transport, the focus for future transport has changed towards "co-modality" as opposed to "modal-split". The review therefore concentrates on enhancing the efficiency of all transport modes and facilitating interface between transport modes, rather than encouraging migration to modes of higher efficiency (e.g. road to rail).

Demand management analysis in freight transport

In the above analysis, the effect on energy consumption in freight transport has not been explicitly considered. The following effects are worth noting:

- Improved availability of public transport is unlikely to have a direct measurable effect on freight transport.
- If greater use of public transport is encouraged by the development of more compact cities, a minimal reduction in freight transport demand may also result.
- Improvement in urban traffic will affect consumption from private vehicles and freight traffic alike.
- If greater use of public transport is encouraged by higher fuel prices, those higher fuel prices would also encourage mode switching in freight transport, for example from trucks to rail. This is currently happening to a limited extent in the U.S.

The greatest potential in freight transport clearly lies with mode switching to rail (approximately 85% more efficient per tonne-km that truck transport – data from "Mobility 2030"). Potentially a switch could leverage a substantial proportion the nearly 700m tonnes of oil or 28 EJ of energy projected to be consumed by heavy trucks in 2050, which represents 16% of all transport energy consumption. It is recommended that an in-depth analysis of both the potential and implications of switching to rail freight be considered in future studies.

Conclusion

The following conclusions can be drawn from this analysis:

- Significant reductions in demand for personal transportation, and therefore in transport energy consumption, are historically demonstrated in Hong Kong and Singapore, which are each densely populated and apply strict policies which discourage car ownership and use. Such city structures and policy measures will be difficult and undesirable to enforce in most countries, due to their effect on accessibility of mobility. However, measures could be considered which extract only some of the desirable energy consequences of higher density conurbations and associated policies.
- OECD countries have the least potential for development in this area, since they are economically, and in terms of their infrastructure, by definition well developed. However, schemes such as the Smart Growth initiative in the U.S. are well established and have potential for dampening some of the 40% projected increase in transport energy demand in the U.S. by 2050.
- In fast growing non-OECD countries, in particular China and India, there is potential for urban planning measures to be successful, since as cities develop and transform they can be moulded by policy. The potential lies in limiting excessive geographical growth of cities and implementing smart growth techniques at an early stage of development rather than targeting high population density. Some proportion of the projected 250% transport energy demand growth in these areas can be recovered.
- Pricing is an effective tool in encouraging a switch to more energy efficient forms of transport, in particular through automotive fuel. This may occur through the market increase in the oil price or through taxes imposed by governments. Governments must strike a balance between energy savings objectives on one hand and economic and social factors on the other. Limiting personal vehicle use by any method limits personal freedom to a certain extent. In addition, in certain countries or regions, especially many parts of the U.S.A., a widespread alternative to the vehicle is unviable due to the structure of cities and suburbs

whose development has been shaped by the ready availability of personal mobility.

- The convenience factor is to be considered in any scheme to reduce transport demand. Access to a personal vehicle, is for people living in certain locations, a convenience in itself. Therefore, discouraging the ownership or use of such a vehicle can be considered as limiting individuals' level of convenience. This, from a policy point of view, may prove to be untenable, especially if policies are enforced with a lack of consideration for those with particular mobility needs.

5. Breakthrough scenarios – "What if?"

In addition to the analyses above, which are based on current knowledge and reasonable projections of technologies, the Transport Specialist Study Group has identified "breakthrough" technologies. These are technologies which could conceivably emerge, given the appropriate conditions and, which could have a material effect on energy and/or petroleum consumption in the long term 2050 timeframe. These will be considered in a "what if?" exercise.

In this context, a breakthrough technology requires the following characteristics:

1. Currently not considered to reach the mainstream even by 2050 or not expected to be high penetration.
2. Could conceivably become technically and economically effective with the stated characteristics and penetration level by 2050.
3. Would have the potential to realise a significant reduction in energy, petroleum or fossil fuel consumption or GHG emissions if it gained significant penetration.

Once such technologies have been identified, the following questions are to be addressed:

1. What are the required conditions for the technology to reach this level of development and penetration?
2. What is the potential for reduction in energy consumption in 2050?
3. What are the primary market, technical or social implications of this technology becoming widespread?

Analysis method

The following study procedure is to be followed for breakthrough technologies:

- Select technology according to criteria above.
- Identify the barrier(s) to be addressed to allow the technology into the mainstream and the necessary conditions to overcome these barriers and reach the stated penetration level.
- Calculate range of energy, petroleum, fossil and CO_2 reduction potential with widespread introduction.
- Discuss market, technical and social implications of technology.

Breakthrough technologies and analysis results

Table 5-1 summarises the six breakthrough technologies to be considered, the barriers to entry and the conditions for entry.

Table 5-1 Breakthrough parameters and range of energy balance (see Appendix 10)

Technology	Barriers to breakthrough	Conditions for breakthrough	Current energy balance (c.f. gasoline ICE)
Fuel cell vehicle (with H_2) to 50% penetration in new vehicles sales	• Cost of stack • Fuel storage density / vehicle range • Fuel availability (especially developing countries)	• Breakthrough in stack technology • Breakthrough in storage technology • Efficient H_2 production • Widespread H_2 infrastructure	WTW energy: -35% to +170% WTW fossil energy: -95% to +80%
Electric vehicle to 50% penetration in new vehicles sales	• Cost of battery • Energy storage density / vehicle range • Refuelling facility	• Breakthrough in battery technology • Widespread fast charge infrastructure	WTW energy: -75% to ±0 WTW fossil energy: -95% to -35%
Plug-in hybrid vehicle to 50% penetration in new vehicles sales	• Cost of battery • Energy storage density / vehicle range	• Breakthrough in battery technology	WTW energy: -50% to – 20% WTW fossil energy: -55% to -32%
CTL + carbon capture	• Low WTW energy efficiency of process • No high volume carbon capture process available	• Improve process efficiency • High volume carbon capture technology breakthrough	WTW energy: +70% WTW fossil energy: +70%
BTL high yield	• Low WTW energy efficiency of process • Availability of biomass	• Improve process efficiency • Increase global biomass yield	WTW energy: +85% WTW fossil energy: -95%
Cellulosic ethanol high yield	• Low WTW energy efficiency of process • Availability of biomass	• Improve process efficiency • Increase global biomass yield	WTW energy: +100% WTW fossil energy: -75%

Fuel cell vehicle as mainstream technology with high penetration in OECD countries

Due to the potential for emissions-free driving using hydrogen fuel, fuel cell vehicles are widely considered to be an important element in future mobility. It is therefore informative to study the conditions necessary for fuel cell vehicles to become mainstream and the energy benefits that can be gained. In this study, hydrogen fuel is to be considered.

Fuel cell drive system

The fuel cell stack is the most costly element in the fuel cell vehicle and, together with the remaining components in the drive system, comprises the majority of the incremental cost compared to a conventional ICE vehicle. The following graph shows the historical and projected cost of the system in $/kW in comparison to conventional engines. In order for a market breakthrough to occur by 2050, the cost of the stack would have to approach the cost of conventional engines (data from IEA report "Prospects for Hydrogen and Fuel Cells").

Extrapolating out to 2050, it appears that there is potential for the cost per kilowatt to drop to a level of a similar order, but not close to that of internal combustion engines (the data shows approximately twice the ICE cost per kW). The validity of this assumption depends on the capacity for continuous improvement, although it is quite likely that there is a floor to the cost per kilowatt due to the fundamental structure and materials requirement of the stack. From the IEA data used, the floor may be at approximately $50/kW, within reach of the $30/kW of conventional vehicles.

Figure 5-1 Projected cost of FCEV drive systems
Source: IEA, (mid range estimate)

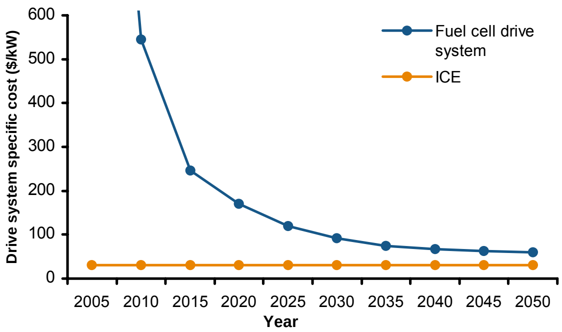
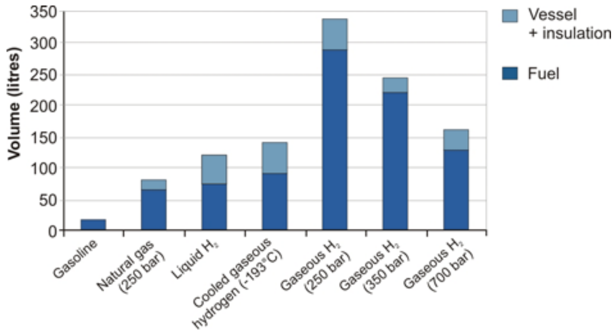


Figure 5-2 Volume requirements of hydrogen storage systems
Source: "Prospects for Hydrogen and Fuel cell, Energy Technology", IEA 2005



The market viability of the fuel cell vehicle would then depend very strongly on the price of the fuel and therefore the consumer's economic calculations of initial investment and recovery of that investment through lower running costs. The factors in this calculation are the consumer price of conventional petroleum fuels and the consumer price of hydrogen for the fuel cell. For the fuel cell vehicle to become a breakthrough technology, the conditions must be in place for this economic calculation so that makes sense to the consumers. The evaluation will continue on this basis.

Fuel storage density / vehicle range

It is reasonable to assume that for fuel cell technology to reach high penetration, the driving range of fuel cell vehicles would need to approach that of conventional vehicles, a few hundred miles. For it to be economically and technically viable, energy losses on refuelling and in the distribution chain from fuel production through delivery to the pump would need to be minimised.

The following analysis and data are extracted from "Prospects for Hydrogen and Fuel cell, Energy Technology", IEA 2005.

"Although hydrogen storage is required for both stationary and automotive applications, the main R&D focus is directed at the question of on-board storage in either fuel cell vehicles or ICE/electric hybrid vehicles. Storing hydrogen, with its low energy content density, is a challenging pre-condition for introducing hydrogen as a transportation fuel.

Hydrogen can be stored as a compressed gas in pressure vessels, as a liquid in cryogenic tanks or absorbed in solid materials. The mechanism is either physical or chemical bonding. The development target which meets expectations of a marketable vehicle technology, quoted in the IEA report, is the following:

- small-volume vehicle assumed
- store 5 kg of hydrogen (i.e. 460-580 km range for a midsize FCV)
- at least 5-6 weight % of hydrogen (the so-called "gravimetric density")
- a release temperature of 80-150°C
- rapid refuelling time (few minutes per full tank)
- low refuelling energy
- tank cost of around USD 150/kg

Figure 5-2 suggests that cryogenic liquid storage and gaseous storage at 700 bar requires the least volume of the technologies currently under development. 140 to 160 litres is the projected volume to meet the target. (These storage methods require seven to nine times more volume than gasoline fuel tanks to achieve an equivalent energy content. This is compensated partially by the greater tank-to-wheel efficiency of the fuel cell vehicle by a factor between 2 and 3.)

Table 5-2 Targets for hydrogen storage systems
Source: IEA 2005

Desirable technical characteristics: Low volume/weight tank, high H_2 content (>5-6 wt% H_2) low pressure, temperature suitable for fuel cell engines (80-150 °C), short refuelling time, low storage energy, prompt H_2 release and low costs (USD 150/kg) for storage of 5kg H_2 for 500 km drive in a FCV.

Current performance

	Gaseous storage C-fibre vessels	**Liquid storage cryo-tanks**	**Solid storage metal hydrides**
Weight (wt % H_2)	4 (6)	4-5 (20)	8 ?
Volume (l)	240-160	120-130	60-80 ?
Pressure (bar)	350-700	1 bar	10-60 bar
Temp. (°C)	room T	-253 °C	?
Cost (USD/kg)	600-800	700-800	?
Storage energy (% LHV H_2)	22-30	60	Low ?
Status	Commercial	Commercial	Developmental
Pros	temperature and time	volume, pressure and time	volume, pressure, energy and H_2 purity
Cons	lifetime, volume, safety, cost and storage energy	lifetime, boil-off, safety, cost and storage energy	lifetime, weight, time, reversibility and cost
Alternative options	Glass micro-spheres	$NaBH_4$, C_7H_{14}, C_7H_8	Nano-C, MOF HAS, alanates, borohydrides, thermal hydrides

Note: Storage energy for gaseous hydrogen is calculated starting from 1 bar and assuming 50% efficiency in electricity production. The storage energy will be lower if hydrogen is received under pressure via a pipeline.

The projected maximum potential storage density is offered by solid metal hydrides, with a estimated tank of volume 60-80L for a 500km vehicle range and low storage energy, thereby enabling vehicle design and range performance equivalent to conventional vehicles. There remain significant technical and economic barriers:

- The weight of the storage system.
- The cost of the metal hydride.
- Refuelling time.
- Lifetime, reversibility.

Further materials are also under consideration, including metal organic frameworks, borohydrides ($NaBH_4$) etc.

In conclusion, the fundamentals of hydrogen storage appear to offer potential to enable convenient fuel cell vehicles by 2050, but only if a number of further barriers are overcome with sufficient lead time to support mass production. Significant further investment in research is necessary to develop this technology.

Availability of fuel

The availability of fuel is dependent on two main factors: production of the fuel and a delivery infrastructure. These factors are to be discussed in turn for hydrogen.

Production of hydrogen:

There is a significant amount of literature regarding the methods of producing hydrogen fuel and the energy required to produce and transport it. It is valid to state the main conclusions, which are drawn primarily from data from the EUCAR/CONCAWE Well-to-Wheel Study:

- Well-to-wheel total and fossil energy and GHG emissions for electrolysis from water are to be assessed according to the energy generating mix available, which differs in different regions and countries. Assuming sufficient generating capacity, fuel cell vehicles may therefore bring greater energy and GHG benefits for regions with high penetration of nuclear or biomass electricity generation.

A diesel fuelled truck transporting hydrogen at 200 bar uses an equivalent of 7% of the hydrogen energy on board per 100km travelled.

- Natural gas reformation is currently a popular method by which to produce hydrogen, due to the widespread availability of the gas and the low volumes of hydrogen currently produced. The overall energy efficiency of the process is higher than with electrolysis (EUCAR/CONCAWE Well-to-Wheel Study). Natural gas is in high demand for heating and its reformation emits CO_2 equivalent to the energy content of the natural gas. It will continue to be a source of H_2 but availability issues and GHG emissions will make it eventually less attractive than electrolysis and it is unlikely to be the long-term sustainable method.

- Wood gasification is of similar energy efficiency to natural gas reformation and exhibits very low full-cycle CO_2 emissions, equivalent to that of electrolysis using renewable electricity (EUCAR/CONCAWE).

- Coal gasification is of similar energy efficiency to wood gasification but exhibits very high fossil fuel consumption and CO_2 emissions, although each of a similar order to that of electrolysis with the current energy mix.

For simplicity, calculations in this chapter have been performed assuming electrolysis due to the potential for low-fossil fuel and low-CO_2 production. Equally, wood gasification could provide similar advantages and higher efficiency and could be the subject of further in-depth study.

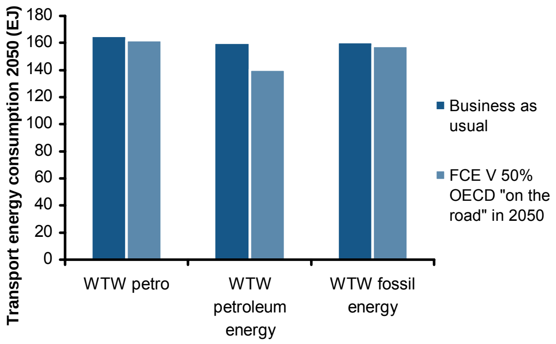
Hydrogen infrastructure

Assuming high penetration of H_2-FCEVs, a widespread refuelling infrastructure similar to today's gasoline and diesel filling station networks would be essential to ensure convenient mobility for drivers. According to the study "The Future of the Hydrogen Economy: Bright or Bleak", the energy consumed in transport of hydrogen from central production locations to dispersed hydrogen filling stations is significant.

A diesel fuelled truck transporting hydrogen at 200 bar uses an equivalent of 7% of the hydrogen energy on board per 100km travelled. This figure reduces to 1.5% per 100km for liquid hydrogen, but the energy cost for cryogenically stored hydrogen is, as in the table 5-2, approximately 60% of the energy content. Even with pipeline delivery available, a significant proportion of hydrogen would still have to be delivered by truck. For pipeline delivery of hydrogen, the estimated energy losses are 7% over 1 000 miles, accelerating to 34% over 3 000 miles (data from "The Future of the Hydrogen Economy, Bright or Bleak?").

The extent of these losses can be reduced by distributed hydrogen production. The more distributed the production, i.e. local to the refuelling stations, the less energy is lost in distribution. This then leads to further challenges of the cost of distributed hydrogen production facilities and the availability of sufficient local electrical energy for the production of reasonable quantities of hydrogen. As an illustration, a filling station

Figure 5-3 Global transport fossil energy potential, 50% on-the-road FCEV penetration in OECD countries, 2050 (natural gas reformation)



serving 1 000 vehicles per day would require approximately 25MW of continuous energy (1/40th the capacity of a modern nuclear power station) and 2.5L of water per second for hydrogen produced by electrolysis. These are challenges which can conceivably be overcome, but require significant investment and technological research to be realised.

The greatest challenge may be in the cost of building a hydrogen refuelling infrastructure itself, which requires an entirely new distribution system and fuel pumps. Some estimates have projected costs of hundreds of billions or even trillions of dollars to achieve global coverage. It is more likely that a widespread infrastructure be built up gradually, with local networks initially gaining a foothold. For example, in California the state government is providing $6.5m to fund hydrogen vehicle projects including purchase of vehicles and construction of a small number of stations.

Further, current plans envisage a "Hydrogen Highway" that will by 2010 make hydrogen fuel available across the state's interstate highway network. Other areas in North America have made tentative steps towards a similar programme. If such schemes come to fruition and encourage further investment, one could imagine a point at which availability in certain areas of the country is sufficient to serve a substantial niche market. The fuel cell could then remain a niche vehicle mainly for urban areas or the momentum thus created could encourage a full nationwide network of hydrogen filling stations.

Whether built in a comprehensive programme from scratch or evolving gradually over time, the investment involved would be massive. Due to the existence of potential alternatives to fuel cells, such an undertaking must be considered rationally alongside those alternatives and entered into on a grand scale at the point when the economics have been proven.

Energy potential

The energy potential for the fuel cell vehicle technology has been assessed using three input energy assumptions for the source energy for hydrogen electrolysis:

1. Using natural gas reforming (Figure 5-3)
2. Electrolysis using current energy mix (mostly coal and nuclear, Figure 5-4)
3. Electrolysis using 100% renewable energy (Figure 5-5))

Whilst this third case may appear unrealistic according to current knowledge, as a breakthrough technology it is appropriate to consider the optimum case.

Assuming the current energy mix, it is striking that fossil energy consumption is actually increased, due to the high primary energy consumption of electricity generation, in particular nuclear (EUCAR/CONCAWE Well-to-Wheel Study – although for wind energy, the study assumes primary energy = output energy of turbine).

Figure 5-4 Global transport fossil energy potential, 50% on-the-road FCEV penetration in OECD countries, 2050 (hydrolysis, current energy mix)

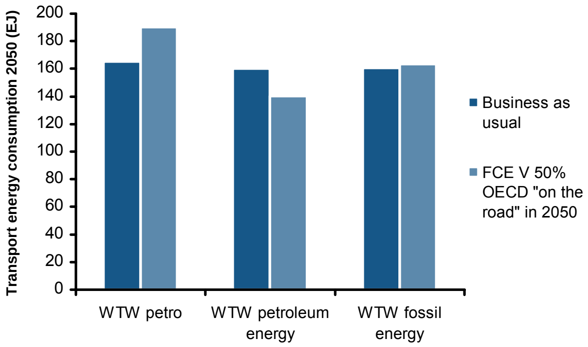
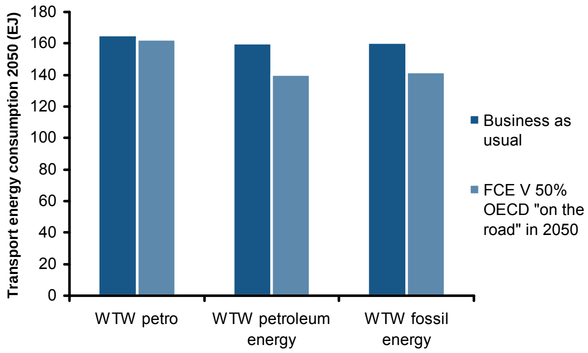


Figure 5-5 Global transport fossil energy potential, 50% on-the-road FCEV penetration in OECD countries, 2050 (hydrolysis, 100% renewable energy)



The energy potential in the optimum case using 100% renewable electricity demonstrates, a 11% projected reduction in global WTW fossil energy. Since this represents a 50% on-the-road penetration only in passenger vehicles in OECD countries, it is a substantial energy achievement.

