CRANFIELD UNIVERSITY

COLIN JAMES PLUMB

A TECHNICAL, ENVIRONMENTAL AND ECONOMIC ASSESSMENT OF FUTURE LOW-CARBON HEAVY-DUTY POWERTRAIN TECHNOLOGIES

SCHOOL OF ENGINEERING
MSc Automotive Technology Management

MSc THESIS
Academic Year: 2011-12

Supervisor: Dr. G. Sherwood
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This thesis is submitted in partial (40%) weighting fulfilment of the requirements for the degree of Master of Science

Abstract

The development of low-carbon powertrains, to both reduce our reliance on fossil fuels and minimise greenhouse gas emissions, has become a key technological focus for automotive companies. This study investigates, assesses, and critiques future powertrain solutions to determine which technologies demonstrate the ability to both satisfy the environmental requirements while fulfilling the demands of commercial vehicle heavy-duty drive cycles. The implications of low-carbon technologies on the automotive industry are also reviewed. The technologies discussed are identified through; industry research, patent reviews, published low-carbon roadmaps, and academic literature.

The internal combustion engine is expected to remain the primary heavy-duty powertrain technology until beyond 2030. Although increased electrification is anticipated, the demands of heavy-duty drive cycles prohibit the use of the current electric and hybrid electric powertrain technologies being developed for light-duty applications. Increasing engine efficiency will remain a key focus of truck and engine manufacturers as the reduction of fuel consumption and CO_2 emissions becomes a legislative requirement. Waste heat recovery and parasitic loss reduction technologies are expected to be seen on the majority of new truck models. The use of alternative fuels in the existing diesel powertrain offers the fastest route to reducing both GHG and exhaust emissions. Biofuels which can be blended with mineral diesel and easily integrated with the current infrastructure are likely to dominate the alternative fuels market. It is anticipated that over the next 5 to 10 years the choice of automotive fuels will diversify as countries move to utilise local biomass resource and increase their own energy security.

Existing technical competencies, strategic assets, and R&D expertise puts established manufacturers in a good position to maintain their market position and also gain competitive advantage in emerging markets as they aim to implement stricter emissions legislation.

Acknowledgements

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Nomenclature

Notation

CH_4	Methane
Co	Cobalt
CO	Carbon Monoxide
CO_2	Carbon Dioxide
Fe	Iron
g/kWh	Grams per Kilowatt-hour
Gt CO_2 e	Gigatonnes of CO_2 Equivalent
H_2	Hydrogen
H_2O	Water
lge	Litre of Gasoline Equivalent
MJ/L	Megajoule per Litre
mpg	Miles per Gallon
Mt CO_2 e	Million Tonnes of CO_2 Equivalent
N_2O	Nitrous Oxide
NG	Natural Gas
Nm^3	Normal Cubic Meter
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxide
ppm CO_2 e	Parts per Million of CO_2 Equivalent
t C/ha	Tonnes of Carbon per Hectare
Wh/mile	Watt Hours per Mile

Acronyms

AD	Anaerobic Digestion
APU	Auxiliary Power Unit
BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
BTL	Biomass-to-liquid
CCS	Carbon Capture and Storage
CI	Compression Ignition
CNG	Compressed Natural Gas

CTL	Coal-to-liquid
CV	Commercial Vehicle
DECC	Department of Energy and Climate Change
DI	Direct Injection
DME	Dimethyl Ether
DOE	Department of Energy
DPF	Diesel Particulate Filter
EC	European Commission
EGR	Exhaust Gas Recirculation
ERTRAC	European Road Transport Research Advisory Council
EU	European Union
FAME	Fatty Acid Methyl Ester
FIE	Fuel Injection Equipment
FT	Fischer-Tropsch
GHG	Green House Gas
GTL	Gas-to-Liquid
GVW	Gross Vehicle Weight
GWP	Global Warming Potential
HC	Hydrocarbons
HD	Heavy-duty
HECC	High Efficiency Clean Combustion)
HEV	Hybrid Electric Vehicle
HGV	Heavy Goods Vehicle
HPCR	High Pressure Common Rail
HPDI	High Pressure Direct Injection
HPL EGR	High-pressure Loop EGR
HVO	Hydrogenation of Vegetable Oils
ICE	Internal Combustion Engine
IEA	International Energy Agency
iLUC	Indirect Land Use Change
ITS	Intelligent Transport Systems
JRC	European Commission Joint Research Centre
LCFS	Low Carbon Fuel Standard
LD	Light-duty
LNG	Liquefied Natural Gas

LPG	Liquefied Petroleum Gas
MD	Medium-duty
NREL	National Renewable Energy Laboratory
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
PM	Particulate Matter
RED	Renewable Energy Directive
RTFO	Renewable Transport Fuels Obligation
SCR	Selective Catalytic Reduction
SI	Spark Ignition
SSL	Small Scale Liquefaction Plants
TER	Large Scale Regasification Terminals
UNFCCC	United Nations Framework Convention on Climate Change
WEO	World Energy Organisation
WIPO	World Intellectual Property Organization
WTW	Well-to-Wheel

1. Introduction

The impact of fossil fuels on climate change, alongside concerns over the future security of fuel supplies, has highlighted the need for sustainable energy production [1; 2]. The development of low-carbon solutions, to reduce our reliance on fossil fuels and minimise greenhouse gas (GHG) emissions, has become a key technological focus for automotive companies [3]. Current low-carbon transport assessments are primarily focused on light-duty vehicles such as passenger cars and light trucks, or focused on specific technologies, such as biofuels, hybrid electric or hydrogen. An application specific study is required to determine low-carbon solutions for long-haul heavy-duty commercial vehicles[1].

This Thesis aims to provide industry decision makers with a comprehensive and critical review of future low-carbon powertrain technologies, identifying solutions which demonstrate the ability to both satisfy the environmental requirements and the demands of heavy-duty commercial vehicles (CV).

The objectives of this Thesis are to;

- Investigate and critically assess the suitability of current and future low-carbon powertrain technologies for use in heavy-duty commercial vehicles.
- Investigate current CV manufacturers and government low-carbon strategies to identify which technologies have the potential to gain support from the industry, government initiatives and legislation.
- Evaluate the viability of introducing these technologies within the next 20 years. Assessing the technical, economic and environmental challenges influencing these technologies.

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[1] The commercial vehicle market is segmented by gross vehicle weight (GVW). Light-duty trucks refer to vehicles between 3.5 – 6 tonnes GVW, Medium-duty trucks range between 6 – 15 tonnes GVW. Heavy-duty refers to vehicles >15 tonnes GVW (see Appendix 1 for a detailed overview of market segmentation).

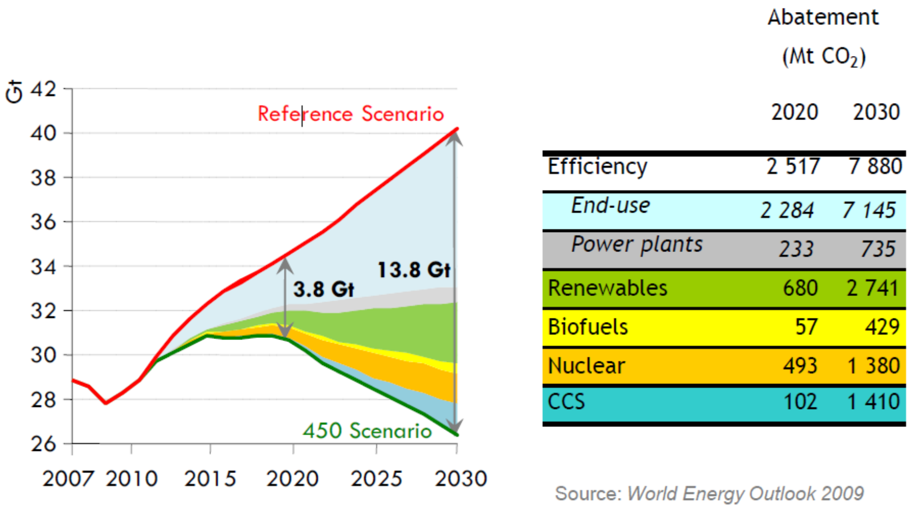
- Review the ability of these technologies to help achieve global GHG reduction targets while maintaining or improving current tailpipe emissions.
- Assess the implications of these potential low-carbon technologies on the automotive industry in order to provide guidance for future business strategy.

The remainder of Chapter 1 reviews the global focus on reducing GHG emissions, heavy-duty emissions legislation, and current industry focus on low-carbon technologies. Chapter 2 identifies potential low-carbon powertrain technologies through a mix of industry research, reviews of government low-carbon initiatives, and academic literature. Chapters 3 and 4 provide a technical, environmental and economic review of the identified technologies. Chapter 5 provides an analysis of the potential effects of these technologies on the industry. Chapter 6 presents the Thesis conclusions and recommendations for further work.

1.1 The Challenge to Reduce Global GHG Emissions

In 1998 the Kyoto protocol set binding targets for the EC and 37 industrialised countries to reduce GHG emissions to, on average, 5% below 1990 levels by 2012 [4]. In 2008 the Climate Change Act also legally bound the UK to reduce its greenhouse gas emissions by 34% by 2020, and 80% by 2050 against the 1990 baseline [5]. In 2009, the UNFCCC Copenhagen Accord acknowledged that climate change is one of the greatest challenges of our time. It also agreed with the scientific view that a global temperature increase greater than 2°C above pre-industrial levels is likely to lead to catastrophic climate change and that deep cuts in global emissions are required [6]. Although not legally binding, the accord attempts to provide a basis for a successor to the Kyoto protocol which expires in 2012.