The energy result is heavily dependent on the proportion of renewable energy in the generating mix. The conclusion can be drawn that the H_2-FCEV makes a superior energy case when renewables are a substantial part of the electricity mix or if there is a method to produce hydrogen using renewable energy, which does not compete with electricity generation. Such a method would be difficult to identify, since it is reasonable to assume that any method to harness energy to make hydrogen could equally be used to produce electricity for local use or transfer to the public grid.

Breakeven analysis:

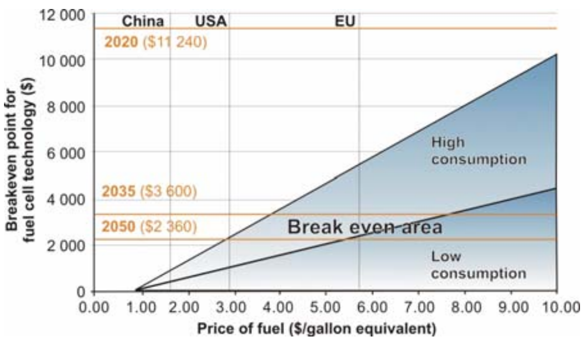
Using the same assumptions as in Chapter 3, a breakeven analysis has been performed for the fuel cell vehicle (see Figures 5-6a-c). In this case, an assumed consumer price of hydrogen fuel has been used, with three hydrogen price scenarios for comparison. The rationale for the $1.50, $5 and $10 per gasoline gallon equivalent (gge) price scenarios is as follows:

$1.50 Represents the cost of electricity at 8¢/kWh required to produce 1 gge H_2 plus a 20% markup (optimum case, see Appendix 9.)

$5 Increased electricity cost estimate assuming trend to low CO_2 fuels for generation and high infrastructure costs (see Appendix 9.)

$10 Extreme case, factor of 2 compared to above calculation

Figure 5-6a Breakeven analysis for fuel cell electric vehicles ($1.50 /gge H_2 breakeven analysis)
Source: Cost data IEA projections, WEC Transport Study Group calculations



To provide an indication of the point at which breakeven for the hydrogen fuel cell technology could be expected, a projected estimate for the incremental vehicle costs is shown on the graphs. The figures for FCEVs are the projected

Figure 5-6b Breakeven analysis for fuel cell electric vehicles (\$5 /gge H_2 breakeven analysis)
Source: Cost data IEA projections, WEC Transport Study Group calculations

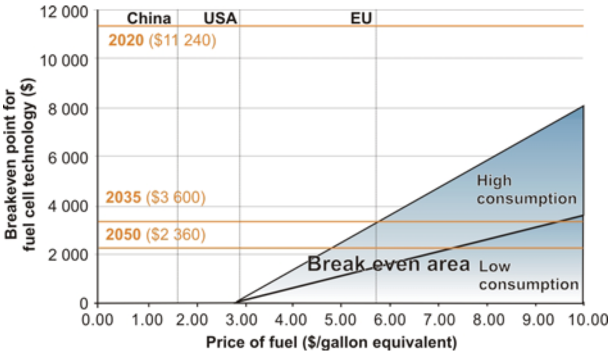
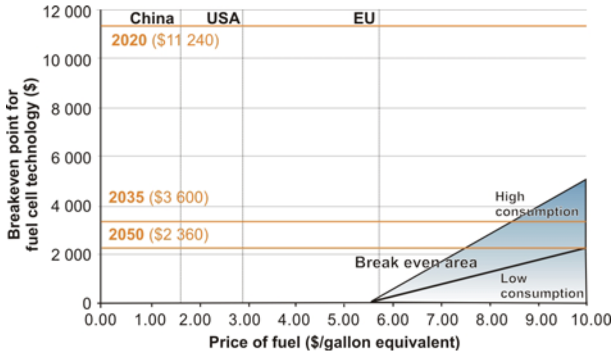


Figure 5-6c Breakeven analysis for fuel cell electric vehicles (\$10 /gge H_2 breakeven analysis)
Source: Cost data IEA projections, WEC Transport Study Group calculations



cost of the fuel cell vehicle for an 80kW powertrain from IEA's "Prospects for Hydrogen and Fuel Cells" in 2020, 2035 and 2050.

In the optimistic case of \$1.50/gge H_2, FCEVs present a potentially positive business case by 2050 in those regions where hydrocarbon fuels are sufficiently expensive. According to current fuel prices, this includes EU and US but not China. Should hydrocarbon fuels significantly increase in price by that time, the business case may become positive in all regions. In high petroleum fuel cost regions such as EU, the business case may arise between 2020 and 2035.

With a higher (more realistic) H_2 price of \$5/gge, only higher fuel price regions (EU according to current prices) approach a positive business case for FCEVs by 2050. Again, higher petroleum fuel prices will change this calculation for regions (e.g. US) which show a negative business case at current petroleum fuel prices.

At the extreme but conceivable case of \$10/gge H_2, a significant increase in the price of petroleum fuel would be necessary to provide a secure positive business case for FCEVs.

The potential for FCEVs to gain significant market share depends strongly on hydrocarbon and H_2 fuel prices, which in turn depend on policies of individual countries or in some cases regions as well as the realisation of the vehicle cost improvements projected in the quoted IEA report. Assuming the accuracy of the IEA's vehicle cost figures, it can be concluded that high petroleum fuel prices (at a minimum at the level of those in European countries today) and reasonable H_2 prices at \$5/gge or below would present a sufficiently positive business case to approach significant market share (and conceivably the 50% target) by 2050, making FCEVs a strong candidate as the primary future breakthrough technology.

Electric vehicle as mainstream technology with high penetration in OECD

Electric vehicles have been in existence for many decades and have recently been considered as a potential mainstream technology by parties such as the California Air Resources Board. There are currently electric vehicles in certain road applications, including low speed vehicles such as the electric motor vehicle of Global Electric Motors (GEM) and electric motorcycles, such as the EVT. The existence of these vehicles and of a viable market for them (over 30 000 GEMs sold since 2000) indicates that the potential for more widespread penetration may exist.

It is reasonable to assume that a high penetration would be dependent on convenience factors of high range, sufficient performance and short refuelling duration, similar to conventional vehicles. In contrast, the above mentioned GEMs and similar low-speed "neighborhood" electric vehicles are relatively inexpensive (<\$10 000), have a top speed of around 30 mph and range of about 20 miles.

The great advantage of electric vehicles lies in zero tailpipe emissions and zero petroleum

Table 5-3 Summary of current and potential automotive battery technologies for BEV application

Battery type	Energy mass density (Wh/kg)	Energy volume density (Wh/L)	Power mass density (W/kg)	Dura-bility (cycles)	Potential cost per unit energy capacity ($/kWh)	Data source/ comment
Lead acid (Pb-acid)	30-40	65-85	250	500	50	IEA, SUBAT
Nickel metal hydride (NiMH)	70	115	350	1 350	559 (2012)	SUBAT
Nickel cadmium (NiCd)	60	-	200	1 350	490 (2012)	SUBAT
Sodium nickel chloride (NaNiCl)	125	-	200	1 000	212 (2012)	SUBAT (High temp)
Lithium ion (Li-ion)	125-200	450-720	400	1 000	360 (2012) 160 (long term)	IEA, SUBAT
Comparison						
Zinc air (Zn-air)	200	720	-	-	n/a	Mechanical recharging only
Gasoline	12 000	9 000	-	-	0.0002	15 gal tank cost $400

consumption. The overall energy and GHG potential depends on the energy mix in the region or country in which they are deployed. Again, from an energy and CO_2 point of view, electric vehicles use may make more sense in those regions or countries with high penetration of biomass or nuclear energy.

Battery cost and capacity

Currently the battery technology prevents BEVs achieving the high range required by modern consumers, causing the primary use for electric vehicles to be in niche applications such as city or local community driving, perhaps as a second or third family vehicle. The viability of a high penetration in this segment depends on the cost of the vehicle, the utility of such vehicles and the economic calculation of the vehicle purchase and the running costs.

Table 5-3 shows the energy capacity per unit volume and mass for known battery technologies for battery electric vehicles (high energy density) in comparison to gasoline, assuming high volume production.

Of the listed battery technologies, Pb-acid, NiMH and Li-ion have proven their technical feasibility, for automotive applications. Much current research concentrates on Li-ion, due to its superior energy density and widespread commercial use in electronic applications. Studies indicate a potential cost of $200 per kWh at high production volumes. For a midsize sedan to reach a reasonable 300 mile range, requiring about 90 kWh, the potential battery costs would therefore be $18 000-22 500, assuming high volume production. Battery weight would be 450kg, volume 200L. Charging times are typically a few hours. These figures, in particular the cost, indicate a niche market rather than mainstream technology, unless further breakthroughs are achieved.

This niche is indeed being investigated commercially, by companies such as Tesla Motors. Tesla is planning a 2007 introduction of a high performance electric sports car using lithium-ion batteries, with 250 miles range and 4 second 0-60mph acceleration. Its projected customer price of $100 000 puts it out of reach of mainstream buyers, but a successful launch would create a new niche market and be a commercial scale test of the technology.

More modestly, the G Wiz electric vehicle is currently popular, especially in London and has sold about 2 000 of these small vehicles with a maximum speed of 45mph and cost around $15 000, representing a larger niche of city drivers.

The great advantage of electric vehicles lies in zero tailpipe emissions and zero petroleum consumption

Further battery advancement to approach the energy density of gasoline and the cost of an ICE would require a significant leap in technology towards the energy density level claimed for aluminium batteries. These are at a very early stage of development at companies such as Europositron, which uses nanotechnology and claims to have overcome the typical problems of Al batteries, which include corrosion of the aluminium and production of hydrogen gas at the electrode. Europosition claims a potential energy density of over 2 000 Wh/kg, although this has not been independently validated.

The Japanese Ministry of Economy, Trade and Industry has set a target of 500-700 Wh/kg and $50/Wh for future battery technologies

Progress in aluminium and other battery technologies in order to approach the claims and targets stated would have to address the following in order to compete with current technology:

- Energy densities approaching those in the table above
- Production costs below $100/kWh (below ~ $10 000 per pack)
- Fast charging possible (<10 min)

It is not clear whether such advancements by 2050 may be feasible, since even the current status depends on the validity of claims for new battery technology.

Electric refuelling

In order for a high market penetration to be accepted by consumers, the convenience of owning an electric motor vehicle would have to be secured. In particular the refuelling process would have to be of a similar duration to conventional vehicles (a few minutes) and be readily available.

Refuelling a high range electric vehicle in, for example, less than 10 minutes, requires a significant amount of power, of the order of half a megawatt per vehicle. Such an amount of electric power is substantial for a standard commercial electricity grid and may therefore require proximity to a dedicated source of electric power. The refuelling stations themselves may have to be constructed specially in order to provide a safe and sufficient service.

Home refuelling overnight is a complement to refuelling stations, which would take much of the burden from the stations. However, to become a high penetration technology, electric refuelling stations would be essential in order to provide the necessary convenience for drivers.

An alternative is mechanical refuelling, either by replacing the battery itself or refilling liquid electrolyte. Either of these would require a new infrastructure and potentially a new type of vehicle configuration, but they both offer fast refuelling as a long-term solution.

Figure 5-7 Global transport well-to-wheel total and fossil energy for FCV and BEV scenarios (assuming energy mix)

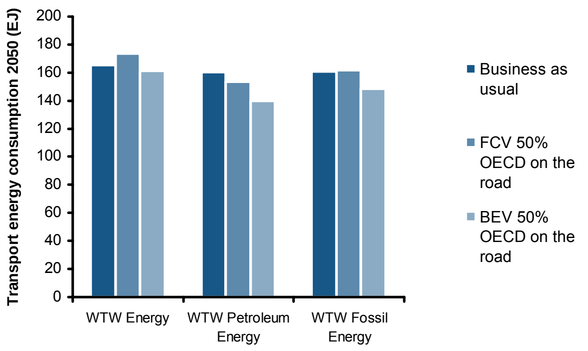
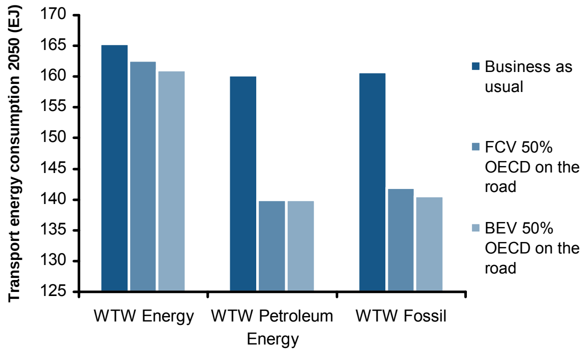


Figure 5-8 Global transport well-to-wheel total and fossil energy for FCV and BEV scenarios (renewable energy)



Energy potential

For pure electric vehicles, every full-function vehicle sold represents one petroleum consuming vehicle not sold and, therefore, a corresponding vehicle lifetime reduction in petroleum consumption. There is a proportional increase in electrical energy consumption and the fossil energy component of this depends on the energy mix in the country or region in question. It is indeed conceivable to use only renewable electricity generation to provide the energy required by electric vehicles. However, any renewable electricity produced could equally be supplied to the general power grid, making it impossible to couple the fossil energy savings to the hydrogen vehicle itself.

An illustrative scenario is presented in here to assess an aggressive BEV introduction, corresponding to the FCEV penetration scenario discussed above with 50% on the road fleet penetration by 2050:

The following assumptions are made:

- OECD electricity energy mix (Enerdata).
- Little change in OECD electricity energy mix by 2050 (World Energy Outlook 2005).
- Tank-to-wheel energy consumption of BEV = 0.2 of ICE consumption (see Eaves – University of Arizona and Electric Vehicle Association of Canada).

The above scenario is compared to the base scenario (nearly zero FCV penetration) and the equivalent FCV scenario with 50% on the road fleet penetration by 2050. Results are shown in the Figures above and in tabular form below.

The further comparison using the assumption of 100% renewable energy is shown for illustrative purposes in Figure 5-8 (notwithstanding the comment above).

The well-to-wheel total energy performance of BEVs is superior to FCVs, due to the higher overall efficiency of BEVs. This implies a high opportunity cost for FCEVs, for which a considerable amount of primary energy is used to produce the fuel. The balance in terms of well-to-wheel fossil energy is similar for the two technologies, assuming the energy used for producing electricity is renewable. This particular conclusion is also valid assuming nuclear power instead of renewable.

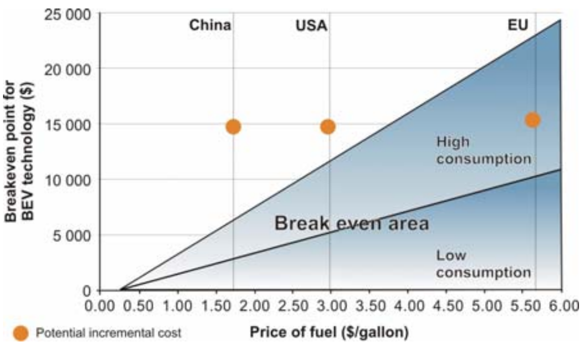
Breakeven analysis

Again a breakeven analysis is performed (see Figure 5-9). In this case an electricity price of 8 ¢/kWh is assumed (comparable to current retail prices in US and Europe). The electricity costs are very small in comparison to the respective cost of gasoline and the breakeven analysis therefore demonstrates only a weak dependence on the consumer price of electricity. This analysis, however, neglects the infrastructure costs for fast recharging or on-highway recharging.

Table 5-4 Comparison to business as usual of well-to-wheel total and fossil energy effects for FCV and BEV scenarios

	WTW energy compared to business as usual		WTW petroleum energy compared to business as usual		WTW fossil energy compared to business as usual	
	Energy mix	**Renewable**	**Energy mix**	**Renewable**	**Energy mix**	**Renewable**
FCV 50%	+15.2%	-1.6%	-12.6%	-12.6%	1.6%	-11.7%
BEV 50%	-2.5%	-2.5%	-12.6%	-12.6%	-7.5%	-12.5%

Figure 5-9 Breakeven analysis for battery electric vehicles
Source: Cost estimate derived from SUBAT & IEA data, WEC Transport Study Group calculations



Customer breakeven can be achieved for high consumers for incremental price, up to $25 000 if petroleum fuel prices are as high as $6/gallon, as in parts of Europe. In regions with mid-range petroleum costs such as the US, the breakeven is below $15 000, therefore requiring further cost and price reduction. According to the figures stated in Table 5-3, for an 80kW vehicle, potential technology costs below $15,000 with Li-ion batteries are feasible ($160/kWh), therefore possibly enabling this breakeven for some customers. Clearly, for BEVs to be economically feasible in all markets, further cost and price reduction would be necessary. The METI target of $50/kWh would bring the technology within reach for regions such as China, with lower petroleum fuel prices and low consumption per vehicle. To reiterate, mass penetration of the technology depends on customer acceptance, requiring sufficient performance and range as well as ease and speed of refuelling.

Plug-in hybrid vehicles

Plug-in hybrid electric vehicles (PHEVs) have recently acquired much attention, in particular in the USA, due to their petroleum savings potential. Due to their ability to use existing infrastructure, they have a significant advantage over pure electric or fuel-cell vehicles. The following table shows their advantages and disadvantages in comparison to pure electric vehicles:

Table 5-5 Overview of advantages and disadvantages of plug-in hybrid vehicles

Advantages	Disadvantages
Uses existing infrastructure	Requires two full powertrains per vehicle
Lower cost electric battery and motor	Consumes petroleum fuel
High range	
Compatible with BEV and FCEV	

Energy and petroleum savings potential

PHEVs are seen as a high-potential interim solution due to the petroleum savings on offer through pure electric driving in addition to the conventional hybrid regeneration function. Petroleum savings per vehicle of up to 100% are possible, dependent on the typical trip distance of the driver and the all-electric range of the PHEV. Typical per-vehicle petroleum savings have been estimated to be 65% for a PHEV40 – i.e. with 40 miles all-electric range (Santini, Argonne National Labs). Cost savings are on offer for consumers through overnight recharging by mains electricity at off-peak prices, with all-electric driving being equivalent to $0.80 per gallon gasoline (US EPA's Transport & Climate Division).

The petroleum savings potential of PHEVs is highly dependent on driving behaviour and all-electric range. PHEVs demonstrate greatest potential if used in a commuting mode in which the daily mileage is lower than the all-electric range. Therefore as all-electric range increases, a larger proportion of daily mileages are covered by all-electric driving. Since half of US households have daily mileage under 30 miles, PHEV20 vehicles may offer a beneficial proposition to a substantial proportion of drivers.

A rollout scenario in the EPA analysis estimates PHEV passenger vehicle sales penetration of 15% by 2030, resulting in 9% of vehicle stock in 2030. In this scenario, nearly 2 billion barrels of gasoline are saved by 2030. Savings in 2030 represent approximately 5.5% of annual consumption. The net costs are calculated to be negative by approximately 2024, through cost reductions with high production volumes and fuel savings.

Technical barriers

The barriers to PHEV introduction include the following:

- System cost: battery costs are high, other components (chargers, power electronics) add to cost, high volumes are required to reduce costs.
- Deep discharge reduces battery life compared to conventional HEVs.
- 240V charging circuit may be necessary.
- Customers without garages would have difficulty recharging.

In addition to technical barriers, the energy requirements for PHEVs must be taken into account, since PHEVs are recharged from the mains consume electricity, which may be generated from coal, gas, oil or renewables. In the EPA analysis above, it is assumed that PHEVs are charged at night and therefore increase the consumption of the base load coal generation, as in Figure 5-10. Figure 5-11 shows the projected increase in US electricity generation out to 2025.

In other regions with differing electricity generation profiles, the effects of higher overnight loading would also differ. For example, in Japan, large scale overnight charging would result in higher natural gas consumption for generation.

In the long term it could be expected that the increased electrical energy demand would affect the electricity mix and could be used as a way to promote increased non-fossil generation including renewable and nuclear.