The IEA's *World Energy Outlook 2009* reported that current government targets would lead to an increase in global warming of greater than 5°C [7]. In order to keep global warming below 2°C major CO_2 reductions will need to be achieved (see Figure 1). To provide a pathway the IEA have produced the 450 Scenario, the end target being that the concentration of GHG in the atmosphere should be limited to around 450 parts per million of CO_2 equivalent. To achieve this ambitious target, by 2020 global emissions need to return to 1990 levels and by 2050 global GHG emissions will need to be reduced by a further 80%. In the 450 Scenario, by 2030 zero-carbon fuels make up a third of the world's primary sources of energy demand.



	Abatement (Mt CO_2) 2020	2030
Efficiency	2 517	7 880
End-use	*2 284*	*7 145*
Power plants	*233*	*735*
Renewables	680	2 741
Biofuels	57	429
Nuclear	493	1 380
CCS	102	1 410

Source: *World Energy Outlook 2009*

Figure 1. IEA Global Emissions Forecast (Gt CO_2)

Source: IEA [7]

CO_2 is the main contributor to GHG emissions, accounting for 84% of the UK’s total GHG emissions in 2009. Transportation accounted for 26% of the UK’s total CO_2 emissions (see Figure 2) with road transport producing 93% of all transport emissions [8]. While energy supply and business CO_2 emissions have reduced by 23% and 31% respectively since 1990, road transport emissions have increased by 3% (see Figures 3 and 4).

Transport is also the second largest contributor to global CO_2 emissions, and with global transport demand expected to grow by 45% by 2030 there is increased focus on the reduction of transport emissions [2; 7]. Recently the EU has produced white papers detailing roadmaps towards a low carbon economy and efficient transport system. The analysis in these reports indicate that although other sectors of the economy are in a position to achieve greater reductions, transport GHG emissions need to be cut by up to 9% by 2030 and up to 67% by 2050 [9; 10].

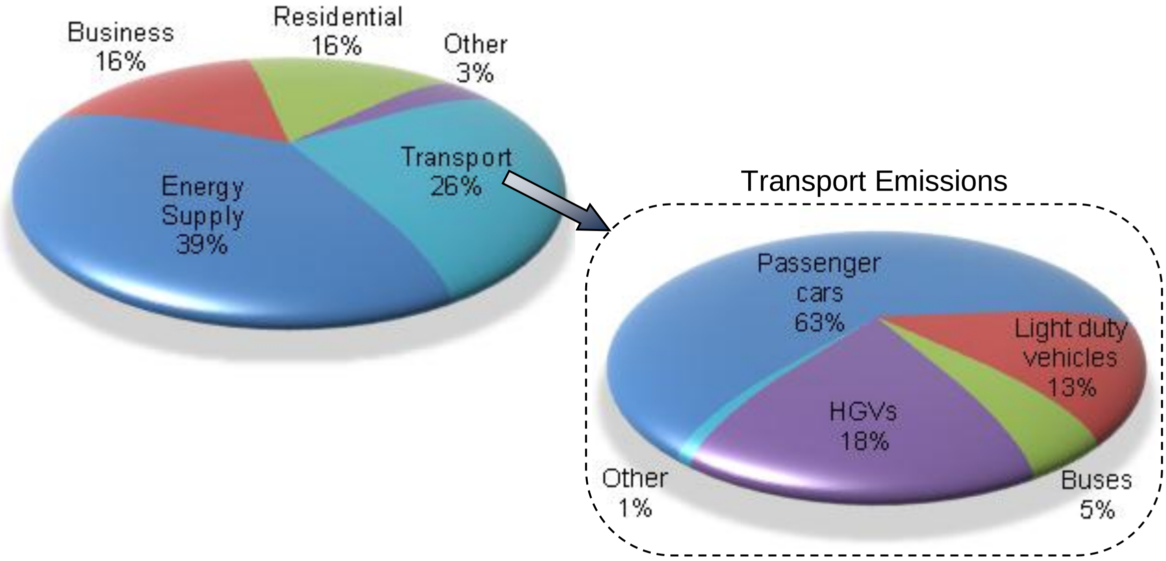


Figure 2. UK CO_2 Emissions by Source – 2009

Source: DECC [8]

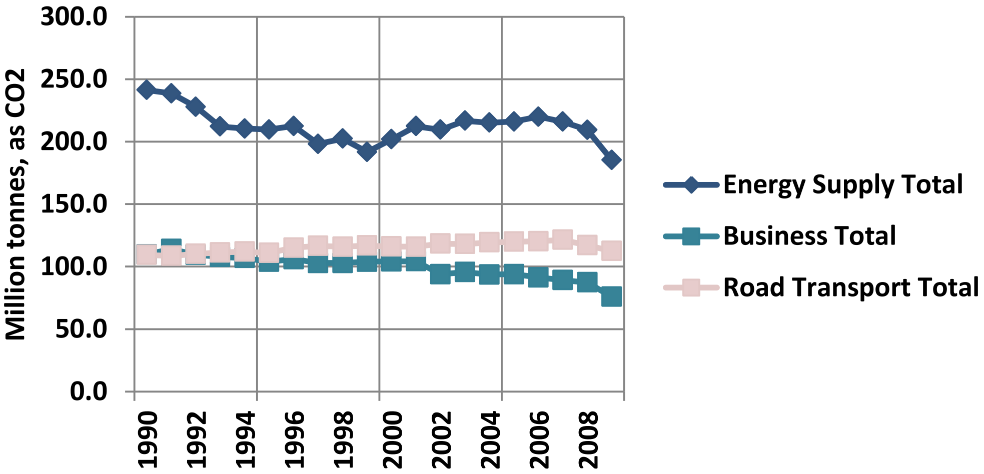


Figure 3. UK CO_2 Emissions for Energy, Business and Road Transport

Source: DECC [8]

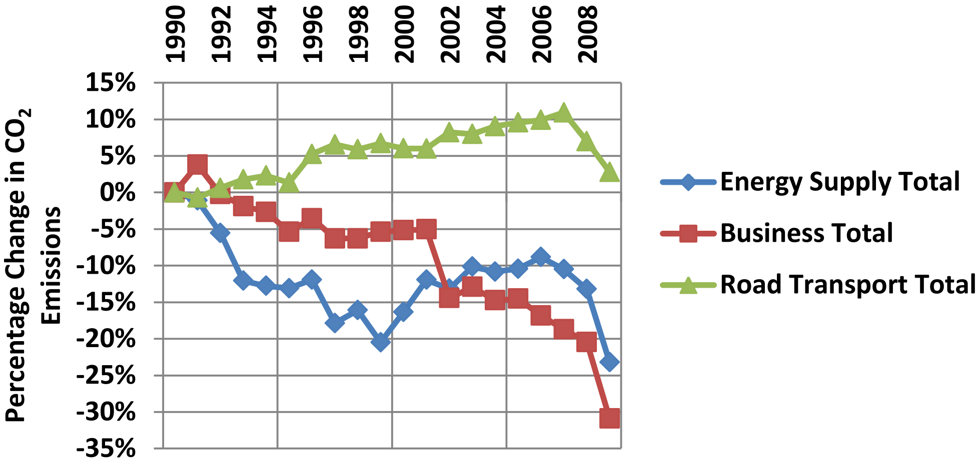


Figure 4. Changes in CO_2 Emissions Since 1990

Source: DECC [8]

Industry roadmaps for low carbon transport have, until recently, been focused on passenger vehicle applications (see Figure 5) [11]. Passenger vehicles however account for just over 60% of UK transport CO_2 emissions, with almost 20% of transport emissions coming from heavy goods vehicles (see Figure 2).

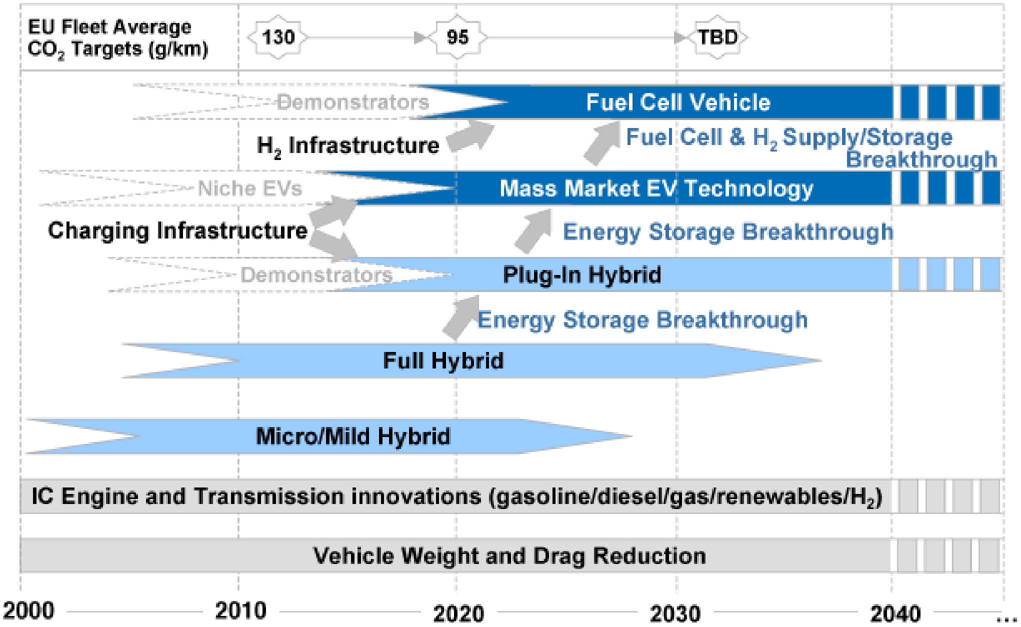


Figure 5. NAIGT Common Product Roadmap

Source: NAIGT [11]

1.2 Heavy-duty Emissions Legislation

Heavy-duty vehicle emission test cycles such as the European ESC (European Stationary Cycle) and the American FTP (Federal Test Procedure) Transient Cycle are used for heavy-duty emissions testing. These cycles aim to represent urban, rural and motorway driving. Heavy-duty cycles require the engine to run at higher torque and loads compared to light-duty drive cycles in order to represent the real world use of commercial vehicles [12].

While the light duty sector has focused on the reduction of CO_2, commercial vehicle legislation has focused on the reduction of environmental pollutants such as nitrogen oxides (NO_X), carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM). The US, Western Europe and Japan have led the way for the introduction of tighter limits. The evolution of commercial vehicle emissions limits for both PM and NO_X in these markets can be seen in Figures 6 and 7.

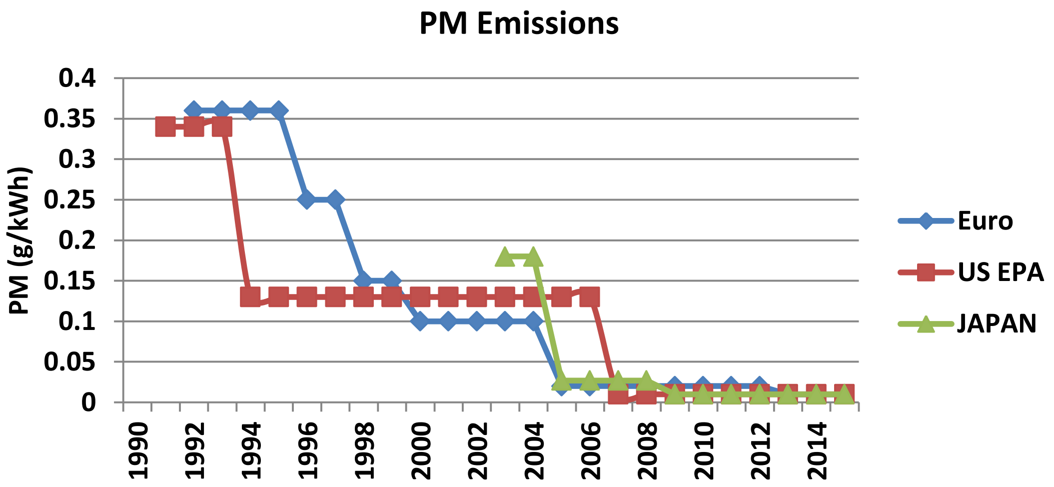


Figure 6. Legislative PM Emissions Reduction for Diesel Commercial Vehicles

(US, Western Europe and Japan - Vehicles >3.5 tonnes)

Source: Delphi

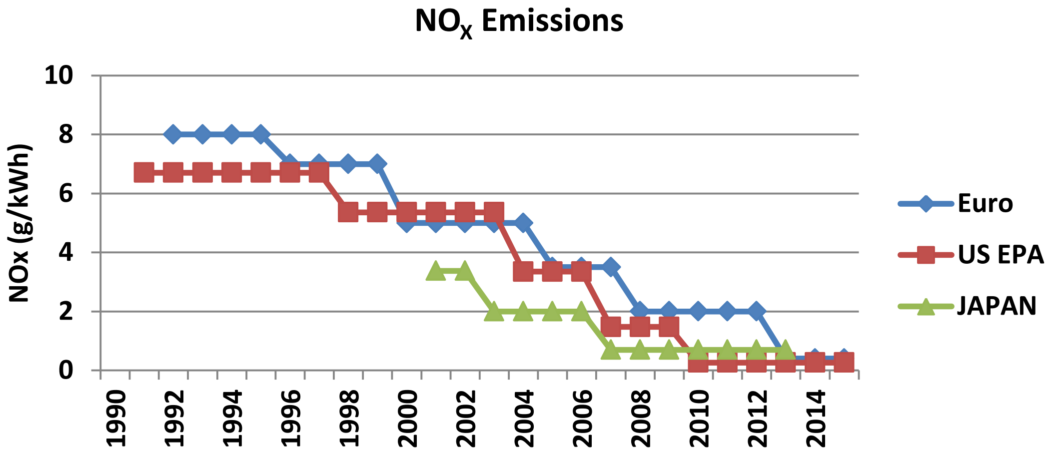


Figure 7. Legislative NO_x Emissions Reduction for Diesel Commercial Vehicles

(US, Western Europe and Japan - Vehicles >3.5 tonnes)

Source: Delphi

This increasingly stringent legislation has resulted in major reductions in the tailpipe environmental pollutants produced by commercial vehicles to a point where further reductions are limited and focus is now beginning to turn to reducing fuel consumption and CO_2 emissions. By 2020 CO_2 emission targets are expected to be in place for most of the major commercial vehicle markets (see Figure 8).

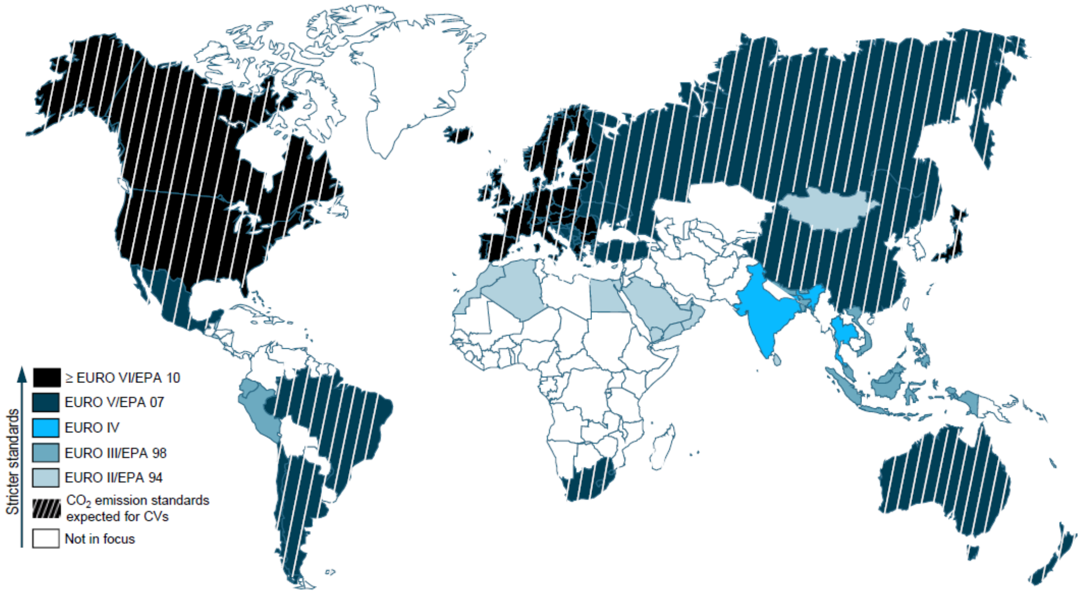


Figure 8. 2020 Forecast CV Emission Standards

Source: Roland Berger [13]

1.3 Current Industry Focus on Low-Carbon Technologies

The development of low-carbon powertrains has now become a key technological focus for automotive companies, with many organisations interpreting this as a requirement for the introduction of electric and hybrid electric vehicles (HEV) [11; 14; 15; 16]. KPMG's *Global Auto Executive Survey 2011* indicates that almost 90% of automotive industry investment over the next five years is focused on hybrid, electric, and fuel cell technologies [3]. These studies and opinions however are focused on passenger car applications and the requirements of commercial vehicle applications have largely been ignored.

While electric vehicles are commercially available for light and medium-duty applications, they are currently limited to a range of around 100 miles per charge. This limited range makes them unsuitable for heavy-duty long-haul purposes and they are most often used for short range urban applications or where zero tailpipe emissions are required [17; 18]. Current CV HEV development is mainly focused on medium-duty and start-stop applications such as bus, delivery trucks and refuse vehicles. Fuels savings of between 25% and 30% are commonly quoted for stop-start operations while long-haul vehicles may only be looking at saving of between 4% and 10% [19; 20]. During heavy-duty drive cycles where the efficiency of the powertrain is already high there may be no benefit at all, or even a fuel efficiency reduction due to the additional weight of the hybrid components [21]. Although forecast figures for the heavy-duty HEV market vary, the expected production figures are between 8,000 and 14,000 units in 2015 from an estimated 2 million heavy-duty units [22; 23; 24]. In 2008 diesel trucks accounted for 99% of heavy-duty truck sales [25].

The diverse range and power variation required for different medium and heavy-duty applications means the choice of powertrain technology in the future will be highly application specific. With many of the technologies considered for use in the light duty and passenger vehicle sector currently unable of satisfying the demands of long distance, heavy-duty drive cycles, current focus is on Internal combustion engine (ICE) development to reduce CO_2 emissions and fuel consumption. Chapter 2 aims to identify the prominent powertrain technologies for future global heavy-duty applications.

It should be recognised that the powertrain is only one area where low-carbon benefits can be achieved and there is also considerable focus on other vehicle improvements. Technologies such as intelligent transport systems (ITS), tyre pressure monitoring and adjustment, improved cab, chassis and trailer aerodynamics, and the use of lightweight materials, all have their part to play in reducing both fuel consumption and GHG emissions. These technologies however are beyond the scope of this Thesis.