Figure 5-10 Electricity demand profile with PHEV overnight charging
Source: EPA

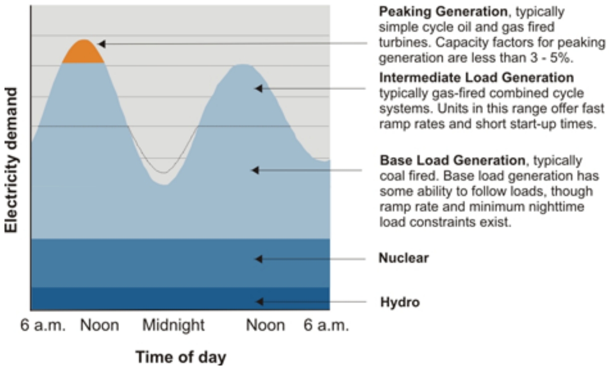
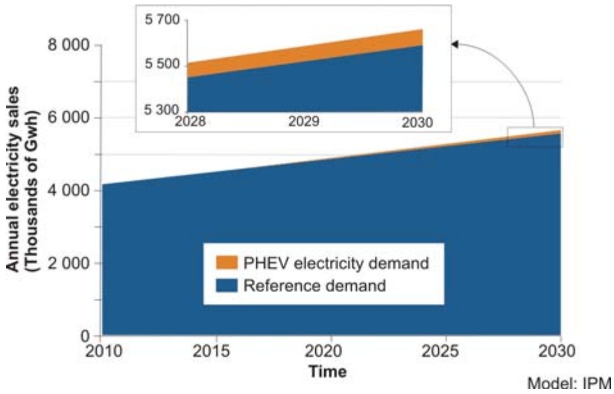


Figure 5-11 Projected energy use for PHEVs (15% market penetration by 2030)
Source: EPA



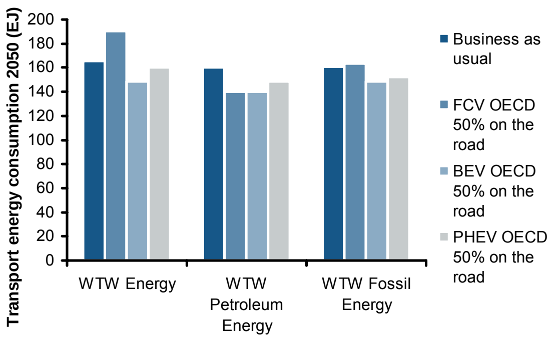
Energy potential (PHEV20)

The PHEV will be analysed with equivalent market parameters to the BEV above for a direct comparison, with 50% market penetration by 2050, and the following assumptions:

Assuming:

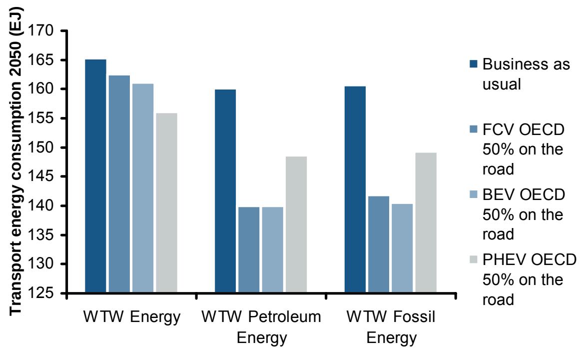
- OECD electricity energy mix (Enerdata).
- Little change in OECD electricity energy mix by 2050 (World Energy Outlook 2005).
- PHEV efficiency under gasoline mode equivalent to conventional HEV.
- PHEV20 leads to 40.6% all-electric VMT (Santini, Argonne).

Figure 5-12 Global transport well-to-wheel total and fossil energy for FCV, BEV and PHEV scenarios (energy mix)



The energy results are presented in comparison to business as usual and to FCEV and BEV at 50% penetration (Figure 5-12 – the same graphs as Figure 5-7 with one extra column for PHEV). Again, the comparison, assuming renewable energy sources, is also included (Figure 5-13).

Figure 5-13 Global transport well-to-wheel total and fossil energy for FCV, BEV and PHEV scenarios (renewable)



In terms of total well-to-wheel energy consumption, the PHEV and BEV technologies perform approximately equally. The PHEV's well-to-wheel fossil performance is around 55% that of the BEV. Since the PHEV contains two powertrains compared to one for the BEV, it's costs may not justify in policy terms its fossil energy performance. However, since PHEVs avoid the necessity for electric refuelling, they have a much smaller barrier for introduction than BEVs. Indeed, high volume introduction of PHEV technology would allow further developments to arise in FCEV and BEV vehicles as the battery technology improves and consumers become more used to electric refuelling.

Table 5-6 Comparison to baseline of well-to-wheel total and fossil energy for FCV, BEV and PHEV scenarios

	WTW energy compared to business as usual		WTW petroleum energy compared to business as usual		WTW fossil energy compared to business as usual	
	Energy mix	Renewable	Energy mix	Renewable	Energy mix	Renewable
FCV 50%	+15.2%	-1.6%	-12.6%	-12.6%	1.6%	-11.7%
BEV 50%	-2.5%	-2.5%	-12.6%	-12.6%	-7.5%	-12.5%
PHEV 50%	-3.1%	-5.5%	-7.2%	-7.2%	-5.1%	-7.1%

PHEV summary

In order for PHEV to be successful in the market, attractive products must be available at affordable prices. Currently, on-the-road PHEVs are limited to a DaimlerChrysler test fleet and converted conventional hybrids using home-made or off-the-shelf conversion kits costing upwards of $10,000. DaimlerChrysler's PHEV fleet is being developed in conjunction with the Electric Power Research institute, will consist of 30 PHEVs by 2008 based on the Dodge Sprinter van and will test technology and customer acceptance. GM has recently announced plans to mass produce a plug-in hybrid version of the Saturn Vue Hybrid.

Moving from test fleets into the mainstream will require a customer proposition in which the option price is offset by the expected fuel savings and any premium performance element built in to the vehicle. As a condition for success, the production cost of the hybrid componentry, currently very high, must be reduced to a level at which a cost breakeven for the customer is viable. As with other technologies, this proposition is heavily dependent on the oil price and therefore unpredictable.

To reach significant volumes, a "push" over the initial barrier may be necessary. Should consumer incentives be considered, these would have to be designed to be technology neutral, their value dependent only on the performance of the vehicle in achieving petroleum, energy or greenhouse gas savings and fairly assessed alongside other technologies.

Breakeven analysis

The breakeven analysis is performed again using an electricity retail price of 8¢/kWh. Assuming 40% electric driving and 60% gasoline hybrid (measured by distance), breakeven appears feasible for technology price premium below $7 000 in regions of mid-range petroleum fuel costs (e.g. US current) and below $14 000 in high price regions (e.g. EU). This represents an average status using this assumption. The actual breakeven for each consumer will be strongly dependent on his/her specific driving mode.

Since the maximum breakeven price of the technology shown in the calculation is for high consumption vehicles, it may be necessary to take into account the driving patterns of the users who drive such distances (~17,600 km average in US). Such longer distance driving could be expected to include longer journeys and less stop-start cycles, reducing the effectiveness of both pure electric PHEV driving and the hybrid regeneration function. It may, therefore, be more prudent to consider the low consumption case to represent more accurately the breakeven point for this technology – therefore being $3,000 and $6,000 respectively for US and EU petroleum fuel prices.

These breakeven figures provide some encouragement for the economic viability of PHEVs, but a high penetration in the order of 50% appears unlikely in all but the most congested markets, where short trips are the norm and a high proportion of driving in pure electric mode can be expected. This highlights

Figure 5-14 Breakeven analysis for plug-in hybrid electric vehicles (July 2006 fuel prices)
Source: WEC Transport Study Group calculations

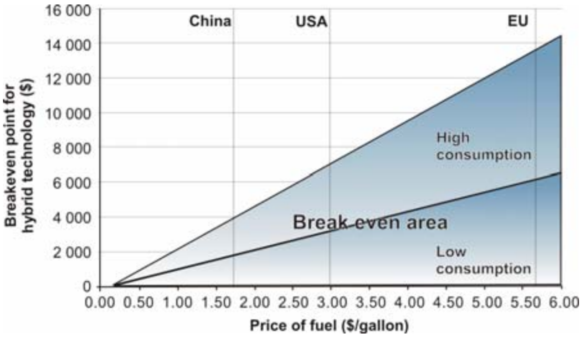
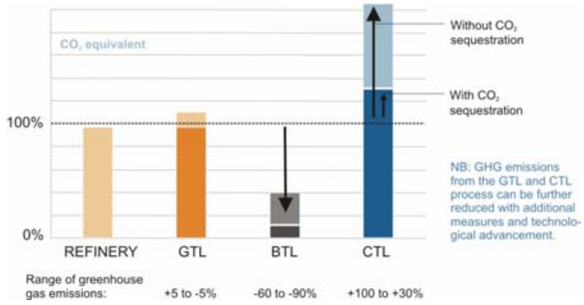


Figure 5-15 Well-to-wheel CO_2 emissions of x-TL fuels in comparison to petroleum diesel
Source: Alliance for Synthetic Fuels in Europe



the disadvantage of a vehicle which has two fully functional powertrains. This effect can be minimised if the performance requirements of the electric powertrain are not equal to those of the conventional powertrain – thereby the cost of most expensive part of the concept, the electric battery and system, can be limited.

CTL and GTL for all fuel types with carbon capture

Coal-to-liquid using the Fischer-Tropsch catalytic synthesis method is an established technology, with current production in South Africa and potential plants in the U.S.A. As shown in the CONCAWE report, the overall energy efficiency of this technology in its current stage of development is low (approximately 50%), though the petroleum reduction potential is high. In addition, the full-cycle GHG emissions of CTL are very high in comparison to the use of conventional petroleum fuels (about double, see Figure 5-15). These include the tank-to-wheel emissions of the fuel consumed by the vehicle and the CO_2 emissions from the CTL production process. The production CO_2 emissions can be significantly reduced by the use of carbon capture and storage (CCS), although well-to-wheel emissions still exceed those of petroleum diesel.

The price on offer is a clean automotive or aviation fuel produced from an abundant energy source (coal), but with GHG emissions about 30% higher than petroleum diesel (CTL). A number of fuel products can be considered using this process, including diesel, methanol, hydrogen and aviation fuel (for example Peabody Energy Corp.). An associated technology, high temperature Fischer-Tropsch, produces gasoline. A further advantage to be considered is that high quality x-TL fuels can enable advanced combustion technologies if used as a pure fuel, not as blend. To the extent that pure x-TL is widely available in the long term, efficiency advantages can thereby be realised.

GTL, produced from natural gas using the Fischer-Tropsch process is also well established, with production in Malaysia and Qatar and further plants under construction/consideration. The efficiency of the GTL process has improved, and is currently in the range 61-65%, with conventional diesel. Full cycle GHG emissions of GTL (without CCS and efficiency improvements) are broadly comparable with for conventional diesel. These are expected to improve further with active R&D investment. In addition, the development of dedicated GTL drivetrains can improve the efficiency of use – thus improving the full cycle emissions compared with conventional diesel.

Efficiency of CTL/GTL processes

The existing CTL process has low overall energy efficiency (in comparison to diesel fuel production from crude oil), due primarily to the waste heat produced in the gasification phase. This is also the cause of the high full-cycle CO_2 emissions.

A portion of the waste heat can potentially be harnessed for useful purposes, for example:

The existing CTL process has low overall energy efficiency

- Production of electricity. The low temperature limits this potential.
- Heat for buildings, similar to a combined heat and power plant.
- For input to an associated chemical plant.

The efficiency of the CTL process is currently estimated at 50% (CONCAWE). The potential total energy efficiency through using some of the waste energy as above may increase to above 60%. Even considering all feasible advancements, CTL production energy efficiency would not approach the 90% level of refining diesel fuel from crude oil.

The GTL process is more efficient and currently in the range 61-65% (EUCAR/CONCAWE Well-to-Wheel Study). The process is in two stages: partial oxidation to 'syngas', then a synthesis process using special catalysts to create long chain paraffins, which are hydrocracked into the required products. Extensive research and development into heat integration and catalyst improvement is expected to increase efficiency by some 20% in the coming years. A range of 63-67% is considered realistic for the next generation of GTL plants.

Carbon capture and storage

Carbon capture and storage (CCS) technologies are being intensively investigated by commercial companies, academic institutions and government agencies and are considered to hold significant potential in reducing CO_2 emissions to the atmosphere. In the case of a CTL plant, the gasification process produces a highly concentrated CO_2 gas, which as an inert gas, is therefore viable for use in processes such as enhanced petroleum recovery, which is an established technology.

The limits to the implementation of this technology lie in the huge amounts of CO_2 that would be produced. As an illustration, if 50% of all U.S. automotive fuel were CTL, the approximate volume of CO_2 produced at the plant would be about 900 cubic kilometres per year (WEC calculations). Even condensed to the maximum extent (liquid form), this would still occupy over 1.5 cubic kilometres per year. Even with carbon capture and technologies becoming available, finding the space to store so much CO_2 safely appears daunting.

A 2003 review by the U.K. Department of Trade and Industry (DTI) indicates the CO_2 storage potential in the U.K. and North Sea (see the figure on the following page). For comparison, the total U.K. annual CO_2 emissions are approximately 0.5 Gt.

Even considering only depleted oil and gas fields, capacity appears to be present to store 40 years of U.K. CO_2 emissions. Deposits in similar structures in other regions would offer additional capacity. Considering aquifers, the capacity potential appears to be practically limitless in comparison to local emissions, but the technology and consequences of such methods of sequestration are in a very early stage of development.

Table 5-7 U.K. CO_2 storage capacity
Source: DTI

	Depleted oil fields	Depleted gas fields	Deep saline aquifers	
			Closed	Open
North Sea				
Denmark	0.1	0.4	0	0
Netherlands	0	0.8	0	0
Norway	3.1	7.2	10.8	476
UK	2.6	4.9	8.6	240
Total	**5.8**	**13.3**	**19.4**	**716**

Notes:

1. The potential for storage in deep unmineable coal seams has not been included in the table because this remains at the research stage.
2. Estimates for the UK apply only to the North Sea with further potential in other areas including West of Shetland and the Irish Sea

The IPCC Special Report on Carbon Dioxide Capture and Storage includes a comprehensive assessment of the potential and costs of CCS. The economic potential of CCS with storage in geological formations is estimated at between 220 and 2,200 $GtCO_2$. In comparison, the annual amount of CO_2 which would be created by CTL production, assuming 50% diesel fuel penetration globally and 50% diesel substitution by CTL, is less than 2$GtCO_2$ (around 1/20th of global emissions). The storage potential therefore exists to cover emissions from CTL, but this would compete with other sources of CO_2 emissions.

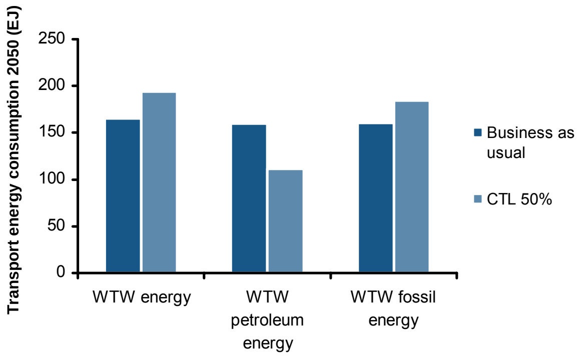
Again, the storage potential in oceans may be still greater, potentially thousands of $GtCO_2$, but the environmental implications, especially pH change of the ocean water are constraints whose effect on CO_2 storage capacity are not accurately known. Uncertainty therefore exists in the assessment of this potential.

Total costs of CCS are estimated from US$17 – 91, which corresponds to 14 - 76¢ per gallon of fuel (4 – 20¢ per litre). This compares to the estimated potential cost of CTL fuel of around $1 per barrel (26¢ per litre). Due to the high uncertainty in the cost of CCS, no specific conclusion can be drawn. However, it is clear that for CTL to gain any significant market penetration, direct government support or economic incentives would have to be in place. Forcing measures such as mandates are not recommended as they rely on picking technologies. If incentives are in place, which proportionally incentivise reduced petroleum usage in transportation fuels, CTL would be eligible for such an incentive. Since well-to-wheel CO_2 emissions of CTL are higher than petroleum diesel, even with CCS, government policy would have to be strongly directed to reducing petroleum consumption in preference to reducing GHG emissions. In the current climate this seems unlikely but it is a plausible scenario.

Sequestration in physical deposits such as depleted oil reservoirs necessitates guaranteed indefinite storage of the CO_2. Especially with the high pressures required to limit the volume of CO_2 to approach the volume of the fossil fuel from which it was produced, significant uncertainties are clearly present. The costs of capture and storage are significant and in developing countries are likely to be challenging for the foreseeable future, reducing the accessibility of energy dependent on it.

The alternative to capture and storage is enhancement of natural processes which store carbon, through forestation. This would appear to be a secure method, since it is how carbon has been extracted from the atmosphere and stored naturally almost since life began. The implications are similar to those for producing high quantities of fuel from biomass, since large extra amounts of woody biomass are required,

Figure 5-16 Global transport fossil energy potential, 50% CTL penetration in diesel fuel in 2050



The alternative to carbon capture and storage is enhancement of natural processes which store carbon, through forestation.

with the associated land and water requirements competing with other uses.

Significant research is continuing in each of these areas, in particular through governmental bodies such as the DTI, the U.S. Department of Energy's National Energy Technology laboratory and international bodies such as the Carbon Sequestration Leadership Forum.

Prudence recommends at this stage not to assume that carbon capture and sequestration will be able to offer a substantial long term solution to global carbon emissions, but it may prove to be viable local option for CTL plants with appropriate geological surroundings. If proven technically and economically viable, it is likely to be one of a combination of upstream and downstream technologies to reduce CO_2 emissions.

Energy potential

Results for CTL have been calculated assuming that the stated advances enable a 50% penetration of CTL in diesel fuel by 2050, assuming 50% global diesel passenger vehicle penetration and 60% total energy efficiency of the CTL production process.

A significant reduction in global petroleum energy consumption, and therefore petroleum consumption, is achieved with this scenario (approximately 33% reduction in 2050). However, the fossil energy is also substantially increased compared to the business as usual case, resulting in significant increases in GHG emissions.

BTL for all fuel types with high yield

BTL fuel possesses the same properties as CTL and GTL and also, therefore, many of the same barriers to mainstream market entry. Its particular advantage is the lack of fossil fuel consumption and the associated near zero well-to-wheel CO_2 emissions. The potential global production capacity may be limited by the amount of biomass that can be grown for this purpose, and land and water availability in particular when competing with food production for a growing global population

At the same time it is necessary to consider ethanol made from cellulose, which is currently under investigation by governments and companies. Most of the same barriers to entry exist as for BTL. The main difference is that BTL can be considered a fungible fuel, whereas with known technology, ethanol requires separate automotive technology and infrastructure. Analysis will be provided below for BTL fuel and brief comparisons will be made for cellulosic ethanol as appropriate.

Efficiency of BTL process

The energy efficiency of the BTL production process is similar to that of CTL (around 50%). Again, if the efficiency of the process can be improved and a facility can be constructed to take advantage of the waste heat from

Table 5-8 Potential technical fuel yield from biomass assuming all biomass for transport
Source: IFEU

Country / region	Data source	Biomass potential as proportion of road fuel
U.K.	Sustainable Development Commission	10% in 2010, 20% in 2020
Global	EUCAR	40% potential
Global	Dreier (2000)	300% potential
Germany	IFEU (2004), DLR(2004), Thraen (2004)	Maximum 15-20% in 2050
EU	CONCAWE 2002	Maximum 15%

gasification, the process efficiency can be increased, but not sufficiently to compete on this measure with conventional fuels. The potential efficiency has been indicated above in the CTL discussion.

Biomass yield

The potential biomass fuel production capacity has been estimated by a number of studies (see Table 5-8 for examples).

The study by Dreier has projected a 300% potential for road fuel from biomass sources, which is clearly an outlier in comparison to the other estimates. It is retained here in order to demonstrate that the outcome of such estimates depends strongly on the assumptions made. Since we are performing a breakthrough analysis, the Drier estimate may indicate a future direction if technology allows those extreme assumptions to be realised.

Ideally, associated with improved fuel production efficiency would be an increased yield of BTL fuel per hectare of farmed biomass. In addition, advances in farming techniques and particularly in genetically modified organisms may increase the yield potential significantly. For example, the world grain yield per hectare increased by a factor of 2.6 between 1950 and 2000 (USDA). As a further example, the yield per hectare of corn, an energy crop itself, increased in the U.S. by 34% between 1990 and 2004 (UN FAO), representing a similar growth rate to the USDA data. If the yields achieved in developed countries can be transferred through modern farming techniques to developing countries and if the historical yield trends continue, there is increased potential for future global energy crop capacity to approach some of the higher estimates of biomass potential (around 40%).

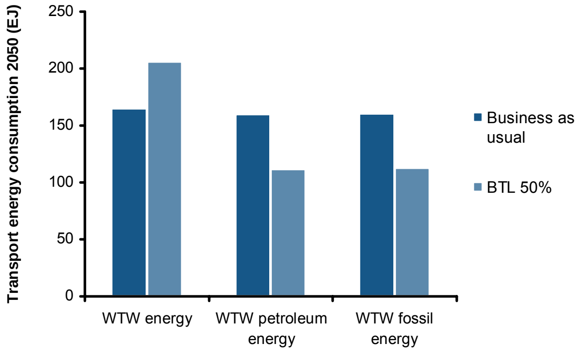
There are two technical limits to be considered in this case. The first relates to the water content of biomass. A massive increase in biomass farming would require availability of correspondingly large amounts of water, which comprises a substantial proportion of woody biomass. The second refers to the opportunity cost of producing fuel. Even with the most efficient plant, BTL production may be no more energy efficient than electricity generation from biomass co-firing and therefore direct electricity generation may be considered the more desirable long-term policy option. A rational assessment is to be made in each case to determine the most effective use of the biomass resources.

The viability of BTL therefore depends in part on the policy objectives. As an automotive fuel it can contribute to reduction in petroleum consumption and imports, which is of greater importance in some countries than reduction in greenhouse gas emissions and which cannot be achieved by using the same biomass resources for electricity generation.

Energy potential:

The energy potential for BTL has been calculated assuming 50% global penetration of BTL in diesel fuel, 50% diesel passenger vehicle penetration in 2050 and a total BTL plant

Figure 5-17 Global transport fossil energy potential, 50% BTL penetration in diesel fuel in 2050



efficiency of 60% (c.f. 50% in Chapter 3 analysis).

The 31.2% reduction in fossil energy demonstrates the high potential of BTL fuel at high penetration rates to achieve the stated objectives of the study.

Further advanced biofuels options

A diesel fuel similar in characteristics to BTL is hydro-treated vegetable oil. This fuel can be produced from oil plants and, potentially, from other forms of biomass, including agricultural waste and algae. This is a potential complement to BTL and its success will depend on its production investment requirements (projected to be lower than BTL) and its yield potential. Assuming a high yield from non-food crops this fuel has significant potential and offers the vehicle compatibility advantages of BTL.

Cellulosic ethanol has already been discussed and the results and conclusions for BTL can mostly be transferred to ethanol, due to the common characteristics of the Fischer-Tropsch and cellulosic processes, which are:

- Many sources are possible for each – wood, grass, stalks etc.
- Similar energy input to fuel content ratio - approximately 2 to 1.

It is therefore appropriate to consider cellulosic ethanol and BTL fuels as equivalents in terms of their energy balance. However, the disadvantages of ethanol are also to be taken into consideration:

A diesel fuel similar in characteristics to BTL is hydro-treated vegetable oil.

- Lower energy content than gasoline by over 30% - the potential efficiency gains through ethanol's higher octane rating may, in the future, partially compensate (BTL has about 7% lower energy content than petro-diesel).
- Vehicle adaptation required for compatibility.

Of these factors, the lower energy content presents a permanent disadvantage to drivers. Even if the per-gallon price of ethanol fuel is sufficiently lower than that of gasoline to take account of the energy content, the convenience factor of lower vehicle range and more frequent fuel stops is a potential dampener on demand and acceptability.

The second factor of vehicle compatibility depends on vehicle technology, which is likely to continue advancing (all new gasoline vehicles in the US are already certified to run on 10% ethanol) and on fuel availability. These are factors which are already under development (ethanol vehicle technology and increased penetration of E85 fuelling stations). It is reasonable to expect that with a significantly increased penetration of ethanol in the gasoline fuel stock, that these challenges will be met through investment and further technical development.

In addition to ethanol, some recent attention has been given to bio-butanol due to a new commitment by BP and DuPont in the UK to construct substantial production capacity for this

Table 5-9 Summary of breakthrough technologies discussion

Technology	Summary of potential
Fuel cell high penetration	• Fuel cell stack has potential for market-enabling breakthrough before 2050 • Storage technology has potential for market-enabling breakthrough before 2050 • Barriers to hydrogen distribution and infrastructure are high, require significant breakthrough
Electric drive high penetration	• Battery technology has potential for market-enabling breakthrough by 2050 • Convenient public refuelling requires significant advances in high power quick recharge technology
Plug-in hybrid electric vehicles	• Convenience factor of ICE is major advantage. • Cost of two full power-trains may be prohibitive.
CTL high efficiency & penetration	• Efficiency of CTL process can be improved • Carbon capture technology requires a major technological breakthrough for high global capacity operation and public acceptance • Well-to-wheel GHG emissions cannot be reduced below that of petroleum fuel • Enables use of high efficiency ICE engines
BTL high yield & penetration / cellulosic ethanol	• Efficiency of BTL process can be improved • High global capacity requires major breakthrough in biomass yield though greater agricultural efficiency • Water availability may limit overall potential • These conclusions apply equally to cellulosic ethanol

fuel. The proposal initially plans fermentation of sugar beet but other feedstocks and eventually cellulosic processes are under consideration. Bio-butanol has the following advantages over ethanol:

- Lower molecular polarity – can be transported by pipeline like regular gasoline.
- Potentially no vehicle modification necessary for high concentrations (to be investigated and confirmed by further testing).
- Lower RVP when blended with gasoline, leading to lower permeation.
- Higher energy content (about 5% lower than gasoline).
- This technology is in its very early stages of development and its potential advantages are still to be realised. A policy framework which rewards performance would be the appropriate one to ensure that the successful development of this or other technologies leads to market success.

Breakthrough technologies and analysis results

Table 5-9 summarises the results of the discussion above for the four technologies.

A preliminary assessment can be made on the basis of the results above. All of the technologies evaluated demonstrate significant potential in energy and CO_2 reduction and at this stage selecting or ranking the technology is inappropriate due to the low development maturity level of the technologies in question. However, the following general conclusions can be made, referring to the four technologies in turn:

- Continuous improvements in fuel cell technology hold promise, but in addition to technical advances, a rational assessment of the long term infrastructure requirements is essential.
- Improvements in automotive battery technology are to be complemented by a consideration of future high power refuelling requirements.

- A significant breakthrough in carbon capture technology is necessary for CTL fuel to demonstrate an acceptable GHG balance.
- The significant future potential of second generation biofuels (e.g. BTL, ethanol from cellulose) is strongly dependent on increased biomass yields and availability of water.

Until research activities result in sufficiently concrete information to assess the relative potential of these technologies and enable concentration of resources on the most promising, it is recommended to continue research on each. Regular periodic review with comparisons to the energy goals is necessary for effective assessment and eventual concentration.

6. Discussion of results: technology and policy implications

In order to reach valid final conclusions as a basis for viable recommendations, it is necessary first to remind ourselves of the underlying policy objective of this study. The primary objective is to reduce reliance on fossil hydrocarbon sources, with the associated objectives of reducing petroleum consumption and greenhouse gas emissions, whilst ensuring the 3 A's criteria are met in OECD and developing regions of the world.

To meet the stated objective, the results of this study are to be assessed thus:

- Which technologies / measures have the greatest energy reduction potential?
- What are the remaining barriers to high penetration?
- What policies are required to enable the technologies the reach the stated energy objectives?

By combining the answers to these three questions, the most effective and efficient measures to achieve the energy objective can be determined.

Technology results

Table 6-1 summarises the theoretical fossil energy reduction potential ratio of the technologies studied with a optimistic but conceivable global penetration rate.

The largest fossil energy reduction potential clearly lies with synthetic fuels such as BTL or cellulosic ethanol becoming mainstream and gaining a very high penetration in automotive applications. To reach this mainstream, and stand any chance of reaching the required penetration in developing countries as well as rich countries, the costs in comparison to petroleum fuels must be modest.

Technologies which improve the efficiency of conventional engines, including diesel and hybrid electric for passenger cars and diesel advancements for heavy duty engines may pay for themselves under reasonable assumptions of gasoline prices. The aggregate energy potential of these technologies is relatively modest.

Advanced powertrain concepts, including fuel cell and battery electric vehicles are projected to be expensive still in 2050 and rely on significant advancements to break through to cost competitiveness, even assuming sufficient performance for customer satisfaction. If these breakthroughs arise, the energy potential is significant due to the enabled migration from petroleum fuels. The fossil energy potential indicated above is dependent on availability of clean energy for production of hydrogen or electricity

Conditions for long term success

For any energy saving fuel or automotive technology to reach the mainstream and achieve a high penetration, it must be cost competitive in the long term. There are two main conditions to be met to achieve this status:

Table 6-1 Theoretical fossil energy reduction potential ratio

Technology (@ global penetration)	2050 fossil energy change 2050 vs. business as usual		Main barriers to high penetration
	Absolute	Percentage	
BTL 50%	-36.0 EJ	-22.4%	Total yield, variable cost, initial investment
Cellulosic ethanol (CellEtOH) 50%	-34.7 EJ	-21.6%	Total yield, initial investment, vehicle range, vehicle compatibility
Diesel 50%	-4.1 EJ	-2.5%	Variable cost
Hybrid 50%	-8.1 EJ	-5.0%	Variable cost
F.C.V. 50% on the road	-19.0 EJ	-11.7%	Variable cost, vehicle investment, infrastructure investment
B.E.V. 50% on the road	-20.27 EJ	-12.5%	Variable cost, vehicle investment, vehicle range, infrastructure investment
P.H.E.V. 50% on the road	-7.0 EJ	-10.8%	Variable cost, vehicle investment
CTL 50%	-39.2 EJ	-24.5%	CO_2, investment

1. Volumes must be high to achieve economies of scale, therefore entry barriers must be overcome.
2. The long term consumer cost potential of the technology is competitive with that of petroleum fuels. This depends on the uncertain long term price of crude oil and on the extent of long term government intervention (e.g. carbon taxes or cap and trade schemes).

The first condition is very much dependent on the second, in that the necessary investment for high production volumes is are only likely if a technology has potential to make an economic business case. To determine the potential for a technology, it is therefore necessary to concentrate on the long term economic viability.

Consider the example of BTL or Cell-EtOH fuel. At the massive volumes of fuel necessary to meet even 25% of global fuel needs in 2050, amounting to about five billion barrels of oil equivalent per year, government support through tax breaks or incentives is only viable if the financial sums per unit volume are fiscally manageable. That is, a long term highly unprofitable technology is unviable for both commerce and government. BTL and ethanol must, therefore, at least approach cost competitiveness with petroleum, thus depending on the two primary cost factors: the cost of the technology including investment and the price of oil.

The cost estimate for biofuels in Chapter 3, compared to petroleum fuel costs confirms the uncertainty in predicting the economic viability of such fuels. This creates a dilemma for potential investors in, for example, synthetic fuel technology, who would, in effect, be making a bet on the price of crude oil. This therefore dampens the drive to invest in research and production facilities and slows down the ramp up in volume.

The policy conditions to reach a long-term high volume must, therefore, support the growth of the new technology by helping to overcome initial barriers of technology and investment and then in the long term must help ensure economic viability of the product as a commodity.

This principle can similarly be applied to all technologies.

An integrated approach to reducing consumption

The identification of potential technologies is an informative exercise which can support the development of policy. However, it has been determined that a policy which picks the “correct” technologies is unlikely to be effective. The marketplace is where the most effective

Policy conditions must support the growth of new technology by helping to overcome initial barriers.

It is important to recognise the many contributors to energy consumption in transport.

technologies will be “picked”. From the availability of different measures and technologies (levers), it is important to recognise the many contributors to energy consumption in transport and to direct policy which enables these measures. This recognition is termed an “integrated approach”, which has become a widely used concept in EU policymaking in many fields, especially energy related. The levers and contributors in an integrated approach for reducing transport energy consumption are:

1. Vehicle Efficiency – Manufacturers
2. Fuel energy intensity - Fuel suppliers
3. Efficiency of components - Component suppliers (e.g. air conditioning)
4. Mode selection - Consumers
5. Vehicle purchase - Consumers
6. Travel demand - Consumers
7. Travel efficiency - Consumers & service providers
8. Driving style - Drivers (private or public)
9. Maintenance - Drivers
10. Transport infrastructure - Governments

In this study we have concentrated mainly on measures 1 & 2, the technical options as well as to a certain extent the behavioural ones. Both vehicle efficiency and fuel intensity can be improved by technical measures. Travel demand and mode selection have been shown to have significant potential, with associated social implications. The personal behaviour of private drivers, in particular in selecting how heavily (and therefore efficiently) to load their vehicles and in managing their driving style can be equally effective.

For drivers of cars with manual transmissions (and to a lesser extent automatic), the employment of an efficient driving style can improve fuel consumption by up to 25% (for example the Eco-Driving programme in the EU). This involves such behaviour as shifting gear at lower engine speeds, switching off at traffic lights and braking early when stopping.

Setting up adequate infrastructure, whether public transport or an efficient road system, is essential in both ensuring mobility as well as reducing congestion and therefore consumption.

Taking account of the comprehensive approach to reducing consumption, policy must consider these principles:

1. Supporting or enabling improvement in each of the identified areas.
2. If regulation is employed, recognising all elements of an integrated approach within regulatory measures – technology, behavioural and infrastructure elements.
3. Most importantly, ensuring that all actors are appropriately incentivised to reduce consumption, ideally through measures which allow the market to determine the solutions through financial forces.

Don't try to pick winners.

Principles and framework of policy elements

Initially two assumptions are necessary in considering how to form policy elements for encouraging appropriate technology and other measures identified in the integrated approach:

- Long-term cost competitiveness, implying that in the long term the technology or measure can compete on equal terms with conventional alternatives, therefore that the long-term level of incentive is zero or manageably low.
- The government has specific and consistent energy objectives.

Any financial elements of policy must incentivise all the appropriate elements of the integrated approach equally. While the cost of technology and other measures could be assumed in a first order assessment to be constant worldwide, the term "cost competitiveness" is strongly dependent on regional factors such as energy pricing (including taxation) and other local charges related to the vehicle operation like road tax or registration fees for new vehicles. As an example, a new technology such as hybrid electric could enter regions with high fuel prices (e.g. Europe) even at high additional cost but would have less chance in countries with low fuel prices (e.g. oil producing countries, see Chapter 3 for details). If governmental energy policies are aiming to incentivise efficient technologies, the framework should be long term, in order to provide as much certainty as possible for investors and other stakeholders.

Based on a sound long-term energy strategy, the underlying principles which policymakers should consider are the following:

- The market is the best determiner of successful products
- Incentivise the desired performance factors
- Don't try to pick winners
- Ensure a long-term framework

With a consistent and well defined objective, for example the reduction of fossil energy consumption, policy can be geared specifically to incentivising that objective directly. A well established measure of the performance of technologies in reducing fossil energy is necessary and incentives are then allocated proportionately according to that measure. Since most new technologies have short-term barriers to entry and longer-term incremental costs, the incentives would ideally address both factors.

Let us assume that the policy objective is to reduce consumption of fossil fuels (alternatively this could be petroleum fuels or CO_2 emissions). The most effective government incentive would create a direct proportional financial benefit for the actual reduction in well-to-wheel fossil energy achieved by implementing any fuel or automotive technology. This can be achieved through a tax incentive (or direct subsidy) which therefore assigns a direct price on the well-to-wheel consumption of energy. Disincentives through taxation on the conventional technologies or fuels are equally valid.

Indeed the disincentive method is in operation in Europe, which has historically imposed high taxes on petroleum fuels and reduced the level of those taxes for biofuels. This is in comparison to the United States, in which fuel taxes continue to be low and direct tax incentives on biofuels are in place. In either case, the incentives for biofuels represent a reduction in government income.

The precise form of incentive is up to individual governments, but the rate of the incentive (e.g. in $ per barrel of petroleum saved) must be set appropriately to ensure the technology penetration desired – in effect to make the private production and consumption of the technology sufficiently attractive to reach that penetration level.

This implies that flexibility in the system of incentives and other policy measures is necessary to allow for fluctuations in the underlying parameters, especially the price of crude oil. That is, if the price of crude oil drops, the incentive for low fossil-fuel energy would have to increase to compensate. Such variable incentives would certainly be politically difficult to implement and potentially create a moral hazard – i.e. governments would be shielding their citizens from fluctuations in the price of oil if incentives on the alternatives were to move in tandem with it. In any case, such flexibility would be difficult to “lock in”, because successive governments can easily change priorities and modify objectives.

These are problems that individual governments would have to deal with depending on the circumstances arising in the markets for oil and alternative technologies. The key to long-term focus on the appropriate objectives and measures is to set up a policy framework, which should include the following:

- A statement of the overall objective (e.g. reduction in fossil energy consumption by transport compared to baseline).
- A quantifiable target for this objective (e.g. 25% reduction by 2050).
- The intention to employ direct, proportional, technology neutral incentives as the tool with which to meet the objective.

This framework locks in policymaking decisions onto the end point. The most effective framework to reach the end point, without prescribing specific technological measures, can only be efficiently identified by the commercial activities of those parties involved in energy production and consumption.

Setting up such a framework represents a significant commitment by governments in terms of long-term policymaking and also financially. As the penetration of energy reducing technologies increases, government incentives should decrease and eventually be phased out to maintain the financial commitment within reasonable bounds. For there to be a successful achievement of the energy objective, the final stage of the technology penetration with high volumes must be self sustaining economically. To determine the conditions surrounding this final stage, an honest and comprehensive study of the technologies and their potential costs is necessary. If, by this assessment, it is determined that the potentially available technologies will not provide a sustainable long-term solution for the stated energy objective, under the projected cost conditions, further steps are necessary.

This means either reducing the energy objective to a viable level according to the analysis or, if the energy objective is considered indispensable, accepting the need for a more onerous financial burden on taxpayers and consumers. An honest assessment in this case is necessary, but it is clear that political considerations are likely to prove difficult to overcome if the conclusion is unpalatable.

Both carbon taxes and cap and trade schemes have been put forward seriously by government agencies as a solution for reducing GHGs and could equally be used to achieve related energy goals (e.g. petroleum or fossil fuel reduction, renewable energy targets). Without concluding which of these is the most effective, if implemented properly each meets the conditions required to incentivise effectively the desired energy end point as described above.

Finally, it must be accepted that a certain element of chance and the possibility of failure to meet the objectives remains, should circumstances of fundamental physics, technology potential, economic status and the price of conventional energy not support the commercial development of the appropriate technologies.

Types of government intervention

Intervention can be financial or regulatory and can relate to support for infrastructure development or directly affect the market for products. Market incentives, start-up incentives and mandates are specifically addressed here.

Proportional incentives

Since the “material” of concern in energy consumption is the fuel, the primary application of any incentive should be on the fuel itself. A per-gallon, or more flexibly a per MJ incentive, either to consumers or to producers on alternative fuels, being a proportional function of the well-to-wheel energy reduction in comparison to the equivalent petroleum fuel, would present a direct incentive. Such questions are currently being dealt with in policy discussions in the European Union (Fuel Quality Directive), and the US (Low Carbon Fuel Standard by the Federal Government and California).

It is also valid to provide incentives for automotive technologies that provide energy benefits, such as diesel, hybrid electric and fuel cell vehicles, as currently in place in the U.S.

Table 6-2 Types of incentives

Technology	Incentivise	Ideal incentive method	Current example
Diesel & hybrid electric vehicles	Estimated lifetime petroleum saving vs. equivalent gasoline vehicle	Consumer tax credit until technology reaches significant penetration (e.g. 10%)	U.S.: Advanced technology tax credits
H_2 fuel cell vehicle	Estimated lifetime petroleum saving vs. equivalent gasoline vehicle, depending on expected hydrogen production method and energy mix	Consumer tax credit until technology reaches significant penetration (e.g. 10%)	U.S.: Advanced technology tax credits
BTL	Fossil energy or full-cycle CO_2 savings vs. conventional diesel fuel	Per gallon producer tax credit until fuel reaches significant penetration	U.S.: total $1 / gallon credit for biodiesel. Germany: reduced fuel tax for biofuels

This does not apply to those conventional vehicles, which can accept the use of alternative fuels without modification, since the incentive should be provided through the incentivised fuel. However if cost-inducing vehicle modification is required, as in the case of flexible fuel vehicles which can run on 85% ethanol (E85) or 20% biodiesel (B20), incentives are appropriate in order to overcome the technology barrier and achieve higher penetration.

A simpler yet less effective alternative to this method, is to provide fixed incentives for targeted products, for example the per-gallon producer tax credits available for ethanol and biodiesel in the U.S. Though less effective than the above framework and also subject to greater uncertainty due to the lack of a formal long-term principle of energy reduction, such incentives can perform the task of encouraging production. This method is not a recommendation of this report, but is acknowledged as a valid option, examples of which are in place in many countries.

Table 6-2 demonstrates the types of incentives that can be considered, with existing examples noted.

In the above examples, the level of the incentive should be sufficient to provide an encouragement for the uptake of new and unfamiliar technology.

Breaking technology barriers

Direct per-unit performance-based incentives can be effective in encouraging effective technologies, but for certain technologies, large initial investment may be a significant barrier to entry. In this case, further methods of technology support can be considered.

In particular, governments regularly provide grants for investment in research and development or production facilities to assist in surmounting initial barriers to entry. Examples are the Biorefinery Demonstration Programme of the U.S. Department of Energy (DOE), which provides grants of the order of $60m to assist in building biofuel production plants in the U.S. Such grants will prove effective if their success criteria are structured appropriately to support the governments' energy objectives. The following conditions are suggested:

- An open, competitive application process.
- A transparent measurement method for the performance end result technology.
- A selection method which prioritises those technologies with the optimum combination of projected total energy reduction potential and projected benefit / cost ratio.

Indeed, the DOE grant programme is based on similar guidelines. Necessarily, due to the untested nature of the new technologies, technical and economic viability will not yet have been measured in the commercial realm and the assessment therefore relies on projections and good judgement. To the extent that these are forthcoming, such support should have the effect of helping to kick-start effective new

A well structured program of support can help ensure that the appropriate technologies are available when the market demands them.

technologies. This can be at any stage in the value-chain process, from basic research through product development, construction of production facilities and bringing to market, wherever the greatest leverage of economic support can be achieved. For an effective long term strategy, such support should nevertheless remain subordinate to long term production incentives.

Many governments run their own research programmes, often in conjunction with companies and educational institutions. As they are, to a certain extent, shielded from the market, governments have the opportunity to undertake and promote research into innovative technologies, with the hope of discovering valuable breakthroughs. It is valid for a proportion of resources to be set aside for this objective. Government research programmes which are geared towards shorter-term commercialisation should be held to standards and assessments similar to those stated above for issuing grants for technology demonstration and development. This means assessing programmes on their potential to achieve the governments' documented energy objectives, considering both cost effectiveness and absolute energy potential.

It is to be acknowledged, that such support for future technologies is to a certain extent an exercise in "picking winners". However, in this case, the leverage provided by funds for research and bringing technologies to market is applied to enable the market to arise. It assists in overcoming the "pain" that can be caused when market price signals change but the technology is not available simply due to the time requirements of the innovation and commercialisation process. A well structured programme of support can help ensure that the appropriate technologies are available when the market demands them, with the associated risk of imperfect assessment directing support ineffectively.