2. Review of Future Powertrain Technologies

This chapter reviews, assesses, and critiques the use of future low-carbon powertrain technologies in heavy-duty applications. The technologies discussed have been identified through; industry research, patent reviews from both CV and FIE manufacturers, published low-carbon roadmaps, and academic literature.

2.1 Future Technology Development by the Leading CV Manufacturers

This section provides an industry analysis of low-carbon technologies currently being developed by the top global CV manufacturers. Production forecast data from IHS Global Insight for heavy-duty vehicles has been used to focus the research [26]. The top 10 global manufacturers by production volume can be seen in Figure 9. The chart includes a number of Asian manufacturers who, although matching the established European and US brands on production volume, are focused on providing vehicles into markets aligned to earlier emissions standards.

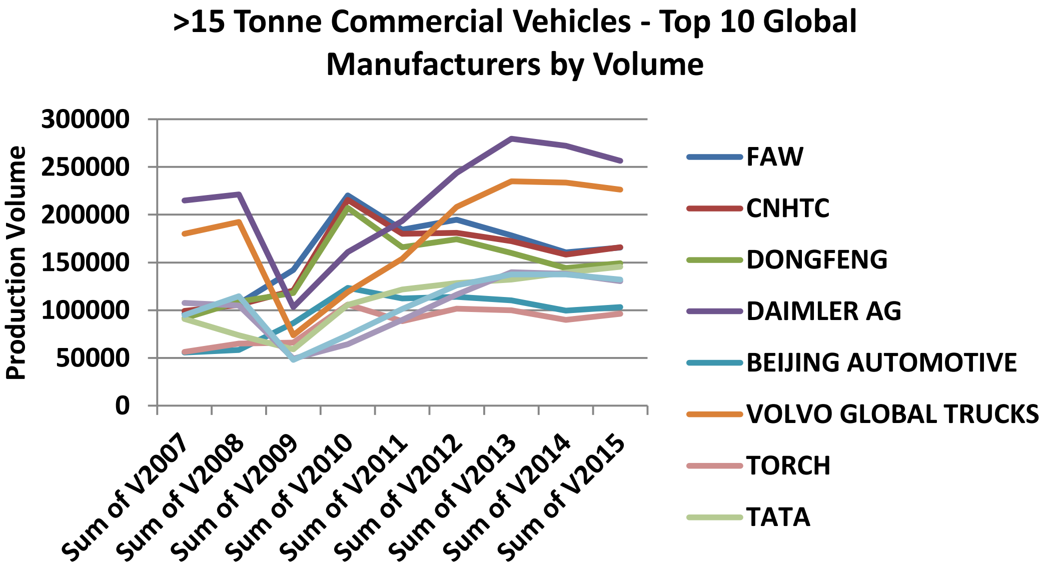


Figure 9. Top 10 Global Heavy-duty CV Manufacturers by Volume

Source: IHS Global Insight [26]

For that reason the production data was also sorted based on Western European / North American production, and Japanese production in order to identify the top manufacturers based in these markets (see Figures 10 and 11).

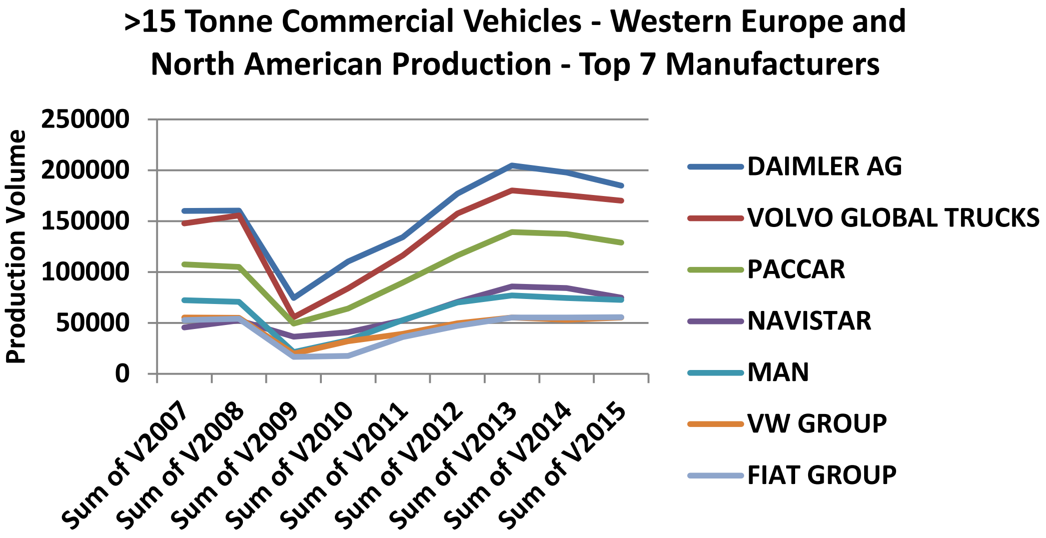


Figure 10. Top 7 Western European and North American Manufacturers Based on Production Forecasts

Source: IHS Global Insight [26]

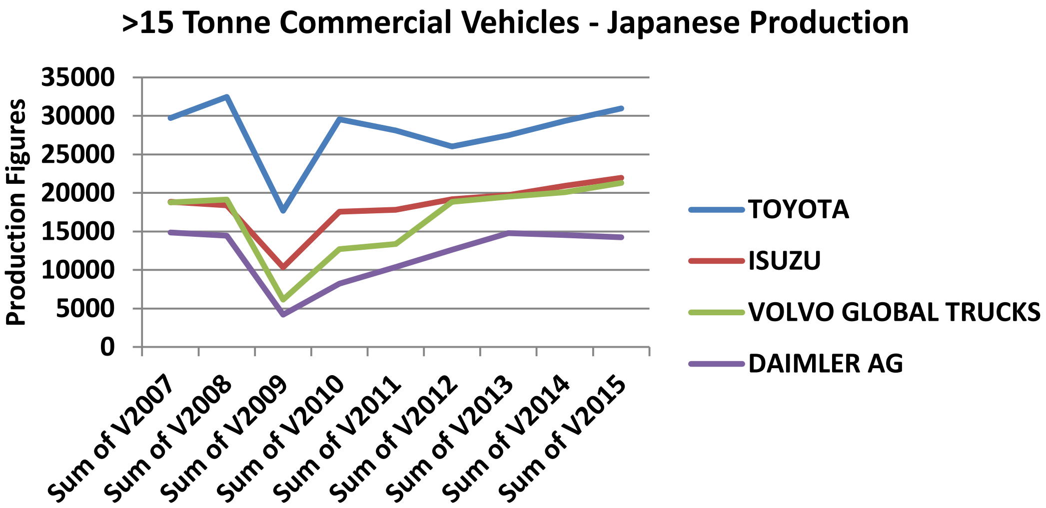


Figure 11. Top Japanese Manufacturers Based on Production Forecasts

Source: IHS Global Insight [26]

Research into each of the major manufacturers was carried out to identify their published low-carbon strategies. Company websites, annual reports, sustainability reports, and press releases were studied. The results can be seen in Table 1.

Current industry focus, in order to achieve Euro VI standards, is on high pressure common rail (HPCR) diesel injection, advanced injection strategies, diesel particulate filters (DPF) exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) [27; 28; 29]. Future technology focus moves away from the tailpipe environmental pollutants discussed in Section 1.2 and is being driven by the requirement for reduced fuel consumption, reduced GHG emissions, and increased regional fuel security. Alternative fuels, such as biodiesel, and dual-fuel ICE powertrains dominate current publicised ICE research and development for all the major heavy-duty vehicle manufacturers. There is also focus on increasing engine efficiency, reducing parasitic losses, reducing frictional losses, and energy recovery. Technologies such as variable flow water pumps, variable speed oil pumps, and clutched air compressors are already available and in series production [30; 31]. Reducing friction between components by means of more precise manufacturing processes, advanced lubricants and component coatings is part of the on-going development for new engines [32].

Hybrid and fuel cell development is prominent both within the media and on company websites, these technologies are however currently focused on specific heavy-duty applications such as bus, local delivery, and refuge vehicles. An overview of the current hybrid vehicle development at the top 3 Western European and North American manufacturers can be found in Appendix 2.

Manufacturer	Low carbon Technology Focus
Daimler AG	- SCR - Alternative Fuels - Natural Gas, Biodiesel, Bio-ethanol, 1st & 2nd Generation Biofuels, BTL, GTL - Parallel and Series Hybrid - Regenerative Braking - Variable flow pumps (mechanical) - Hydrogen fuel cells - Waste Energy Recovery
MAN	- Start-stop technologies - Kinetic energy recovery - Air Pressure Management (APM) - Alternative Fuels - Synthetic Diesel, Biodiesel - Hybrid Technology
PACCAR **(Kenworth, Peterbilt, DAF)**	- SCR - Vehicle aerodynamics - Alternative Fuels – CNG, LNG - Energy Recovery - Hybrid Technology
Navistar (International Trucks)	- Advanced EGR - Alternative Fuels - Natural Gas - Hybrid Technology
Scania (VW)	- High Pressure Fuel Injection Systems - Alternative Fuels – Ethanol, Synthetic Diesel, Biodiesel, Natural Gas - Energy Recovery – inc. turbocompounding - Hybrid Technology - Hydrogen Fuel Cells
Volvo	- Alternative Fuels - Biodiesel, DME, Methanol, Ethanol, Biogas, Methane - Hybrid Technology - Energy Recovery - Turbocompounding
Hino (Toyota)	- SCR - Alternative Fuels – biodiesel, synthetic diesel - Parallel Hybrid Technology
Isuzu	- Alternative Fuels – CNG, DME - Parallel Hybrid Technology - Fuel Cells
Iveco (Fiat)	- Alternative Fuels - Dual-fuel Ethanol/Diesel, CNG - Hybrid

Table 1. Low-Carbon Technology Focus by CV Manufacturers

Source: Company websites and press releases

Mild-hybridisation, auxiliary fuel cells and electric auxiliary components are key technologies being developed as part of the US DOE funded Super Truck programme, which is headed by Daimler Trucks North America, Navistar International and Cummins. The programme aims to develop lightweight efficient components to allow these technologies to be used in future long-haul freight trucks (see Table 2). The target of the Super Truck programme is to achieve 50% brake thermal efficiency compared to a 2009 baseline engine.