Technology mandates

Moves towards prescriptive governmental regulations are common in many countries, in particular in the automotive sector. These may include mandatory fuel economy targets, minimum sales proportions of certain vehicle technologies and alternative fuel production mandates. Whilst provisions which mandate certain technologies often have popular and political support, they are in most cases not be the most effective method to meet energy consumption objectives. There is a clear reason for this: picking specific technologies by regulation runs the risk of picking the wrong technologies, thereby not reaching the objective in the most efficient manner and potentially causing economic hardship for companies and consumers. Neither politicians, bureaucrats, specialist consultants nor even industry experts have sufficient knowledge and predictive skills to make accurate decisions on future technologies.

This method also neglects the integrated approach and therefore disregards the many measures other than technology and the many other actors which are important factors in energy consumption.

To be effective, government regulations should set reasonable performance standards, which are to be met through application of the technical expertise of companies. For this reason, mandates of automotive and fuels technologies are not recommended.

Conclusion

The following summary and conclusions are to be drawn from the technology and policy analysis:

- Diesel and hybrid electric vehicles present a cost effective short-, medium- and long-term method to increase mobility energy efficiency and reduce total mobility energy consumption.
- Fuel cell and battery electric vehicles have high total energy potential and but are expected to be less cost effective than more conventional technologies, even by 2050. Further research towards breakthroughs in technology and cost are necessary for high penetration.
- BTL and Cellulosic Ethanol fuels present significant fossil and petroleum energy savings potential. Their long term cost effectiveness and therefore market penetration depends on production costs and the price of oil. The price of oil must be considered as an unknown variable and government policy will need to be flexible to take account of future market developments.
- CTL fuel presents significant petroleum reduction potential but increases CO_2 emissions. If it is determined that reducing fossil fuel consumption is the greater priority, CTL can represent an appropriate alternative fuel for transportation.
- The ideal form of government intervention is one which ensures an economic incentive for energy saving technologies and measures to be implemented. The energy policy objective must be established and interventions should seek proportionally to incentivise achievement of that objective.
- Production incentives through, for example, taxation must be technically neutral and applied proportionally to the energy performance of the fuel or technology in question.
- Investment support to assist in bringing technologies to market is appropriate if supported by an objective assessment which ensures that the support provides maximum leverage to long-term achievement of energy policy objectives.

7. Regional conclusions

The regional analysis will be performed on the basis of the three groupings discussed in Chapter 1, OECD, non-OECD and potential developed regions.

OECD

The conclusions in the previous chapter can be considered valid for OECD countries. Through their wealth, governments of these regions have the means to invest public money in encouraging technologies which reduce energy consumption, even if these technologies are not commercially viable.

It is worthwhile to consider a numerical example based on high penetration of second generation biofuels such as BTL or cellulosic ethanol. Assume that the long term potential of these fuels allows 50% market penetration in OECD countries and at this penetration level are a consistent $1 per gallon more expensive than using the equivalent petroleum fuels to 100% penetration.

- Projected OECD fuel consumption in 2050: ***266 bn gall / year***
- cost differential of second gen. biofuel: ***$1 / gall***
- Penetration of second gen. biofuels: ***50%***
- **Economic burden of biofuel: *$133 bn / year***

Derived from the figures in Appendix 5, this would result in a 44% reduction in global fossil transport energy consumption in 2050 (compared to business as usual). The expenditure calculated above is equivalent to about 0.2% of projected OECD GDP (GDP data from Mobility 2030). Governments and citizens of relatively wealthy OECD nations may consider that such an investment is indeed appropriate to achieve the energy result stated.

The above calculation should be considered in the context of a sensitivity analysis, since the production cost of biofuels and especially the price of oil cannot be accurately predicted even for this decade. That is, a $2 cost premium of biofuel would double to economic burden to 0.4% of GDP, etc. It is of course entirely feasible that the biofuel cost be less than the petroleum fuel cost, in which case market demand will drive biofuel production and eliminate the case for government intervention.

In the end, if technology and cost optimisation do not produce a market in which energy reducing measures are sufficiently demanded by the market to achieve reasonable energy objectives, governments must decide whether the necessary investment to promote and sustain those technologies to reach the objectives is appropriate. In wealthy countries, in which citizens increasingly place importance on acceptability, whilst taking accessibility and availability for granted, this may well increasingly become the case over the next 40 - 50 years.

Non-OECD

Even by 2050, non-OECD countries are projected to have significantly lower (less than 25%) national income than the OECD North America region, implying that the scope for absorbing technology costs for energy reduction is likely to be low. As in all cases, future development depends strongly on the price of oil.

The 3 A's analysis performed in Chapter 2 reached the conclusion that in non-OECD countries, conventional technology, meaning gasoline and diesel passenger vehicles and diesel freight trucks, is likely to dominate through at least 2050. Ensuring mobility will mean ensuring the affordability, and therefore accessibility, of conventional vehicles. Availability is likely to be problematic only if government policy creates barriers to entry for vehicles and fuels.

Accessibility of personal transport will be a straightforward function of the cost of fuel, assuming vehicle prices remain consistent. Greater mobility, and therefore the underpinnings of faster economic growth, will be supported by lower fuel prices. Conversely, high fuel prices, whilst encouraging the switch to more efficient forms of fuel and transport, are likely to reduce mobility in non-OECD countries rather than encourage the uptake of more expensive technology.

Vehicle efficiency technology, in particular diesel and to a lesser extent hybrid electric, is likely to achieve a certain penetration if it is cost effective, but again higher fuel prices, and therefore lower breakeven prices for vehicles technology, are more likely to dampen overall demand than encourage efficiency.

Alternative fuels will likewise achieve some penetration dependent on the economic case. In particular, there lies an opportunity for developing countries in this respect if a new global market for energy agriculture develops, in which a level playing field in international trade is developed.

It is unlikely that significant government support can be provided by governments of most non-OECD countries for the consumption of new technologies. However, it is worthwhile for those governments to consider policy measures to encourage and support biofuels production as an potentially lucrative agricultural sector with export potential. This may be most effectively achieved by partnership with OECD nations, multilateral organisations or corporations, which can provide funds and expertise. In oil producing nations this could also offer a buffer against future volatility in the oil market or eventual depletion of oil fields.

Potential developed countries

Potential developed countries have been identified as FSU, Eastern Europe, China, South Africa and parts of Latin America. In each of these regions, the GDP per head is projected to remain less than 50% of the GDP per head in OECD North America until 2040. They will likely

Improvements in global communication could enable a more homogeneous global policy movement on energy.

act as developing countries for many years and as we approach 2050, take on some of the characteristics of developed countries.

Performing the same calculation as in the section above:

- Projected fuel consumption of potential developed countries in 2050: ***176 bn gall /year***
- cost differential of second gen. biofuel: ***$1 / gall*** *(assumed)*
- Penetration of second gen. biofuels: ***50%***
- **Economic burden of biofuel:** ***$88 bn / year***

In this case this represents 0.15% of GDP and brings about a global reduction in fossil energy consumption of, again, around 44%. Again a sensitivity analysis using different assumptions would be necessary to assess the situation fully.

It cannot be confidently predicted whether this level of economic burden, in what are expected still to be rapidly growing regions by 2050, is likely to be more or less acceptable to government and their citizens than in OECD countries. The absolute GDP per head in 2050 in these regions is projected to be similar to the 2005 GDP in OECD regions, so it is reasonable to consider that the potential developed group would react to energy issues in a similar way to today's OECD countries. Since there has so far not been massive government intervention in OECD countries to encourage and subsidise alternative energy sources and energy efficiency, it could be concluded that at this level of GDP per head there is not sufficient "headroom" in average wealth to accommodate it.

However, network effects, due to improvements in global communication, are likely to increase over the next decades to 2050, which could produce a more homogeneous global policy movement on energy. This may encourage those middle income countries to increase their uptake of new technologies above the level that could be expected according to their wealth and even apply a proportion of their wealth to achieving the energy objective of, for example, reducing fossil energy consumption.

To assess the potential for individual technologies, it is reasonable to take an average of the 3 A's results for OECD and non-OECD countries from Chapter 2.

This leads to the following conclusions:

- Conventional vehicles will likely remain dominant, in particular in the poorer parts of these vast and disparate regions.
- Diesel and hybrid electric vehicles will achieve penetration according to their economic payoff, with penetration of diesel potentially approaching that currently in Europe and hybrid electric vehicles achieving a significant niche in appropriate city applications.

- Fuel cell and battery electric vehicles may achieve penetration in the wealthier parts, in which “acceptability” gains greater weight by consumers and governments.
- BTL, GTL, Cellulosic Ethanol and CTL fuels will gain penetration depending on the economic case and the price of petroleum fuel.
- These biofuels present an opportunity as an agricultural export from potential developed countries, particularly if the demand for them in OECD countries increases due to their higher level of acceptability.
- Economic support by governments for technologies may include production incentives, which ideally should be technology neutral and targeted to the energy reduction objective (c.f. Chapter 6). Support for initial investment may be limited to supporting or directly investing in production facilities, in particular for alternative fuels, which may present a lucrative export business for those countries with substantial agricultural land or other relevant resources.

8. Overall policy conclusions

In order to summarise the main policy conclusions of this study, it is productive to state the principles for decision making which support effective policy in the transport energy sector.

- The first pillar for policy is the energy objective, which must be described in terms of the type of energy to be saved (total energy, fossil energy, petroleum energy, GHG emissions), the numerical target or target range and the timeframe.
- Policy should be based on an integrated approach, which considers transportation technology alongside contributions from other actors in the energy chain, including fuels, consumers and governments.
- Technologies are an important basis for policymaking, since they demonstrate the potential for energy savings and the options for mobility. Technologies must be objectively assessed according to their performance in achieving the policy objective.
- Government intervention should be as far as possible limited to ensuring that a productive market for technologies and transportation is in place. Regulation should be minimal and support common standards. Technology mandates are inappropriate policy tools.
- Governments can provide funds through the tax system or other economic incentives to gear the market towards achieving the energy objective and towards overcoming obstacles to technologies and measures with the potential for market success.
- The most productive form of incentive is that which rewards the purchase of products proportional to their contribution to achieving the energy objective. Examples are reductions in tax rates for fuels proportional to their well-to-wheel fossil energy or GHG emissions savings and reduced taxes for vehicles according to their specific fuel consumption. This form of incentive supports a functioning market whilst gearing the market towards the energy policy objective. Standardised values for well-to-wheel performance are necessary to support such a system.
- Additionally, government support to bring technologies to market is appropriate, in order to overcome initial obstacles. Direct funding can be provided to leverage value-creation at the most beneficial point, whether in research, development, production or marketing. Assessment of technologies must be objective and

Technology mandates are inappropriate policy tools.

candidates for support should be prioritised according to the potential for contributing to energy objectives and the leverage that can be achieved through financial support.

- In addition, it is the responsibility of governments to provide appropriate infrastructure for private and public transport, with the objectives of ensuring mobility and reducing energy consumption.
- All these elements and actors work in combination, encompassing transportation and fuel technology, consumer behaviour, infrastructure and policies. Government policies must ensure a thriving market-based system which incorporates all these actors, thereby giving rise to the ultimate integrated approach.

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Appendix 2: 3 A's Analysis Voting Tables

Accessibility, Avalability and Acceptability for 2020

	LDV Accessibility addressing the needs of the poor "affordable & reliable"		LDV Availability quality & reliability of service diversified energy portfolio		LDV Acceptability local pollution global climate change	
	OECD	Dev. Countries	OECD	Dev. Countries	OECD	Dev. Countries
Fuels						
Gasoline	5	4.4	4.6	3.2	2.8	2.4
Ethanol blend (L) gasoline	3.6	2.8	2.6	2.4	3.2	3.2
Ethanol (>E85)	1.4	1.2	3	2	4.2	4.4
Diesel fuel	4.6	4.4	4.2	4	2.8	2.8
Diesel blend (L)	1.8	1.2	2.6	2.4	3.2	3.2
biodiesel (FAME)	1.2	1.2	2.6	1.8	4.2	4.2
BTL	1	0.2	1.8	1.4	4.2	4
GTL	1	0.8	1.2	1.4	2.6	2.4
CTL	0.8	0.8	1.6	1.8	1	1.2
CNG/ LPG	2.2	1.6	2	1.4	2.8	3.2
Methanol	0	0.8	0.6	1	1.4	1.6
Fossile H_2	0	0	0.8	0.4	2.6	2.6
Renewable H_2	0	0	0.4	0.4	4.6	4.6
Electricity (mix)	3.2	1.8	1.8	1	3	2.4
Vehicles						
PISI	4.8	4.6	5	4.8	2.6	3.4
DISI	3.4	1.6	4.6	2.8	3.4	3
DICI	4.4	3.6	5	4.4	3	3.4
PISI-HEV	3.4	1.6	5	2.8	4	4
DISI-HEV	1.8	0.8	3.8	1.6	3.2	2.8
DICI-HEV	2	0.6	4.6	1.6	4	4
FC	0.5	0	3	0.8	4	3.6
FC-HEV	0.5	0	3	0.8	4.4	4
BEV	1	0	1.8	0.8	4.4	4.4

Accessibility, Avalability and Acceptability for 2035

	LDV Accessibility addressing the needs of the poor "affordable & reliable"		LDV Availability quality & reliability of service diversified energy portfolio		LDV Acceptability local pollution global climate change	
	OECD	Dev. Countries	OECD	Dev. Countries	OECD	Dev. Countries
Fuels						
Gasoline	4.4	4.6	4.2	3.4	2.2	2.2
Ethanol blend (L) gasoline	4.6	3	4	3.2	2.6	2.6
Ethanol (>E85)	2.8	2.2	3.6	3.6	4	4
Diesel fuel	4.6	4.6	4.6	4.2	2.2	2.2
Diesel blend (L)	3	2.6	3.4	2.8	2.6	2.6
biodiesel (FAME)	1.4	1.4	2.6	2.2	3.6	3.6
BTL	2.2	1.4	3.2	2.4	4.4	4.4
GTL	2.2	1.8	2.4	1.8	2.6	2.2
CTL	1.4	1.6	2	2.2	1.2	1.2
CNG/ LPG	2.2	2	2	2	2.6	2.6
Methanol	0	0.8	0.6	1	0.6	0.8
Fossile H_2	0.8	0	1.4	0.4	2	2
Renewable H_2	0.6	0	1	0.4	4.4	4.4
Electricity (mix)	3.6	2.6	2.2	1.4	3.8	3.4
Vehicles						
PISI	4.6	4.8	3.4	4.2	3.2	3.2
DISI	4.4	3.2	4.2	3	3.2	3.2
DICI	4	4.2	4.6	4.2	3.2	3.2
PISI-HEV	4	2.2	5	3.4	4.2	4.2
DISI-HEV	2.8	1.4	3.8	1.8	3	2.6
DICI-HEV	3	1.2	5	2.2	4.6	4.6
FC	1.6	0.2	3.4	1	4.4	4
FC-HEV	1.6	0.6	3.4	1.4	4.8	4.4
BEV	1.6	1	3.4	2.2	5	4.6

Accessibility, Avalability and Acceptability for 2050

	LDV Accessibility addressing the needs of the poor "affordable & reliable"		LDV Availability quality & reliability of service diversified energy portfolio		LDV Acceptability local pollution global climate change	
	OECD	Dev. Countries	OECD	Dev. Countries	OECD	Dev. Countries
Fuels						
Gasoline	2.8	2.4	3	3	1.4	1.8
Ethanol blend (L) gasoline	3.6	3.2	2.8	2.8	1.8	2.2
Ethanol (>E85)	3.6	2.8	3.6	3.2	4	4
Diesel fuel	2.8	2.8	3.4	3.4	1.8	1.8
Diesel blend (L)	2.2	2.6	2.6	2.6	2.2	2.2
biodiesel (FAME)	2.6	2.6	2.6	2.6	3.2	3.2
BTL	3.8	2.8	4.4	3.6	4.8	4.4
GTL	2.4	2.4	3.8	3.2	2.2	2.2
CTL	2.4	2.2	3	3.2	1.2	1.2
CNG/ LPG	2.8	2.8	2	2	2.2	2.2
Methanol	0	1.4	0.6	1.4	0.6	1
Fossile H_2	2	1.4	2.4	1.2	2.8	2.4
Renewable H_2	3	1.2	2.8	1.6	5	4.6
Electricity (mix)	4.6	3.4	4.2	3	4.6	3.8
Vehicles						
PISI	3.4	4.2	2.6	3	1.6	1.6
DISI	4.2	3.4	3.8	3.8	2.4	2.4
DICI	4	4	3.8	4.6	2.8	2.8
PISI-HEV	4.8	2.8	4.2	3.8	3.8	3.8
DISI-HEV	4	2.6	3.8	2.2	4.2	4.2
DICI-HEV	4.2	2.4	5	2.6	4.2	4.2
FC	3.4	1.2	3.8	1.4	4.6	4.6
FC-HEV	4.2	1.6	3.8	1.8	5	5
BEV	3.8	2	3.8	2.6	5	5

Appendix 3: 3 A's Analysis Integrated Scores

2020 ACCESSABILITY OECD COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	4.2		3.3			
Diesel incl. low blends		3.8		2.5		
Ethanol (E85, >)	2.4		1.9			
biodiesel (FAME)		2.3		1.5		
XTL		2.0		1.4		
CNG/ LPG	3.0		2.4			
H_2	0.0		0.0			0.0
Electricity					1.8	

2020 ACCESSABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	3.3		2.1			
Diesel incl. low blends		3.2		1.3		
Ethanol (E85, >)	1.9		1.2			
biodiesel (FAME)		2.1		0.8		
CNG/ LPG	2.2		1.4			
XTL		1.5		0.6		
H_2	0.0		0.0			0.0
Electricity					0.0	

2020 AVAILABILITY OECD COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	4.2		4.0			
Diesel incl. low blends		4.1		4.0		
Ethanol (E85, >)	3.8		3.6			
biodiesel (FAME)		3.6		3.5		
XTL		2.8		2.7		
CNG/ LPG	3.1		3.0			
H_2	1.7		1.6			1.3
Electricity					1.8	

2020 AVAILABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	3.3		2.5			
Diesel incl. low blends		3.8		2.3		
Ethanol (E85, >)	2.8		2.1			
biodiesel (FAME)		2.8		1.7		
XTL		2.6		1.6		
CNG/ LPG	2.3		1.8			
H_2	1.2		0.9			0.6
Electricity					0.9	

2020 ACCEPTABILITY OECD COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	3.0		3.3			
Diesel incl. low blends		3.0		3.5		
Ethanol (E85, >)	3.5		3.9			
biodiesel (FAME)		3.5		4.1		
XTL		2.8		3.2		
CNG/ LPG	2.9		3.2			
H_2	3.3		3.6			4.0
Electricity					3.6	

2020 ACCEPTABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	3.0		3.1			
Diesel incl. low blends		3.2		3.5		
Ethanol (E85, >)	3.8		3.9			
biodiesel (FAME)		3.8		4.1		
XTL		2.9		3.2		
CNG/ LPG	3.2		3.3			
H_2	3.4		3.5			3.8
Electricity					3.2	

2035 ACCESSABILITY OECD COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	4.5		3.9			
Diesel incl. low blends		3.9		3.4		
Ethanol (E85, >)	3.5		3.1			
biodiesel (FAME)		2.4		2.0		
XTL		2.8		2.4		
CNG/ LPG	3.1		2.7			
H_2	1.8		1.5			1.1
Electricity					2.4	

2035 ACCESSABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	3.9		2.6			
Diesel incl. low blends		3.9		2.1		
Ethanol (E85, >)	3.0		2.0			
biodiesel (FAME)		2.4		1.3		
CNG/ LPG	2.8		1.9			
XTL		2.6		1.4		
H_2	0.0		0.0			0.0
Electricity					1.6	

2035 AVAILABILITY OECD COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	3.9		4.2			
Diesel incl. low blends		4.3		4.5		
Ethanol (E85, >)	3.7		4.0			
biodiesel (FAME)		3.5		3.6		
XTL		3.4		3.6		
CNG/ LPG	2.8		3.0			
H_2	2.1		2.3			2.0
Electricity					2.7	

2035 AVAILABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	3.4		2.9			
Diesel incl. low blends		3.8		2.8		
Ethanol (E85, >)	3.6		3.1			
biodiesel (FAME)		3.0		2.2		
XTL		3.0		2.2		
CNG/ LPG	2.7		2.3			
H_2	1.2		1.0			0.7
Electricity					1.8	

2035 ACCEPTABILITY OECD COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	2.8		2.9			
Diesel incl. low blends		2.8		3.3		
Ethanol (E85, >)	3.6		3.8			
biodiesel (FAME)		3.4		4.1		
XTL		3.0		3.5		
CNG/ LPG	2.9		3.1			
H_2	3.2		3.4			3.9
Electricity					4.4	

2035 ACCEPTABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	2.8		2.9			
Diesel incl. low blends		2.8		3.3		
Ethanol (E85, >)	3.6		3.7			
biodiesel (FAME)		3.4		4.1		
XTL		2.9		3.5		
CNG/ LPG	2.9		3.0			
H_2	3.2		3.3			3.8
Electricity					4.0	

2050 ACCESSABILITY OECD COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	3.5		3.8			
Diesel incl. low blends		3.2		3.2		
Ethanol (E85, >)	3.7		4.0			
biodiesel (FAME)		3.2		3.3		
XTL		3.4		3.5		
CNG/ LPG	3.3		3.5			
H_2	3.1		3.3			3.2
Electricity					4.2	

2050 ACCESSABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	3.3		2.7			
Diesel incl. low blends		3.3		2.5		
Ethanol (E85, >)	3.3		2.7			
biodiesel (FAME)		3.2		2.5		
CNG/ LPG	3.3		2.7			
XTL		3.1		2.4		
H_2	2.2		1.9			1.4
Electricity					2.6	

2050 AVAILABILITY OECD COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	3.0		3.4			
Diesel incl. low blends		3.4		3.9		
Ethanol (E85, >)	3.4		3.8			
biodiesel (FAME)		3.1		3.6		
XTL		3.8		4.3		
CNG/ LPG	2.5		2.8			
H_2	2.9		3.2			3.1
Electricity					4.0	

2050 AVAILABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	3.1		2.9			
Diesel incl. low blends		3.7		2.8		
Ethanol (E85, >)	3.3		3.1			
biodiesel (FAME)		3.5		2.6		
XTL		3.9		2.9		
CNG/ LPG	2.6		2.4			
H_2	2.2		2.0			1.6
Electricity					2.8	

2050 ACCEPTABILITY OECD COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	1.8		2.5			
Diesel incl. low blends		2.4		2.9		
Ethanol (E85, >)	2.8		4.0			
biodiesel (FAME)		3.0		3.7		
XTL		2.8		3.4		
CNG/ LPG	2.1		3.0			
H_2	2.8		3.9			4.4
Electricity					4.8	

2050 ACCEPTABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Gasoline incl. low blends	2.0		2.8			
Diesel incl. low blends		2.4		2.9		
Ethanol (E85, >)	2.8		4.0			
biodiesel (FAME)		3.0		3.7		
XTL		2.7		3.3		
CNG/ LPG	2.1		3.0			
H_2	2.6		3.7			4.2
Electricity					4.4	

Appendix 4: 3 A's analysis results for heavy duty vehicle applications

Heavy duty vehicle technology: Accessibility, Avalability and Acceptability for 2020

	LDV Accessibility addressing the needs of the poor "affordable & reliable"		LDV Availability quality & reliability of service diversified energy portfolio		LDV Acceptability local pollution global climate change	
	OECD	Dev. Countries	OECD	Dev. Countries	OECD	Dev. Countries
Fuels						
Diesel fuel	5	4	5	4	3	3
Diesel blend (L)	4	3	4	3	4	3
biodiesel (FAME)	4	4	4	2	4	4
BTL	4	3	4	4	4	4
GTL	4	2	4	3	4	4
CTL	5	2	4	3	4	3
Vehicles						
DICI	5	5	5	5	4	4
DICI-HEV	3	2	3	2	4	3
PCCI	3	2	4	2	4	3
VVT	5	3	5	4	4	4
WHR-HEV	3	2	3	2	3	3
CVT	5	3	5	3	4	4
Variable Displacement	3	2	3	2	3	3

2020 ACCESSABILITY OECD COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Diesel incl. low blends		4.7		3.5		
biodiesel (FAME)		4.3		3.3		
XTL		4.3		3.3		

2020 ACCESSABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Diesel incl. low blends		4.2		2.8		
biodiesel (FAME)		4.1		2.7		
XTL		3.1		2.0		

2020 AVAILABILITY OECD COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Diesel incl. low blends		4.7		3.7		
biodiesel (FAME)		4.3		3.3		
XTL		4.5		3.5		

2020 AVAILABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Diesel incl. low blends		4.4		2.8		
biodiesel (FAME)		3.4		2.2		
XTL		4.0		2.5		

2020 ACCEPTABILITY OECD COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Diesel incl. low blends		3.6		3.6		
biodiesel (FAME)		3.8		3.8		
XTL		3.7		3.7		

2020 ACCEPTABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Diesel incl. low blends		3.4		3.2		
biodiesel (FAME)		3.7		3.5		
XTL		3.5		3.3		

Heavy duty vehicle technology: Accessibility, Avalability and Acceptability for 2035

	LDV Accessibility addressing the needs of the poor "affordable & reliable"		LDV Availability quality & reliability of service diversified energy portfolio		LDV Acceptability local pollution global climate change	
	OECD	Dev. Countries	OECD	Dev. Countries	OECD	Dev. Countries
Fuels						
Diesel fuel	4	4	5	4	3	3
Diesel blend (L)	4	3	4	3	4	3
biodiesel (FAME)	4	4	4	3	4	4
BTL	4	3	5	4	4	4
GTL	4	2	5	4	4	4
CTL	5	2	5	4	4	3
Vehicles						
DICI	5	5	5	5	4	4
DICI-HEV	3	2	3	2	4	3
PCCI	4	3	4	3	4	3
VVT	5	4	5	5	4	4
WHR-HEV	4	2	4	2	3	3
CVT	5	3	5	3	4	4
Varialbe Displacement	3	3	3	3	3	3

2035 ACCESSABILITY OECD COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Diesel incl. low blends		4.2		3.4		
biodiesel (FAME)		4.5		3.6		
XTL		4.3		3.5		

2035 ACCESSABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Diesel incl. low blends		3.9		2.8		
biodiesel (FAME)		4.1		2.9		
XTL		3.1		2.2		

2035 AVAILABILITY OECD COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Diesel incl. low blends		4.7		3.8		
biodiesel (FAME)		4.7		3.8		
XTL		4.7		3.9		

2035 AVAILABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Diesel incl. low blends		4.4		3.0		
biodiesel (FAME)		3.7		2.5		
XTL		4.2		2.9		

2035 ACCEPTABILITY OECD COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Diesel incl. low blends		3.6		3.6		
biodiesel (FAME)		4.0		4.0		
XTL		3.7		3.7		

2035 ACCEPTABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Diesel incl. low blends		3.4		3.2		
biodiesel (FAME)		3.7		3.5		
XTL		3.5		3.3		

Heavy duty vehicle technology: Accessibility, Avalability and Acceptability for 2050

	LDV Accessibility addressing the needs of the poor "affordable & reliable"		LDV Availability quality & reliability of service diversified energy portfolio		LDV Acceptability local pollution global climate change	
	OECD	Dev. Countries	OECD	Dev. Countries	OECD	Dev. Countries
Fuels						
Diesel fuel	4	4	4	4	3	3
Diesel blend (L)	4	3	4	3	4	3
biodiesel (FAME)	5	4	5	3	4	4
BTL	4	3	5	4	4	4
GTL	4	2	5	4	4	4
CTL	5	2	5	4	4	3
Technologies	1	2	2	2	2	2
DICI	3	3	3	3	3	3
DICI-HEV	4	2	4	2	5	4
PCCI	5	4	5	5	4	4
VVT	4	3	4	3	4	4
WHR-HEV	5	3	5	3	4	4
CVT	4	3	4	3	4	4
Varialbe Displacement	5	3	5	3	4	4

2050 ACCESSABILITY OECD COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Diesel incl. low blends		3.1		3.7		
biodiesel (FAME)		3.4		4.1		
XTL		3.2		3.8		

2050 ACCESSABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Diesel incl. low blends		3.2		2.8		
biodiesel (FAME)		3.5		3.1		
XTL		2.4		2.2		

2050 AVAILABILITY OECD COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Diesel incl. low blends		3.5		3.9		
biodiesel (FAME)		3.7		4.1		
XTL		3.7		4.1		

2050 AVAILABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Diesel incl. low blends		3.3		2.7		
biodiesel (FAME)		3.0		2.4		
XTL		3.2		2.6		

2050 ACCEPTABILITY OECD COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Diesel incl. low blends		3.2		3.9		
biodiesel (FAME)		3.5		4.3		
XTL		3.2		4.0		

2050 ACCEPTABILITY DEVELOPING COUNTRIES

	SI	CI	SI HEV	CI HEV	EV	FCEV
Diesel incl. low blends		3.0		3.6		
biodiesel (FAME)		3.3		4.0		
XTL		3.2		3.8		

Appendix 5:
Assumed relative energy consumption of propulsion methods

Source: WBCSD Mobility 2030

Gasoline Vehicles	1.00
Gasoline Hybrid - Mild	0.83
Gasoline Hybrid - Full	0.70
Diesel	0.82
Diesel Hybrid - Mild	0.76
Diesel Hybrid - Full	0.64
CNG/LPG	1.05
Hydrogen Fuel-cell	0.55
Battery electric vehicle	0.20

Appendix 6: Vehicle Prices

Source: Company price lists

Vehicle	Region	Gasoline version & list price	Technology version& list price	Technology premium
Mercedes-Benz E320CDI	USA	E350 $51 675	E320CDI $52 675	$1 000
VW Passat	EU	1.6 FSI €24 425	1.9 TDI DPF €26 025	€1 600 = $2 000 (2006 exchange rate)
Toyota Camry	USA	SE (Auto) $22 240	Hybrid $25 200	$2 960
Ford Escape	USA	XLT $21 070	Hybrid FWD $25 265	$4 195

Appendix 7: Scenario results

(BAU = Business as usual)

#	Fuel status by 2050	Vehicle: status by 2050	Global WTW mobility energy change (% and absolute)						Global WTW mobility fossil energy change 2050 (% and absolute)					
			Energy change (%)			Energy change (EJ)			Energy change (%)			Energy change (EJ)		
			2020	2035	2050	2020	2035	2050	2020	2035	2050	2020	2035	2050
0	-	BAU	-	-	-	-	-	-	-	-	-	-	-	-
1a	BTL 25%	BAU	4.1%	7.1%	10.1%	+4.5	+9.5	16.8	-4.5%	-7.9%	-11.2%	-4.8	-10.2	-18.0
1b	-	OECD diesel 50%	-0.82%	-1.35%	-1.69%	-0.9	-1.8	-2.8	-0.79%	-1.29%	-1.62%	-0.9	-1.7	-2.6
1c	BTL 25%	OECD diesel 50%	4.1%	7.4%	11.0%	4.5	9.9	18.2	-4.8%	-9.0%	-13.2%	-5.1	-11.7	-21.2
1d	-	Non-OECD diesel 50%*	-0.65%	-1.21%	-2.09%	-0.7	-1.6	-3.5	-0.60%	-0.94%	-1.50%	-0.6	-1.2	-2.4
1e	BTL 25%	Non-OECD diesel 50%*	4.0%	7.2%	10.8%	4.4	9.6	17.8	-4.6%	-8.5%	-13.2%	-4.9	-11.1	-21.2
2a	Cellul 25%	BAU	4.95%	9.00%	13.05%	5.4	12.0	21.6	-4.15%	-7.45%	-10.80%	-4.5	-9.75	-17.3
2b	-	OECD hybrid 50%	-0.76%	-2.00%	-2.64%	-0.8	-2.7	-4.4	-0.77%	-2.01%	-2.66%	-0.8	-2.6	-4.3
2c	Cellul 25%	OECD hybrid 50%	4.15%	6.82%	10.07%	4.6	9.1	16.7	-4.89%	-9.31%	-13.17%	-5.2	-12.1	-21.1
2d	-	Non-OECD hybrid 50%	-0.42%	-1.63%	-3.32%	-0.5	-2.2	-5.5	-0.40%	-1.55%	-3.16%	-0.4	-2.0	-5.1
2e	Cellul 25%	Non-OECD hybrid 50%	4.51%	7.22%	9.30%	4.9	9.7	15.4	-4.53%	-8.88%	-13.62%	-4.8	-11.6	-21.9

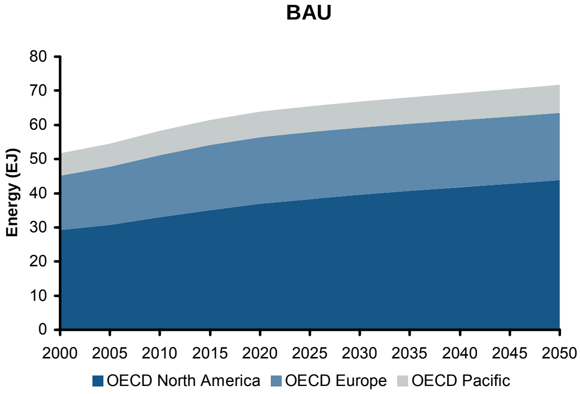
#	Fuel status by 2050	Vehicle: status by 2050	Global WTW mobility energy change (% and absolute)						Global WTW mobility fossil energy change 2050 (% and absolute)					
			Energy change (%)			Energy change (EJ)			Energy change (%)			Energy change (EJ)		
			2020	2035	2050	2020	2035	2050	2020	2035	2050	2020	2035	2050
3	H_2	OECD FCV 25%	+0.2%	+1.2%	+3.6%	+0.2	+1.6	+6.0	-0.2%	-1.2%	-3.8%	-0.2	-1.6	-6.2
3a	OECD pass-km growth -30%		-3.49%	-5.94%	-7.35%	-3.8	-7.9	-12.1	-3.50%	-5.98%	-7.42%	-3.8	-7.8	-11.9
3b	Non-OECD pass-km growth -30%		-1.53%	-4.01%	-7.65%	-1.7	-5.4	-12.6	-1.44%	-3.81%	-7.31%	-1.5	-5.0	-11.7

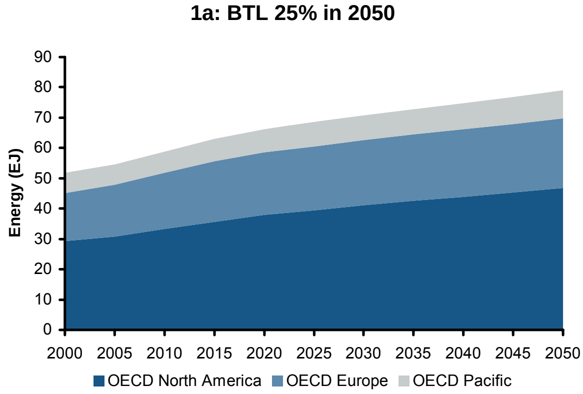
*The following baseline diesel penetrations in 2050 exist in the WBCSD projections:

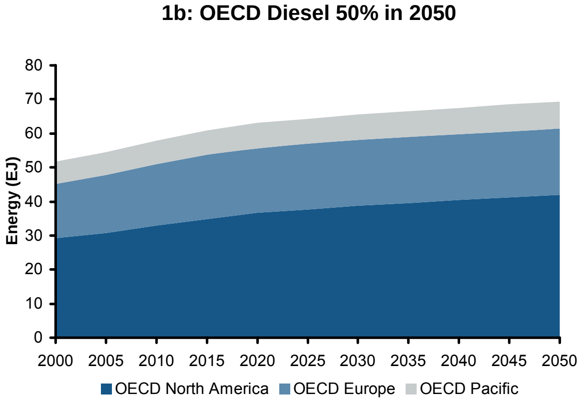
OECD Europe 50%
OECD Pacific 16%
FSU 13% Eastern Europe 50%
China 13%
Other Asia 13%
India 16%
Middle East 13%
Latin America 13%
Africa 13%

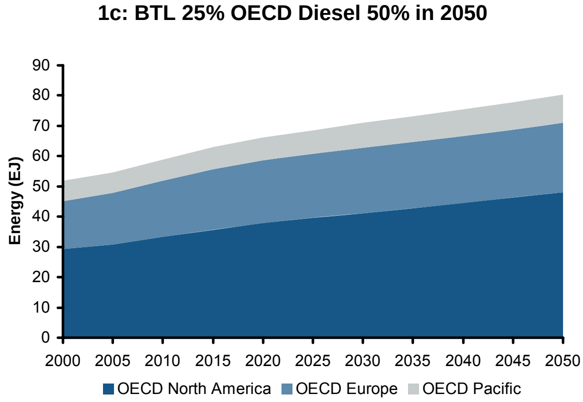
Appendix 8:
Scenario results (Graphs)