Lead Company	Funding	Technology Development
Cummins Inc.	$38,831,115	• Highly efficient and clean diesel engine. • Advanced waste heat recovery system. • Aerodynamic tractor and trailer combination. • Fuel cell auxiliary power unit.
Daimler Trucks North America, LLC	$39,559,868	• Engine downsizing. • Electrification of auxiliary systems • Waste heat recovery. • Improved aerodynamics. • Hybridisation.
Navistar, Inc.	$37,328,933	• Truck and trailer aerodynamics. • Combustion efficiency. • Waste heat recovery. • Hybridisation. • Idle reduction. • Reduced rolling resistance tires.

Table 2. DOE Super Truck Project Summary

Source: DOE [33]

2.2 Government Low-Carbon Transportation Initiatives

Governments have a number of options at their disposal in order to promote the take-up of low-carbon technologies, for example;

- Industry regulation and legislation – such as the introduction of Euro VI emission standards and the EU Fuel Quality Directive - 2009/30/EC requiring member states to reduce life-cycle GHG emissions of existing transport fuels by 6% by 2020 [34].
- Fuel taxation or subsidies – offering financial incentives to purchasers of vehicles run on sustainable fuels, either through the reduction of sustainable fuel prices of increased taxation of fossil fuels.

- Direct consumer support – Reducing the cost of low-carbon vehicles through manufacturer funding or tax rebates on the purchase of vehicles.
- Providing R&D incentives to industry and academic institutions.

Government initiatives have the ability to promote the development of low-carbon transport solutions and also have the potential to dictate which technologies succeed and which do not. For example, the EU Renewable Energy Directive (RED) - 2009/28/EC requires member states to obtain at least 20% of their total energy from renewables by 2020, leaving the method of achieving this up to the individual member states [35]. The UK's Renewable Transport Fuels Obligation (RTFO) however requires fossil fuel suppliers to ensure that their road fuels contain a specified percentage of renewable fuels (3.5% in 2010/11 and 5% by 2013) directly promoting the development of liquid biofuels [36].

The effects of governmental support influencing the success of alternative fuels is best demonstrated by the Brazilian ethanol program [37]. In 2006 83% of vehicles were flex-fuel vehicles able to run on either gasoline or ethanol. Brazilian ethanol is also one of the only biofuels which can currently compete with fossil fuels without financial subsidies, this is unequivocally linked to early and continued governmental support [38].

A major concern with current government low-carbon transport policies has to be their focus towards specific areas and technologies, such as tail pipe emissions or biofuel blending. It is crucial that policies evolve to evaluate the complete lifecycle, or well-to-wheel, emissions of future technologies to avoid "technology forcing". An overview of some key low-carbon transport policies in the EU, US and Japan can be seen in Table 3.

Policy	Description
US - Renewable Fuel Standard (RFS2)	• Volumetric standard increasing biofuel use in the US to 36 billion gallons by 2022. • The US EPA estimates this will result in a reduction of 138 million metric tons of GHG. • The earlier RFS1 led to a major increase in corn derived ethanol – Targets were exceeded in 2008.
US - Low Carbon Fuel Standard (LCFS), California	• Regulated fuel producers & importers are required to reduce fuel carbon intensity by 1% (on average) per year until 2020.
US EPA / NHTSA - Heavy-Duty National Program	• Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles. • Combination tractors – commonly known as big rigs or semi trucks – will be required to achieve up to approximately 20%reduction in fuel consumption and greenhouse gas emissions by model year 2018.
EU - Biofuels Directive (2003/30/EC)	• Sets a minimum EU market share for biofuels. • Has led to a major increase biodiesel production.
EU - Fuel Quality Directive (2009/30/EC)	• Reduction in life cycle GHG emissions from energy supplied. Binding target of 6% 1st step – could increase to 10%. • Phasing in of 10% Ethanol (E10) petrol. • Increase of allowed biodiesel content in diesel to 7%.
EU - Renewable Energy Directive (2009/28/EC)	• Requires member states to obtain at least 20% of their total energy from renewables by 2020.
EU - Promotion of clean and energy-efficient road transport vehicles - Directive (2009/33/EC)	• Requires contracting authorities, contracting entities and operators to take into account lifetime energy and environmental impacts (including CO_2) when purchasing road transport vehicles • The objective is to promote and stimulate the market for clean and energy-efficient vehicles
Japan - Heavy-duty fuel economy standards (part of the 'Law Concerning the Rational Use of Energy'	• Applies to diesel vehicles of GVW > 3.5 t, including trucks and buses. • Fleet average fuel economy is estimated at 12.2% for trucks and 12.1% for buses.

Table 3. EU, US and Japananese Low-Carbon Transportation Policies

Compiled from: [12; 39; 40; 41; 42; 43]

The method of fuel economy or CO_2 emissions measurement for heavy-duty vehicles needs to be carefully established to provide a meaningful metric. In the EU, passenger car CO_2 emissions are measured in g/km with each manufacturer set individual targets based on the average mass of their EU car fleet. There has been some criticism of this method including that it reduces the benefit of vehicle weight reduction and mass is not necessarily a reflection of car performance [42; 44]. For heavy-duty vehicles different metrics will be required based on the drive cycle of the vehicle. For long-haul vehicles a work based measurement of CO_2 or fuel consumption per unit of payload carried is widely accepted to be the most appropriate method [45]. The recently introduced US *Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles* use gram per ton-mile and gallon per 1,000 ton-mile measurements for combination tractors [43].

2.3 Technology Roadmaps

Government commissioned roadmaps, focused on lowering vehicle emissions and reducing dependence on fossil fuels, have been commissioned by the majority of developed countries. Separate heavy-duty roadmaps have also been produced in the UK and US.

In the EU the European Road Transport Research Advisory Council (ERTRAC) aims to *'Provide a strategic vision for the Road Transport sector with respect to Research and Development'*. ERTRAC aims to co-ordinate the individual efforts of its members (including 19 EU member states) while recognising the individual requirements and resources of each country. The Road Transport Scenario 2030+ "Road to Implementation" focuses not only on vehicle technologies but other key areas such as infrastructure, economic development, and information technology. Technology development is focussed on ICEs for the foreseeable future. Mild hybridisation is also expected in order to assist the ICE at peak demand using recovered energy, such as regenerative braking and waste heat recovery, in suitable applications [46].

The Automotive Council in the UK has produced a *Low Carbon Commercial Vehicle and Off-Highway Roadmap* in conjunction with the UK government and automotive manufacturers (see Figure 12). It identifies technology developments for light-duty, medium-duty and heavy-duty drive cycles. The roadmap highlights the importance of continued investment in the development of powertrain technologies which can provide the high energy density required for heavy-duty applications. Heavy-duty development is focused on ICE efficiency improvements and alternative fuels until 2050 [47].

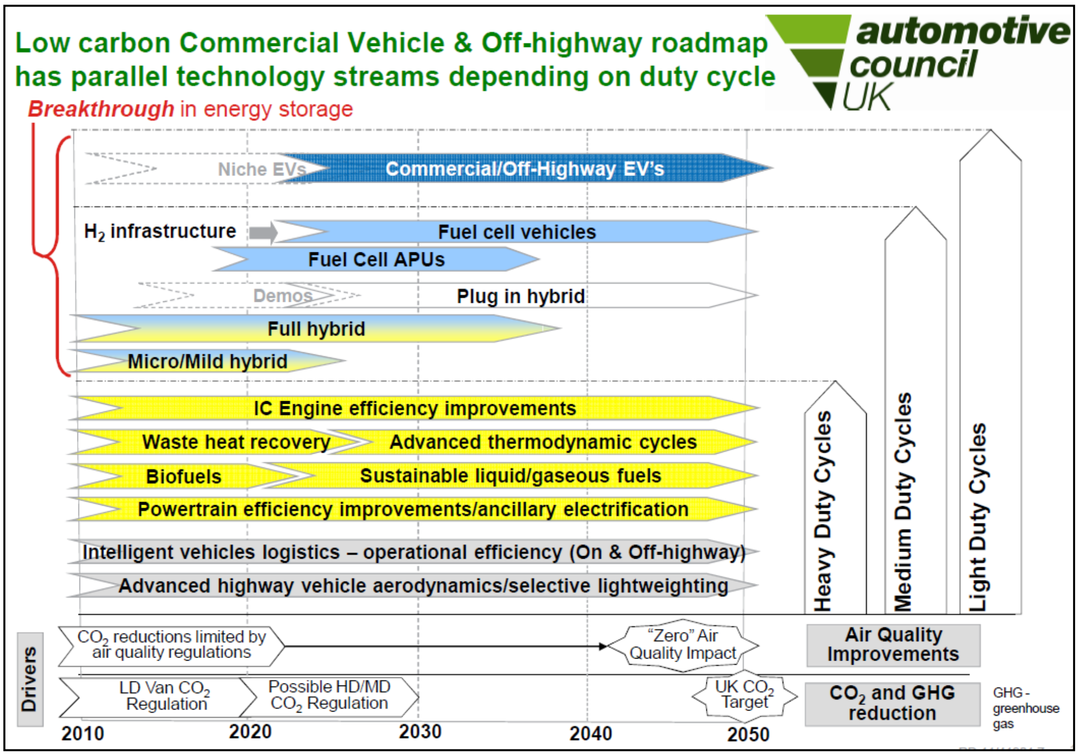


Figure 12. Automotive Council - Low Carbon Commercial Vehicle Roadmap

Source: Automotive Council UK [47]

In the US the Department of Energy Efficiency and Renewable Energy (EERE) 21st century truck partnership and vehicle technologies programmes provide roadmaps for CVs. The CV areas of these programmes focus on advanced ICE development, fuel technology development (including alternative fuels infrastructure), and materials R&D. Further research into hybrid and fuel cell technology for heavy-duty applications is also included [48; 49]. These are both key elements of the DOE funded Super Truck programme (see Section 2.1).

A key aspect of all the roadmaps discussed is that they have been produced in close partnership with the automotive industry. This demonstrates the recognition that a coordinated plan is required to achieve the policies discussed in Section 2.2. Partnerships between government and industry are crucial to the effectiveness of these roadmaps.

2.4 Patent Analysis

Patent analysis has become an established method of analysing technological innovation [50; 51]. The research and development funding in a particular field has been shown to correlate with the number of patent applications raised [52]. As already established in this chapter, both governments and the automotive industry are focused on continued development of the ICE and alternative fuels for heavy-duty transport applications. To ensure that all potential options were addressed in the report a patent search was carried out using the search terms “fuel injection”, “fuel delivery” and “alternative fuel” to investigate technologies patented over the last five years. The search was carried out using the world intellectual property organization (WIPO) patentscope database[2].

Patent descriptions are often left intentionally vague by the applicants in order to protect the purpose of the invention and ensure that the patent covers as broad use of the invention as possible. For example, differentiating between the fuel injection systems for different fuels and market segments is not purposefully made. The search was therefore carried out in stages as to gradually narrow in on the technologies being developed (the search methodology is discussed in further detail in Appendix 3).

A further difficulty faced for this particular study is that the fuel systems are generally developed by first tier fuel injection equipment (FIE) manufacturers. Therefore in many cases the CV manufacturers themselves will not be the applicant. For this reason searches both with and without the applicant being

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[2] http://www.wipo.int

specified were undertaken. This enabled the initial searches to highlight the potential applicants which have the potential to affect the market. The search was then narrowed down to the CV manufacturers identified in Section 2.1 and leading FIE manufacturers identified in the initial searches.

The number of patent applications made by the CV manufacturers can be seen in Figure 13. Results filed by Toyota but not related to the Hino brand are not shown due to the large quantity. To make the analysis of the Toyota patent results manageable they were further filtered to those within the *'supplying combustion engines in general with combustible mixtures'* patent classification. Patent applications made by the FIE manufacturers are shown in Figure 14. A summary of the technologies patented by these companies is given in Table 4 and Table 5.

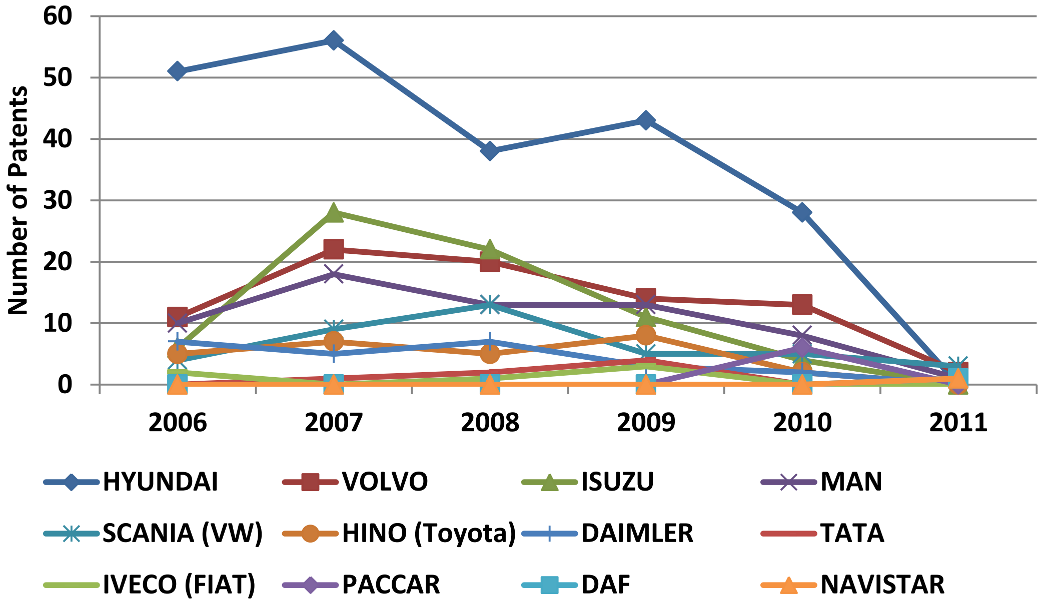

Figure 13. Patent Applications made by CV Manufacturers

Source: WIPO

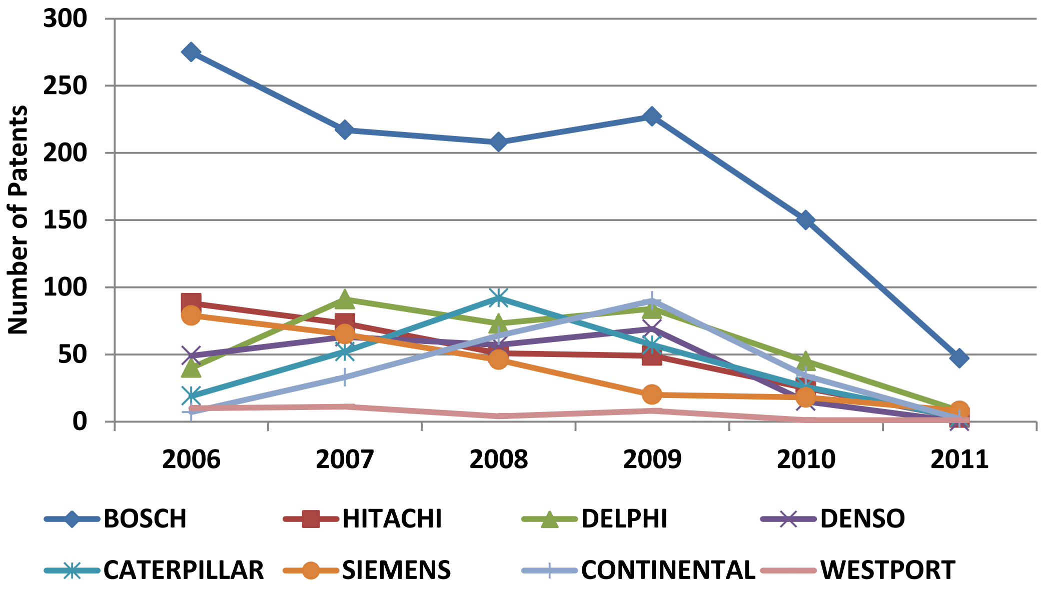

Figure 14. Patent Applications made by FIE Manufacturers

Source: WIPO

Company	Patent Technology Focus
Hyundai	• Increased fuelling control of existing FIE • NOx reduction exhaust technology • Corrosion resistant coating of valve seats • LNG and Ethanol powertrain development
Volvo	• DME Fuel Injection systems • Exhaust purification & after treatment • Hybrid powertrain control systems • Bi-fuel / dual-fuel engine control • SCR & EGR • Variable valve actuation
Isuzu	• Exhaust gas purification systems and system control • Combustion control (fuelling quantity feedback and correction) • Turbocharging • DME powertrain development
MAN	• Development of existing engine and FIE • High pressure seals • High strength and corrosion resistant materials • Biofuel specification • Dual-fuel - Diesel / NG powertrains Note: Half of the applications referred to larger marine diesel engines
Scania	• Vehicle drivetrain development • Vehicle drivability control • Powertrain monitoring & control systems (including cylinder malfunctioning) • DPF regeneration
Hino	• Exhaust gas purification / after treatment • DPF regeneration
Daimler	• Exhaust gas purification / after treatment • Injection quantity control • ICE and ICE control • High pressure fuel pump development
Tata	• Engine downsizing (2 cylinder LD) • Hydrogen generation
Iveco	• NOx control and monitoring • Urea tank design • SCR system control
PACCAR Inc DAF	• Hybrid control and information display systems • Corrosion & wear resistant coating of valve seats
Navistar	• Fuel injection control valve development (1 patent)