Well-to-wheel energy



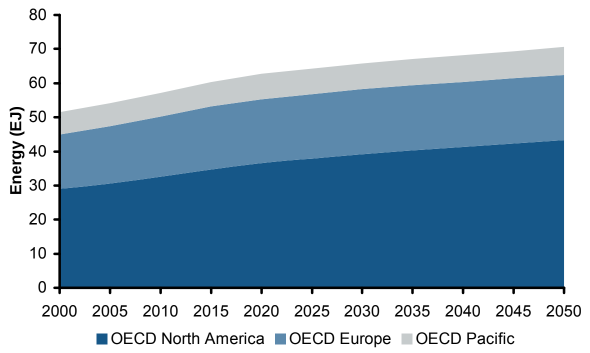




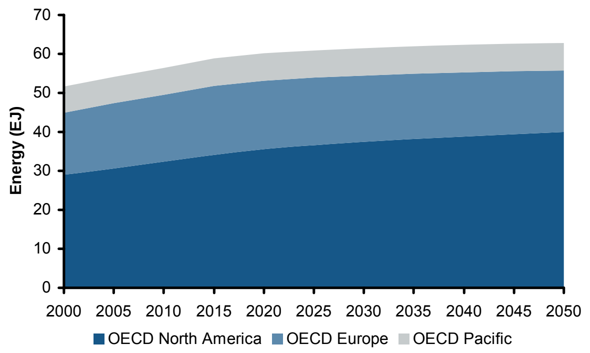


Well-to-wheel fossil energy

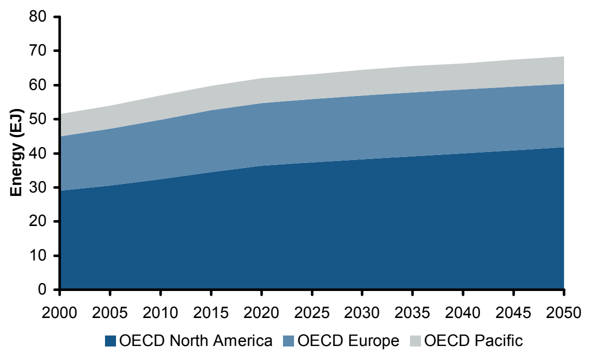
BAU



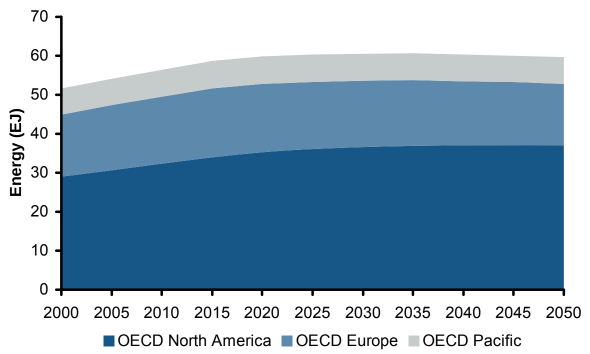
1a: BTL 25% in 2050



1b: OECD Diesel 50% in 2050

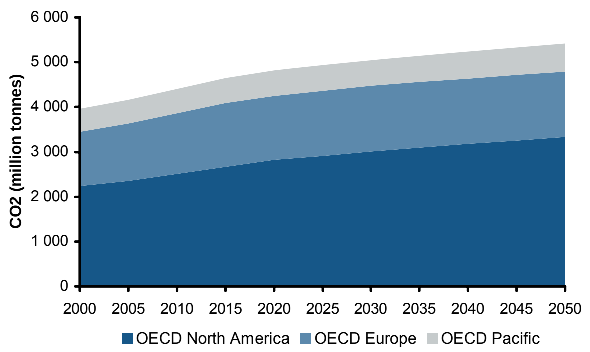


1c: BTL 25% OECD Diesel 50% in 2050

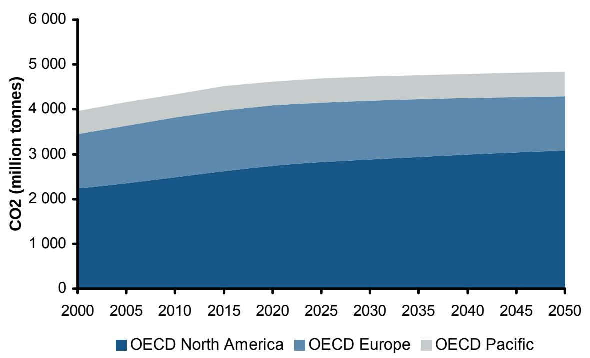


Well-to-wheel CO_2 emissions

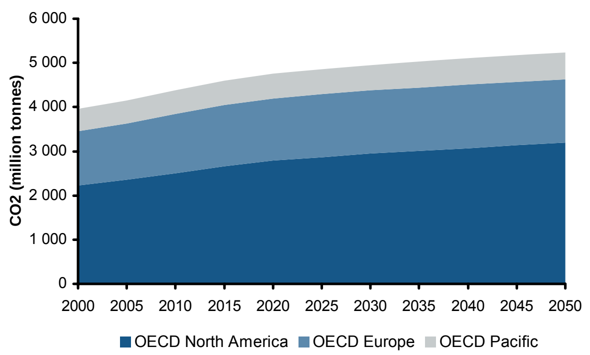
BAU



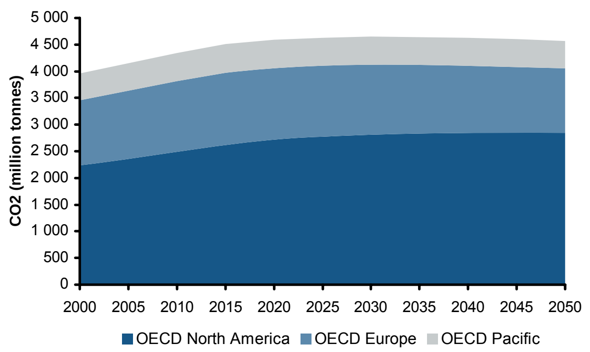
1a: BTL 25% in 2050



1b: OECD Diesel 50% in 2050

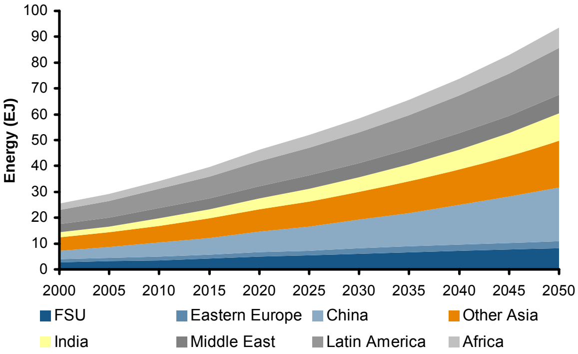


1c: BTL 25% OECD Diesel 50% in 2050

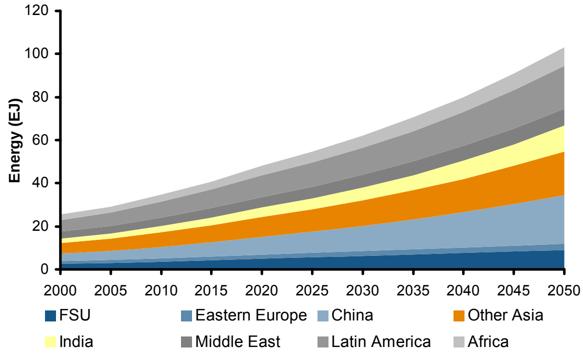


Well-to-wheel energy

BAU



1a: BTL 25% in 2050



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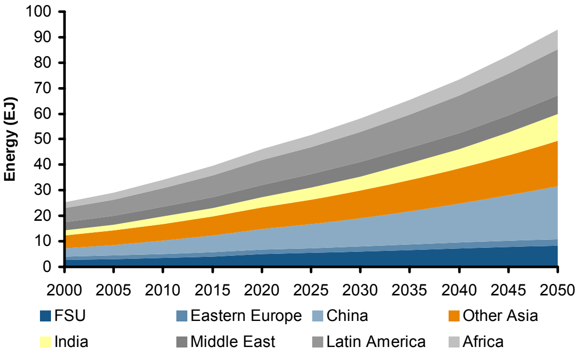
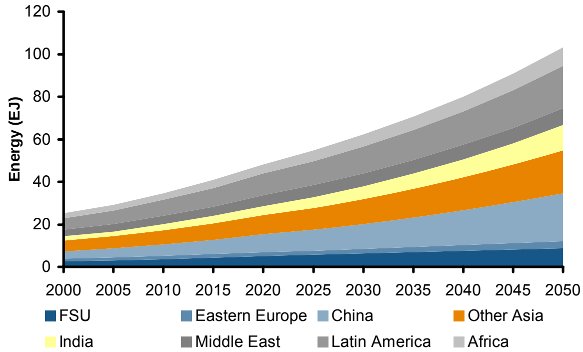
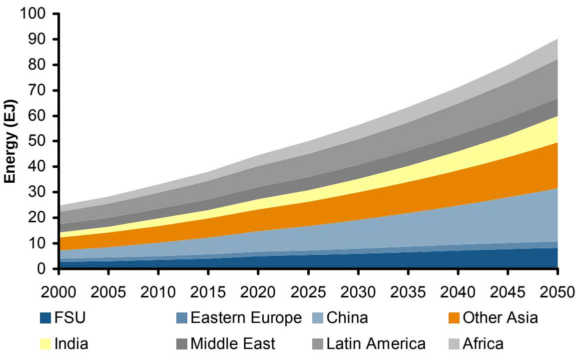


1c: BTL 25% OECD Diesel 50% in 2050



Well-to-wheel fossil energy

BAU



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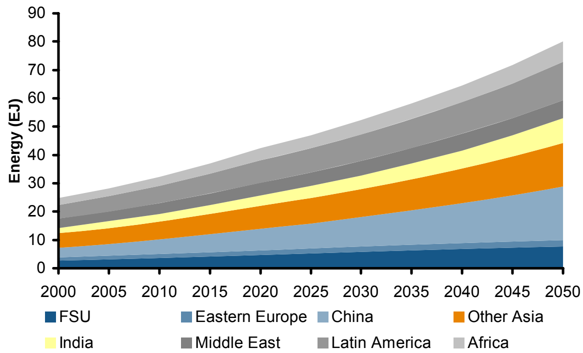

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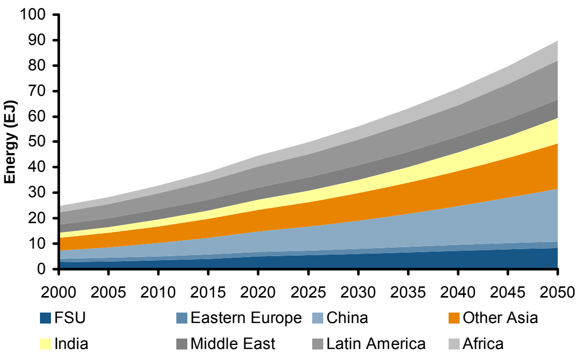
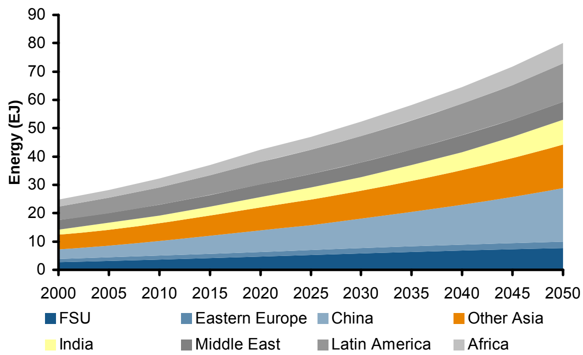
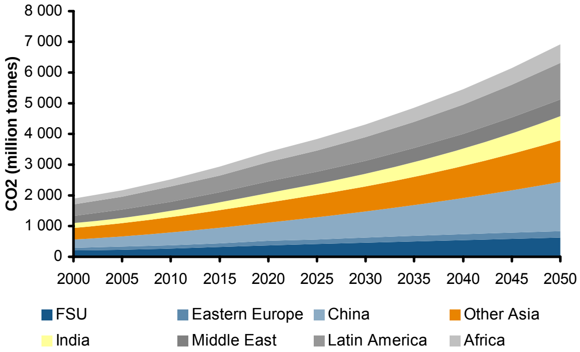


1c: BTL 25% OECD Diesel 50% in 2050

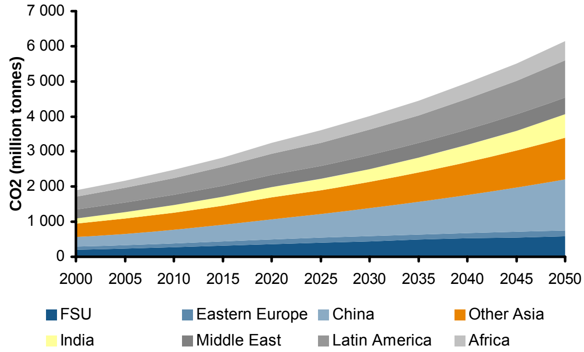


Well-to-wheel CO_2 emissions

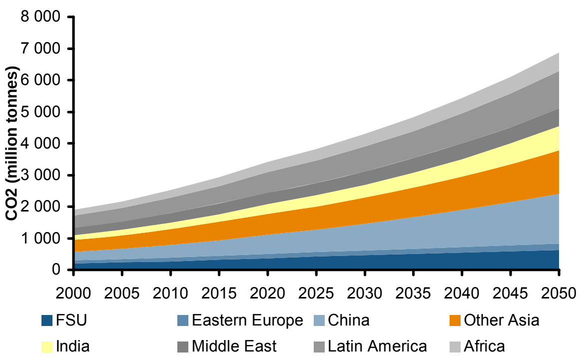
BAU



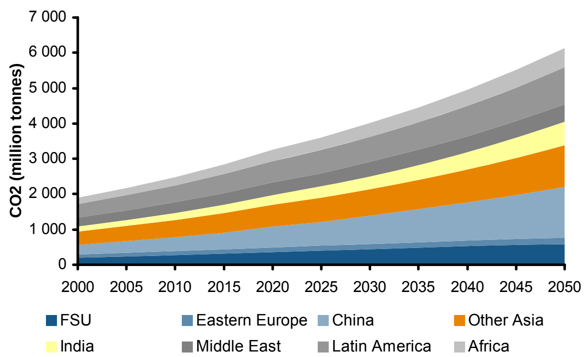
1a: BTL 25% in 2050



1b: OECD Diesel 50% in 2050

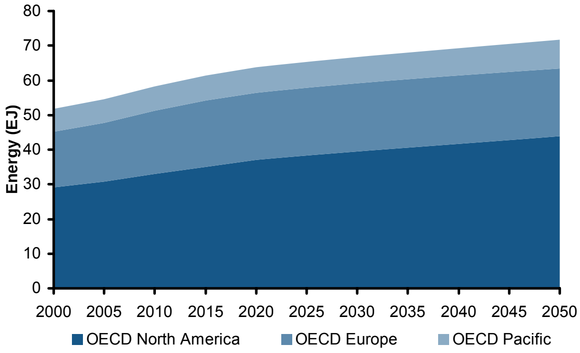


1c: BTL 25% OECD Diesel 50% in 2050

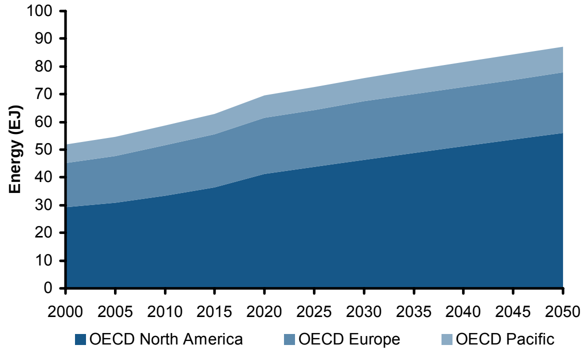


Well-to-wheel energy

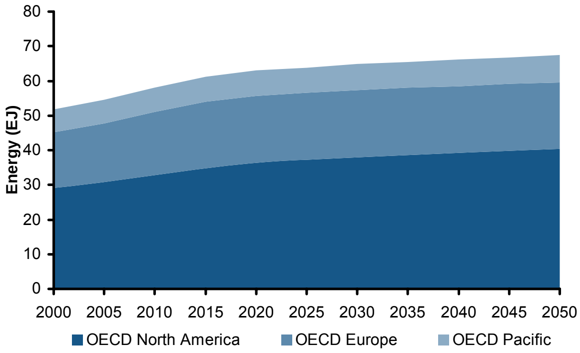
BAU



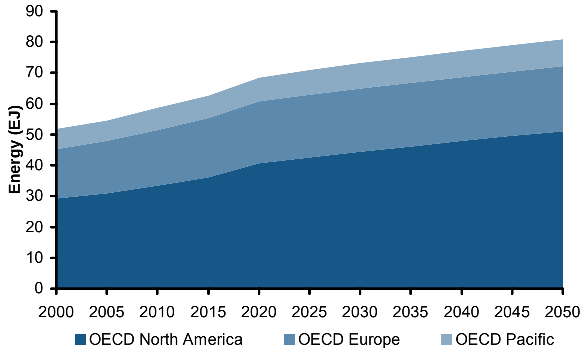
2a: Cellulosic 25% in 2050



2b: OECD Hybrid 50%

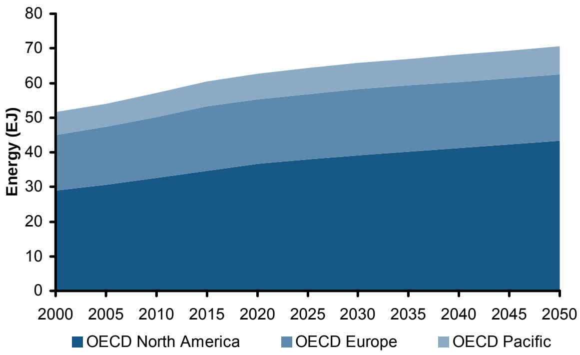


2c: Cellulosic 25% & OECD Hybrid 50% in 2050

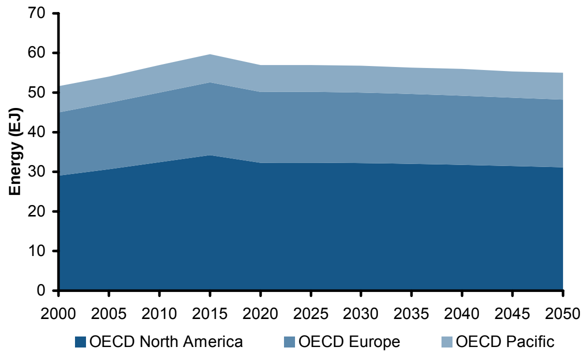


Well-to-wheel fossil energy

BAU



2a: Cellulosic 25% in 2050



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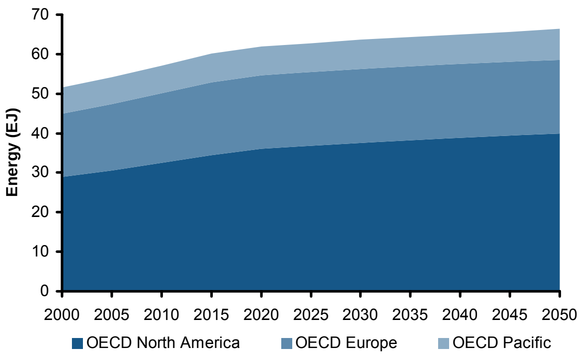
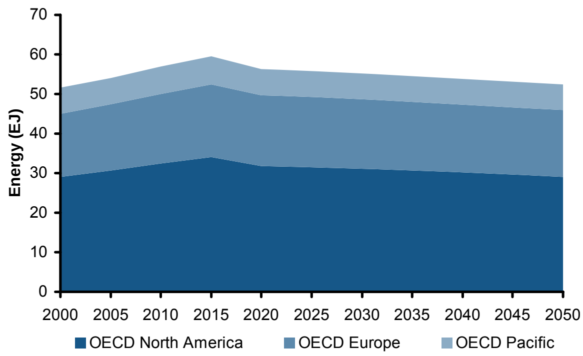
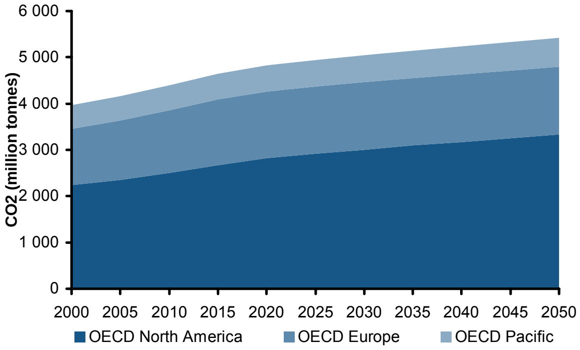


2c: Cellulosic 25% & OECD Hybrid 50% in 2050

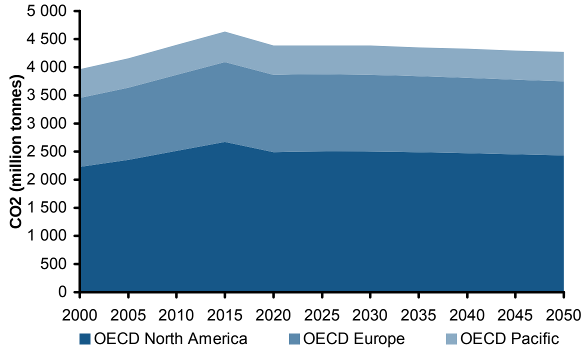


Well-to-wheel CO_2 emissions

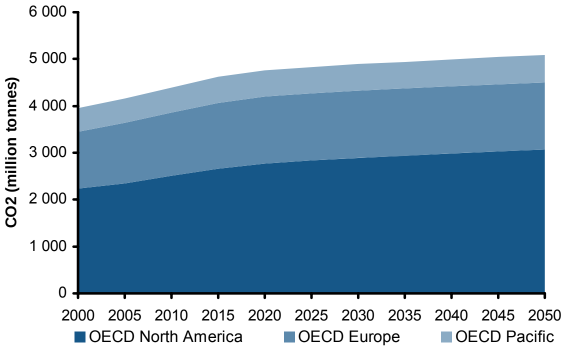
BAU



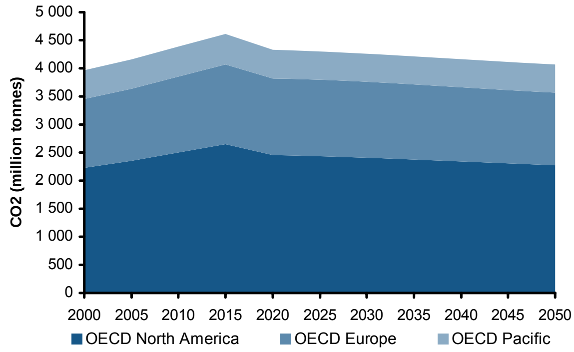
2a: Cellulosic 25% in 2050



2b: OECD Hybrid 50%

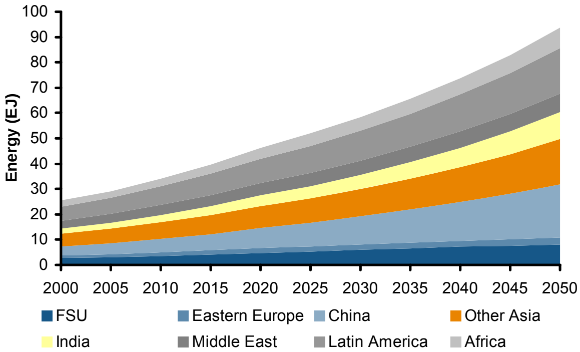


2c: Cellulosic 25% & OECD Hybrid 50% in 2050

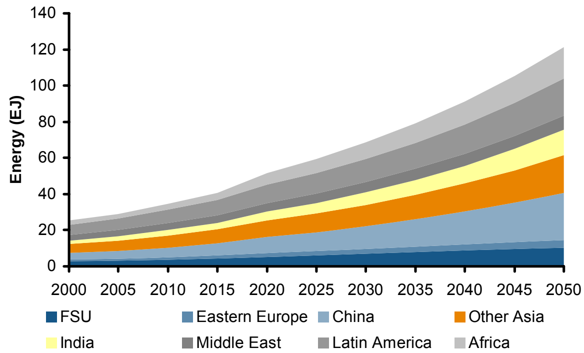


Well-to-wheel energy

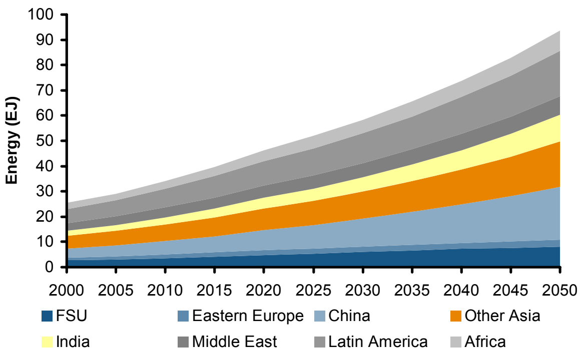
BAU



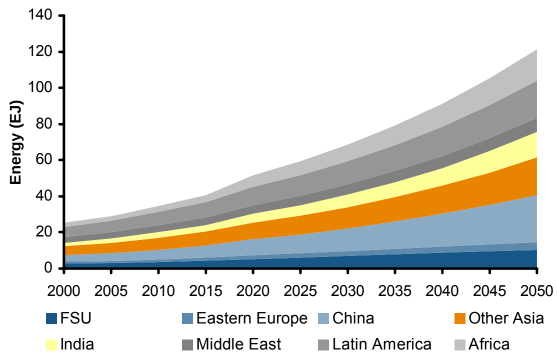
2a: Cellulosic 25% in 2050



2b: OECD Hybrid 50%

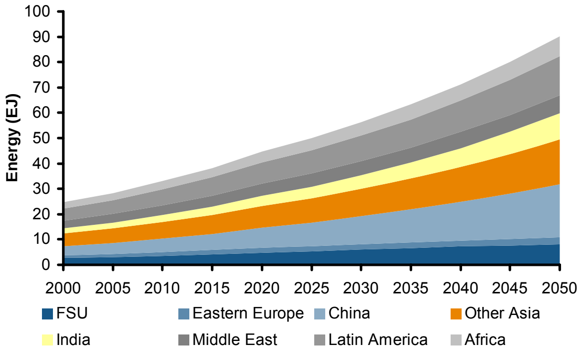


2c: Cellulosic 25% & OECD Hybrid 50% in 2050

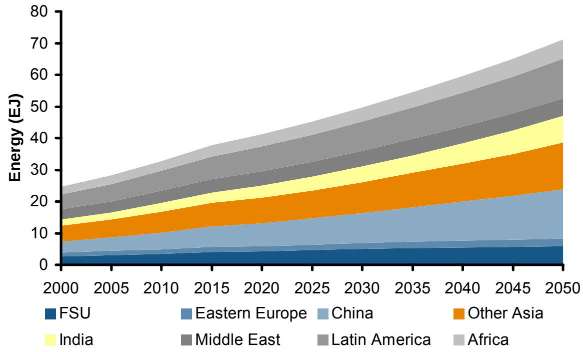


Well-to-wheel fossil energy

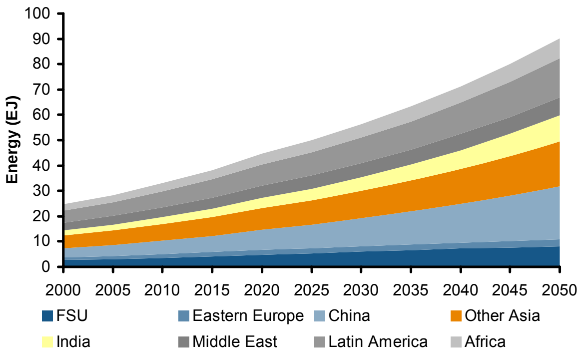
BAU



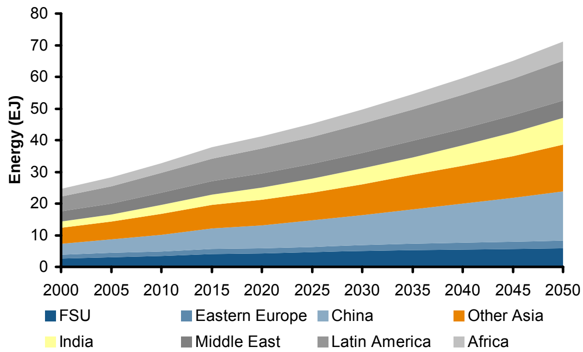
2a: Cellulosic 25% in 2050



2b: OECD Hybrid 50%

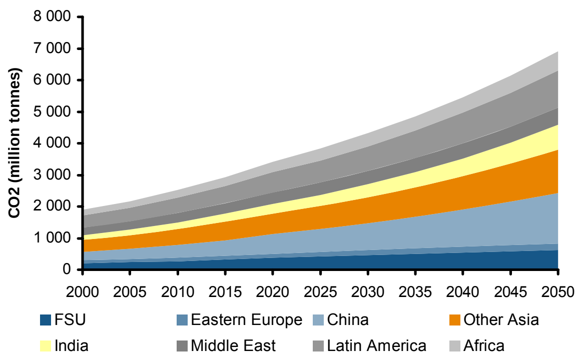


2c: Cellulosic 25% & OECD Hybrid 50% in 2050

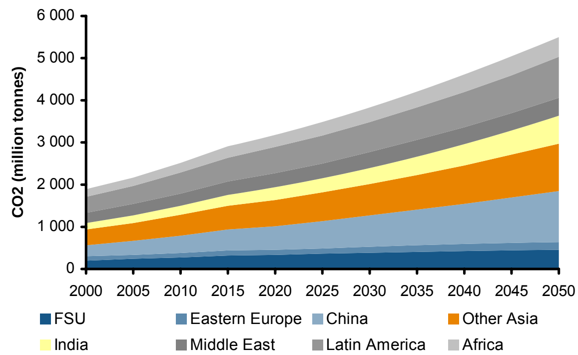


Well-to-wheel CO_2 emissions

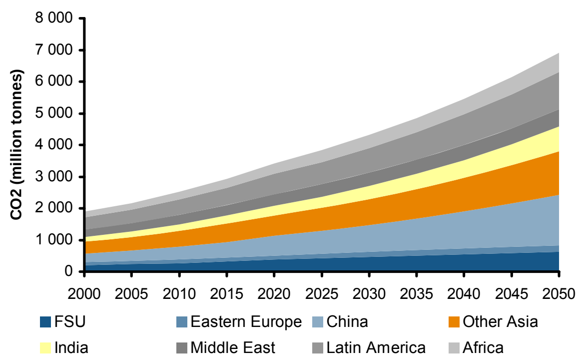
BAU



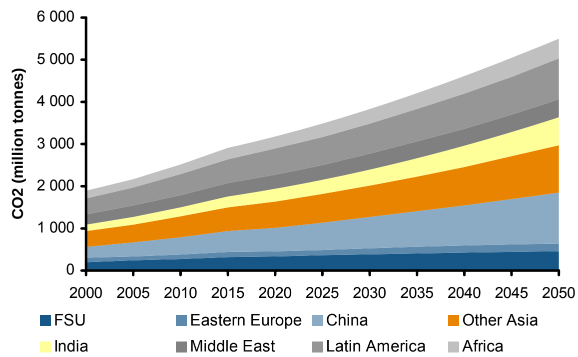
2a: Cellulosic 25% in 2050



2b: OECD Hybrid 50%

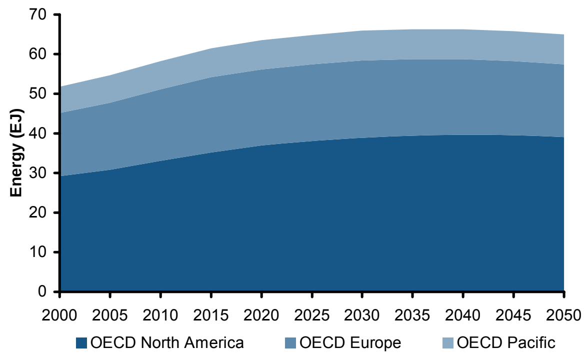


2c: Cellulosic 25% & OECD Hybrid 50% in 2050

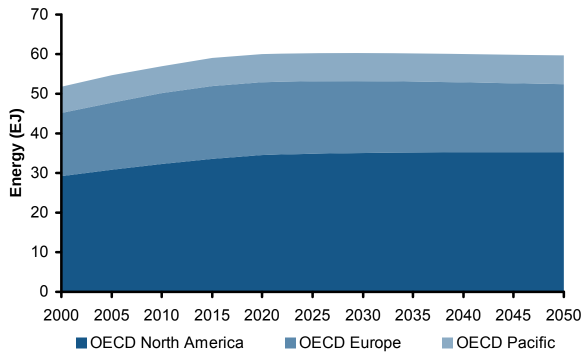


Well-to-wheel energy

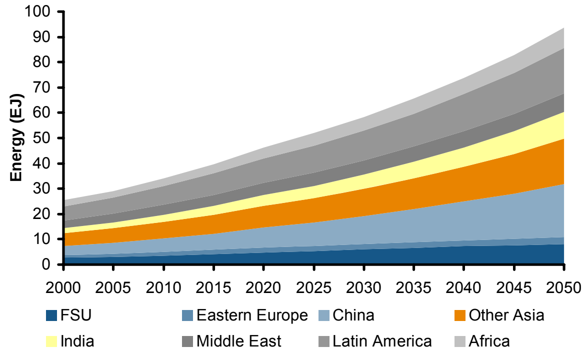
3a: OECD FCV 25% in 2050



4a: OECD pass-km reduction 30% by 2050

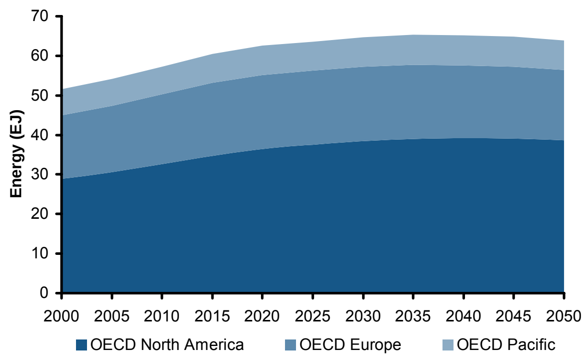


4b: non-OECD pass-km reduction 30% by 2050

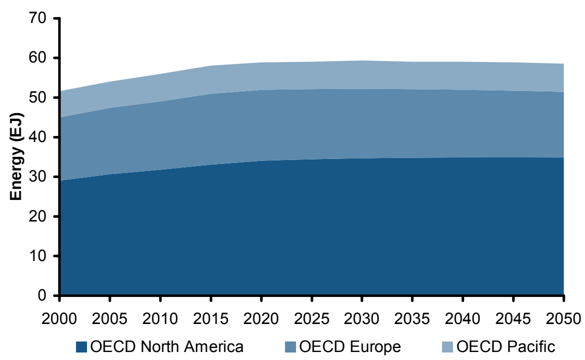


Well-to-wheel fossil energy

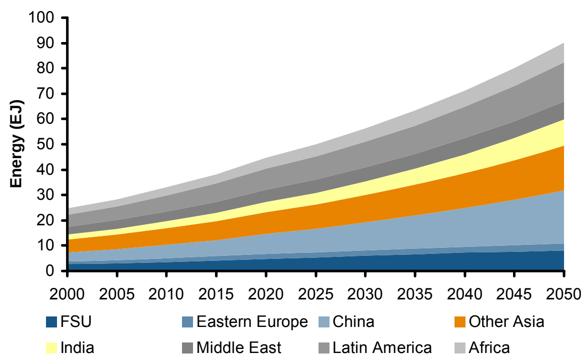
3a: OECD FCV 25% in 2050



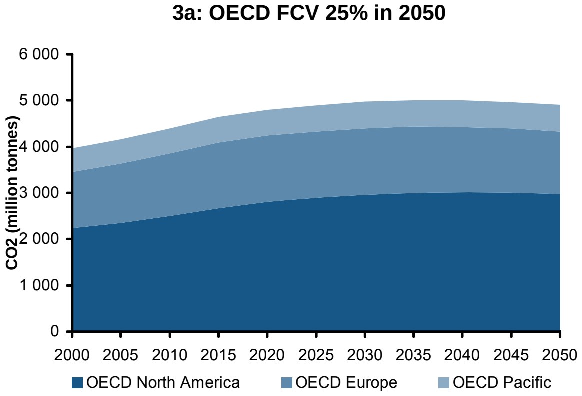
4a: OECD pass-km reduction 30% by 2050

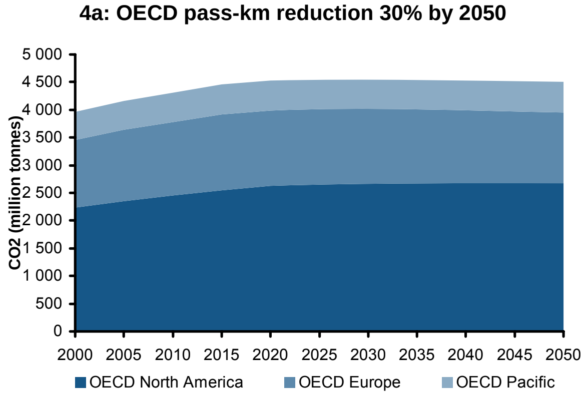


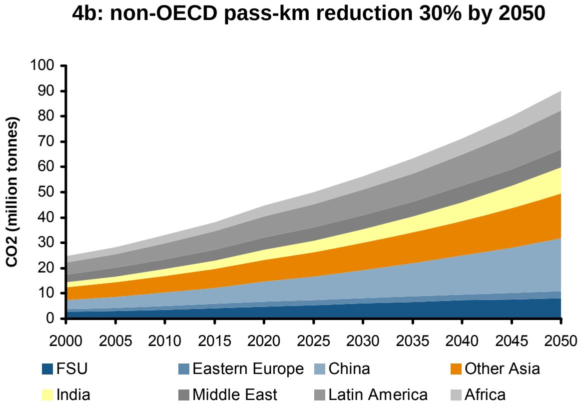
4b: non-OECD pass-km reduction 30% by 2050



Well-to-wheel CO_2 emissions







Appendix 9: Transportation system efficiency options

The measures below represent options which are available for implementation with the objective of improving overall transportation system efficiency

Source: TDM (Transportation Demand Management) Encyclopedia, Victoria Transport Policy Institute, www.vtpi.org)

Improved Transport Options

Alternative Work Schedules	Flextime, Compressed Work Week (CWW), and staggered shifts.
Bus Rapid Transit	Bus system design features that significantly improve service quality and cost efficiency.
Car sharing	Vehicle rental services that substitute for private vehicle ownership.
Light Rail Transit	Light Rail Transit systems are designed to provide convenient local service on busy urban corridors.
Park & Ride	Programmes to provide convenient parking at transit and rideshare stations.
Ridesharing	Strategies for encouraging carpooling and vanpooling.
Telework (Telecommuting, Distance-Learning, Tele-shopping, etc.)	Use of telecommunications as a substitute for physical travel.

Incentives To Use Alternative Modes and Reduce Driving

Congestion Pricing	Variable road pricing used to reduce peak-period vehicle trips.
Distance-Based Pricing	Various fees and taxes based on a vehicle's mileage.
Fuel Taxes	Increasing fuel taxes to achieve TDM objectives.
HOV (High Occupant Vehicle) Priority	Strategies that give transit and rideshare vehicles priority over other traffic.
Parking Pricing	Charging motorists directly for parking.
Pay-As-You-Drive Vehicle Insurance	Converting vehicle insurance premiums into distance-based fees.
Road Pricing	Congestion pricing, value pricing, road tolls and HOT lanes
Road Space Reallocation	Roadway design and management practices that favor efficient modes.
Vehicle Use Restrictions	Strategies to limit vehicle traffic at a particular time and place.

Parking and Land Use Management

Car-Free Districts and Pedestrianised Streets	Designing special areas and times for minimal automobile use.
Location Efficient Development	Development that maximises multi-modal accessibility.

Parking Management	Strategies for more efficient use of parking.
Parking Pricing	Charging motorists directly for parking.
Shared Parking	Sharing parking facilities among multiple users.
Smart Growth Reforms	Policy and planning reforms that encourage Smart Growth.
Land Use Impacts on Transport - Comprehensive	This comprehensive report provides detailed information on how land use factors affect travel behaviour.

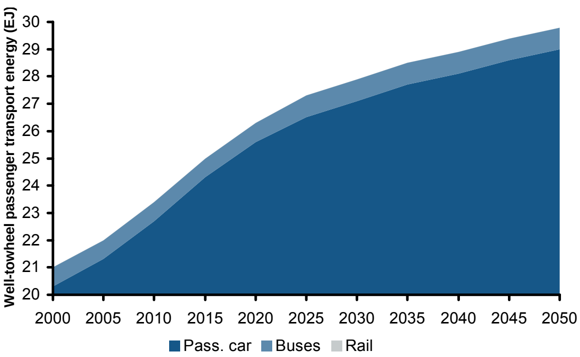
Policy And Institutional Reforms

Car-Free Planning	Reduced driving at particular times and places.
Comprehensive Market Reforms	Policy changes that result in more efficient transport pricing.
Institutional Reforms	Creating organisations that support efficient transport.
Least Cost Planning	Creating an unbiased framework for transport planning.
Operations and Management Programmes	Transport operations and management programmes encourage more efficient use of existing roadway systems.
Prioritizing Transportation	Principles for prioritising transportation activities and investments.
Regulatory Reform	Policy changes to encourage competition, innovation, diversity and efficiency in transport services.

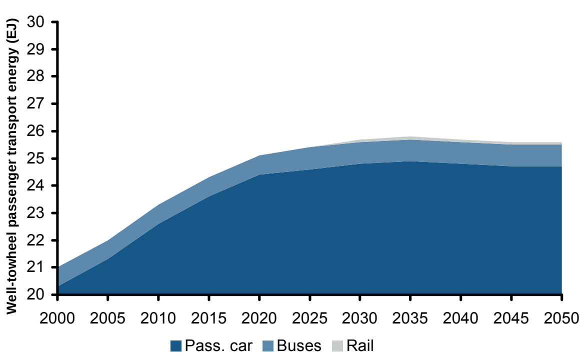
Appendix 10: Transport Energy Demand

OECD North America Total well-to-wheel energy consumption for passenger travel

Base case

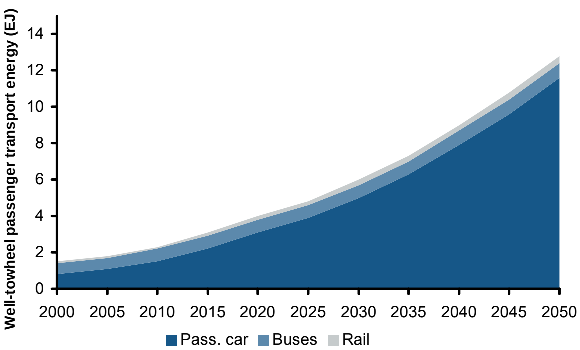


Scenario 1: 15% switch to rail by 2050

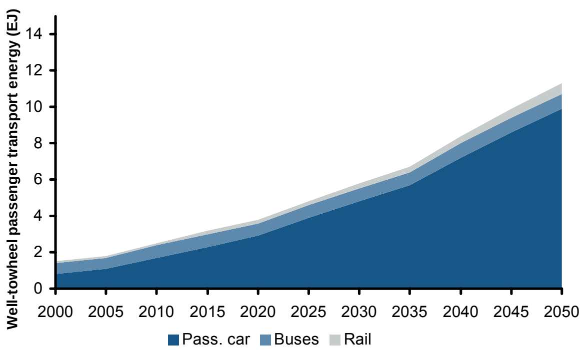


China Total well-to-wheel energy consumption for passenger travel

Base case

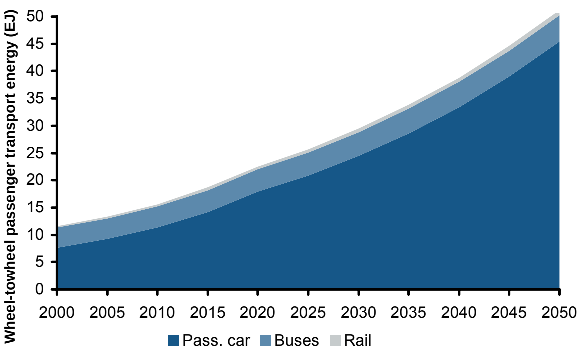


Scenario 2: 15% switch to rail by 2050

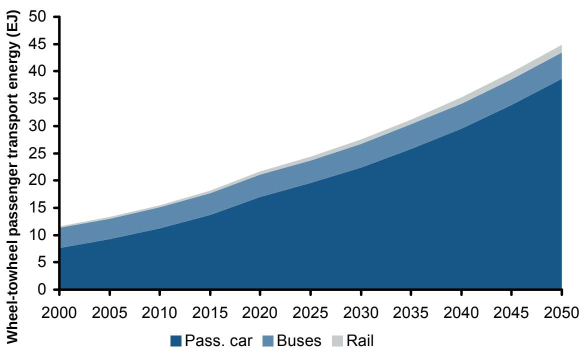


Non OECD Total well-to-wheel energy consumption for passenger travel

Base case



Scenario 3: 15% switch to rail by 2050



Appendix 11:
Cost calculations for FCEV and hydrogen fuel

Best case retail cost of hydrogen fuel

Consumer electricity prices in the US (Jul 2006):	Min	~4¢ / kWh
	Max	~12¢ / kWh
	Mean	~8¢ / kWh

1 gallon gasoline ≈ 44 MJ

1 gge H_2 (electrolysis @ 80% efficiency) = 55 MJ

1 kWh = 3.6 MJ

1 gge H_2 = 15.2 kWh electricity

1 gge H_2 average cost = 15.2 x 8¢

▸ **= $1.22 / gge H_2**

This calculation represents the energy-only cost of hydrogen fuel at today's retail electricity prices. A 20% mark-up brings a final price of $1.46 (rounded to $1.50 for the breakeven calculation in Chapter 5

Rough calculation of retail cost of hydrogen fuel

Assume long-term electricity prices at double current best case (factor in potential resource tightening, carbon pricing etc).

▸ **= $2.44 / gge H_2**

Annual passenger vehicle consumption in 2050 = 500 bn gal/yr (Mobility 2030, BAU case).

Assume in the worst case, on the road penetration is only 5% at 55% energy consumption relative to conventional vehicles

▸ **= 14 bn gge H_2 per year**

Assume global hydrogen infrastructure costs $1 trn (rough estimate of a number of studies) with 30 year amortisation

- **cost per gallon** = $1 trn ÷ (14 bn x 30 years)

  = $2.38 / gge H_2

- **total cost** = $2.38 + $2.44

  = <u>$4.82</u> (use $5 /gge in breakeven analysis)

Appendix 12: Energy balance estimates for breakthrough technologies

Source: CONCAWE/EUCAR Well-to-Wheel Study 2005, WBCSD calculations, WEC Transport Study Group calculations

Technology	Current energy balance (c.f. gasoline ICE)
Fuel cell vehicle (with H_2) to 50% penetration	WTW energy: -35% to +170% WTW fossil energy: -95% to +80%
Electric vehicle to 50% penetration	WTW energy: -75% to ±0 WTW fossil energy: -95% to -35%
Plug-in hybrid vehicle to 50% penetration	WTW energy: -50% to – 20% WTW fossil energy: -55% to -32%
CTL + carbon capture	WTW energy: +70% WTW fossil energy: +70%
BTL high yield	WTW energy: +85% WTW fossil energy: -95%
Cellulosic ethanol high yield	WTW energy: +100% WTW fossil energy: -75%

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