Table 4. CV Manufacturers Technology Focus Based on Patent Applications

Company	Patent Technology Focus
Bosch	• High Pressure FIE • Improved sealing of FIE components • Piezoelectric and solenoid actuators to increase injection control • FI control and injection quantity feedback • Increased strength materials • Nitriding and coating of component surfaces • Alternative fuel FIE
Delphi	• Improved FI control and injection quantity feedback • High Pressure pumps, valves and fuel injectors • Leak reduction from FIE components • Fast acting piezo and solenoid actuated injectors • Variable fuel delivery • In-cylinder pressure diagnosis • Fuel metering • FIE for alternative liquid and gaseous fuels
Hitachi	• High pressure fuel pump and injection systems • Variable Valve Actuation control • ECU and Injection Control strategies • Gas Turbine • Exhaust aftertreatment • EGR Systems • Electromagnetic valves
Denso	• Injection and combustion control • CR fuel injection systems • High pressure FIE • Piezo and electromagnetic actuators • Exhaust gas purification and system regeneration control • EGR systems
Caterpillar	• Variable pressure injection systems • Piezo and solenoid actuators • High pressure pumps and injector components • Increased fuel injection control & multiple injection • Injection systems for alternative and blended fuels • Multi-source fuel systems • Coating and material development to reduce corrosion and wear of components • Exhaust aftertreatment & NOx reduction • Turbocharging • Variable valve actuation and control • Electric turbocompound control

Company	Patent Technology Focus
Siemens	• Piezo and solenoid actuated injectors • Flex-fuel, dual-fuel, and multi-fuel injection systems • Multiple injection • High pressure injector components and sealing devices • Improved injection control • Gas turbine injection and control • Combustion chamber pressure detection
Continental	• Piezo and solenoid actuators • High pressure fuel injectors and pumps • Flex-fuel FIE • Improved injection timing control • NG gas fuel and injection systems • Gas leakage detection • Engine start / stop control systems • Exhaust aftertreatment system control
Westport	• Gaseous fuel injection and control – NG/methane/hydrogen • Dual-fuel injectors and connectors – liquid/gaseous fuel mix • Gas metering • Fuel injection control including piezo controlled actuators

Table 5. FIE Manufacturers Technology Focus Based on Patent Applications

Common trends across the manufacturers are clear from the research. Fuel system components which can withstand higher pressures (used to improve the atomisation of the fuel and reduce emissions) feature extensively and are a major step towards meeting both Euro VI and future emissions legislations with existing fossil fuels [53]. Development of exhaust based emission reduction systems such as EGR and SCR, in conjunction with DPF are also prominent due to the imminent introduction of the Euro VI legislation.

Developments in engine control systems to allow advanced engine control strategies, fuel injection systems with increased injection control (both solenoid and piezo), and fuel injectors which can supply varying fuel quantities dependent on engine conditions through variable injection hole configurations, demonstrate the focus on precise control throughout the combustion cycle.

There is also a focus on corrosion and wear resistant materials. These developments not only apply to the base component material but also to coatings. This is interpreted by the author as a requirement to cope with not only the increasingly hostile conditions within the engine, for example, due to higher pressures and varying combustion strategies, but also the varying global fuel standards, fuel quality and alternative fuel mix.

The development of low-carbon fuels and the development of fuel injection systems to allow their use in future ICEs can be seen in patent applications from all of the companies. The final choice of fuel, whether it is biodiesel, dimethyl ether (DME), biogas, etc appears to be less certain. There is also a trend showing the development of dual-fuel, bi-fuel, and flex-fuel engines[3], able to run on more than one fuel, usually a low-carbon alternative alongside the established fossil fuels. Some of these systems use dual-fuel as part of the emissions reduction strategy while others allow the powertrain to be fuelled independently by either fuel, suggesting a concern over the lack of infrastructure to ensure the new low-carbon fuels are readily available.

There is a reduction in the number of patents published during 2010 and 2011. This is partly due to the time it takes for these patents to be processed and entered onto the database. At the point this patent review was carried out in June 2011 some of the patents issued during these two years were still not available on the WIPO database. The other main reason is the reduction in Euro VI emissions technologies being patented. With Euro VI emissions regulations due to take effect at the end of 2012 these technologies have

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[3] Dual-fuel refers to engines which are fuelled continuously by a mixture of two fuels supplied from two separate fuel systems (for example, a CI gas engine which uses diesel as an ignition source).

Bi-fuel refers to engines which fuelled by different fuels supplied independently from different tanks (such as gasoline and LPG).

Flex-fuel refers to engines which can run independently on different fuels, or a mix of different fuels, supplied from the same tank (such as gasoline and ethanol).

mostly been patented and are now being productionised for implemented into Euro VI vehicles.

As patent details are often left purposefully indistinct the end use of the invention in some cases is the author's interpretation. It should also be noted that just because an invention is patented does not mean it will ever make it to the product line of the particular company. The broad range of companies reviewed during the patent analysis, is an attempt to negate these unsuccessful inventions. Lastly, not all ideas are patented in the first place in an effort to delay competitor's entry into new technological fields. The review of academic literature, independently commissioned reports, as well as the manufacturers published technology attempts to limit the exclusion of technologies undisclosed by the manufacturers themselves.

2.5 Academic Literature

The ScienceDirect[4] and Scopus[5] databases were used to provide an overview of academic literature published on powertrain technology which has the potential to satisfy the demands of heavy-duty automotive applications. This review investigates both the technologies identified in the previous sections and new technologies which are not yet being openly publicised by the automotive manufacturers. This review is not only limited to journal articles but also trusted research institutes such as the OECD, NREL and the IEA.

2.5.1 Hybrid Electric Powertrains

Papers related to heavy-duty hybridisation are far more limited in number than those connected to light duty and passenger vehicles. They are also largely theoretical, using modelling and simulation to form their conclusions [54; 55]. Commercial vehicle hybrid development is focused on buses, delivery trucks, and utility trucks, where the greatest fuel consumption

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[4] http://www.sciencedirect.com

[5] http://www.scopus.com

benefits are seen. These stop start applications are able to collect and store the kinetic energy during braking to recharge the battery pack. The energy is then used to accelerate the vehicle, reducing fuel consumption. It also allows the vehicles to run in an electric only mode in inner city areas positively influencing local air quality.

Figure 15 shows the result of a study carried out by TIAX for the National Research Council and identifies the influence of different technologies on medium and heavy-duty vehicles from a 2008 baseline [56].

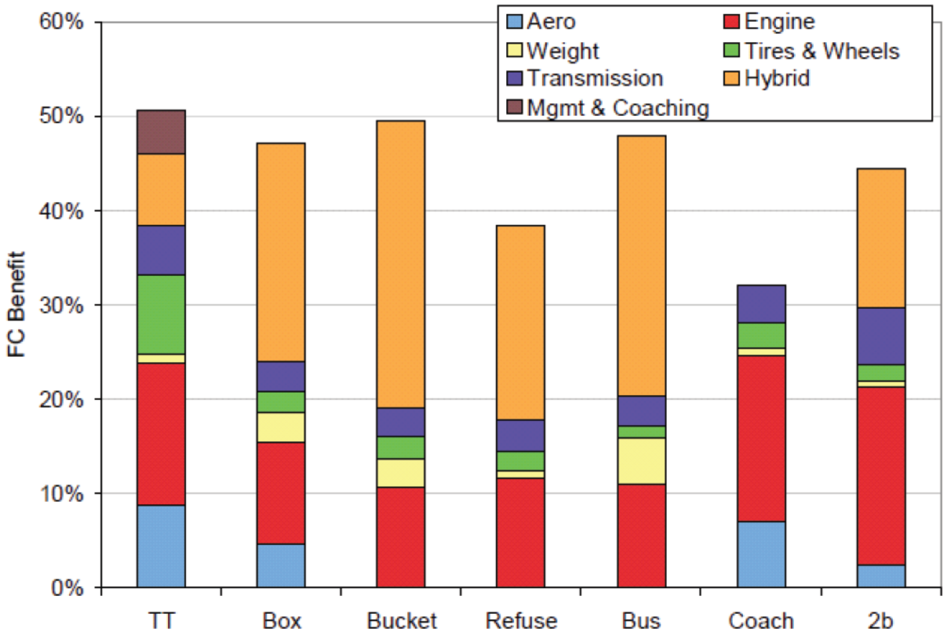

Figure 15. Comparison of 2015-2020 fuel saving technologies

Class 8 Tractor trailer (TT), Class 3-6 box (box), Class 3-6 bucket (bucket), Class 8 Refuse (Refuse), Transit bus (bus), Motor coach (coach), and Class 2b pickups and vans (2b)

Source: TIAX LLC / NRC [56]

Of all the assessed vehicles, Class 8 tractor trailers show the least benefit of hybrid technology. These results were confirmed in simulations carried out by Argonne National Laboratory [55].

Key issues with the use of HEV technology for heavy-duty vehicles are the volume, weight, cost and life of the battery [57; 58]. Heavy-duty vehicles consume between 1000 Wh/mile to 2000 Wh/mile requiring a 30 to 60 kWh battery to provide a 30 mile range. Comparing this requirement to the 5 to 12 kWh battery required to provide the same range for a light duty vehicle demonstrates the scale of the problem [59]. Haulage companies are unlikely to favour the additional weight of the hybrid system if it reduces the overall payload of the vehicle. With heavy-duty engines expected to have a serviceable life of up to one million miles, the target life of 150,000 miles for HEV battery packs and target costs of around $20/kW would add considerable cost over the life of the vehicle [60].

Another issue is the power density of current battery technology (see Figure 16). Although batteries provide good energy density (allowing them to be power the vehicle over a reasonable period of time), power can only be discharged from the battery at a specific rate. The rate at which the battery pack can be discharged and recharged is limited to increase battery life, reduce degradation and avoid events such as thermal runaway leading to catastrophic failure. This requires the ICE or another form of energy storage to be used for high power demands during the drive cycle such as acceleration. One solution is the use of ultra-capacitors which are able to capture and store the large amounts of energy generated during braking and then release this energy when it is required for acceleration. This once again favours urban start-stop applications over long-haul [61].

Major advances in electric storage would be required to enable the use of hybrid electric powertrains in heavy-duty drive cycle applications.

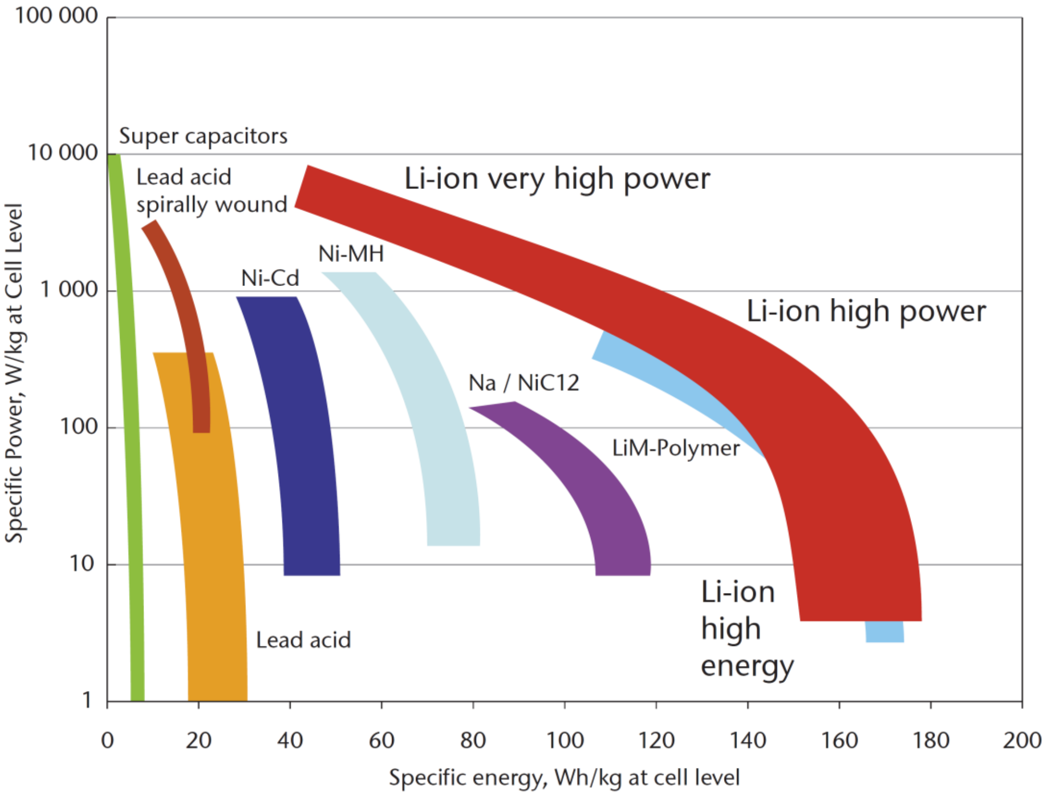

Figure 16. Specific energy and power of different battery types

Source: IEA [62]

2.5.2 Hydraulic Hybrids

Hydraulic hybrids are another option for heavy-duty vehicles. In these systems a hydraulic accumulator and pump is used (in place of the battery and electric motor in an electric system). The main advantage is the high power density of the system. The downside is the low energy density which makes this system most suited to heavy vehicles with stop-start drive cycles, such as refuse vehicles [61]. The usual ICE powertrain is still required for regular operation due to the low energy density of the system. The system carries a weight and cost penalty which fleet operators are unlikely to accept for long-haul, payload dependant, applications.

2.5.3 Alternative ICE Fuels

Academic literature focused on the continued development of compression ignition (CI) internal combustion engines and alternative ‘low-carbon’ fuels is vast. First-generation biofuels account for the majority of sustainable fuel produced around the world. The increase in biodiesel production over the last five years can be seen in Figure 17. First generation fatty acid methyl ester (FAME) biodiesel is currently the most established alternative fuel for use in CI engines [63].

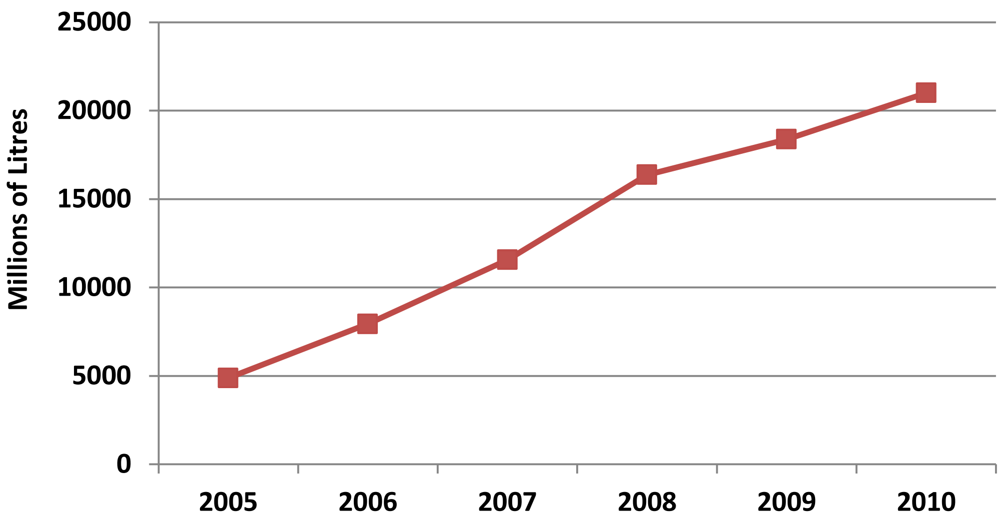

Figure 17. World Biodiesel Production 2005 – 2010

Source: Compiled from OECD-FAO Aglink Database [64]

There is a consensus within the literature that the blending of FAME biodiesel with mineral diesel fuel can offer significant emissions and lubricity improvements [65; 66; 67]. Reductions in PM, CO and HC emissions have been confirmed in the majority of published studies [68]. There is an increase in NO_x emissions caused by increased temperatures during combustion. This side effect however can be effectively managed by engine tuning, modification of the fuel, or using NO_x-traps (made possible due to the low sulphur content) [65].

It is now generally accepted in the published literature that first-generation biodiesel manufactured from oil crops, which need to be grown on prime agricultural land, are not sustainable. There are a number of concerns both around the emissions generated by indirect land use change (iLUC) and the increasing of food prices due to competition between food and energy feedstock [69; 70; 71]. Second and third-generation biofuels aim to address many of the technical and sustainability concerns raised by first generation fuels.

The terms ‘second’ and ‘third-generation biofuel’ cover a number of different technological options including the manufacture of synthetic diesel from lignocellulosic[6] biomass (second generation), and biodiesel from the transesterification of sustainable oil sources such as algae (third generation). These new generation fuels are covered widely in academic literature. The transfer of these technologies from small scale trials to efficient and cost effective commercial processes still requires substantial research and development [72; 73; 74; 75]. The European Joint Research Centre Biofuels Programme predicts that significant volumes of these fuels will not be available until beyond 2020 [76].

The majority of the literature is focused on the use of sustainable biomass such as energy crops, forestry, and waste wood for the production of biodiesel. There are two main second-generation processing routes for the conversion of biomass-to-liquid fuels, bio-chemical and thermal-chemical. The thermo-chemical conversion of biomass-to-liquids (BTL) is generally used for the production of synthetic diesel [72; 77]. These processes, and their technical challenges, are discussed further in Chapter 3.

Other prominent biomass derived fuels discussed in the literature for heavy-duty engines are DME and biogas. DME can be produced from the syngas produced by the thermo-chemical biomass conversion route used for the production of synthetic diesel [78]. DME is liquefied at low pressures simplifying on-board storage. It also offers reduced NO_x emission levels

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[6] “Lignocellulose is a botanical term used for the biomass from woody or fibrous plant materials, being a combination of lignin, cellulose and hemicellulose polymers interlinked in a heterogeneous matrix” [72].

compared to diesel and smoke-free combustion aiding local air quality [79]. However DME has around half the energy density of diesel increasing fuel consumption. A dedicated distribution network would also be required therefore limiting its attractiveness beyond captive fleets. Biogas is most commonly produced by the anaerobic digestion the biomass. Mainly constituted of methane (CH_4) and carbon dioxide (CO_2) biogas can be used as substitute for CNG or LNG in internal combustion engines [80]. Biogas also offers a higher energy conversion efficiency (per hectare of land) compared to biodiesel and BTL fuels.

The IEA *Sustainable Production of Second-Generation Biofuels* report assesses the globally available forestry and agricultural residues in 2030. It concludes that if 25% of these residues were converted to either BTL-Diesel, Bio-SNG or LC-Ethanol this would produce enough biofuel to fully cover the WEO 450 Scenario demand [81]. This assessment is heavily dependent on resources from developing countries which currently do not have an adequate infrastructure or domestic funding opportunities to support second-generation biofuel plants. Although the global biomass resource potential is widely discussed in the literature, many questions remain to be answered before an accurate assessment of economic and environmental impact can be made [71; 81; 82; 83]. Local data is limited especially from developing countries where current commercial energy markets are limited or non-existent [40; 84].

Potential fourth-generation biofuel conversion processes are briefly mentioned in current literature and cover options such as petroleum style hydro processing, advanced biochemistry, and genetically modified carbon negative crops. Data however is extremely limited and therefore these options are not discussed further in this Thesis.

Not all potential alternative fuels were produced from biomass and oil crops, natural gas has been demonstrated in numerous studies to reduce emissions compared to diesel and gasoline [85; 86; 87]. Although many of the studies in the literature focused on spark ignition (SI) engines there has been increasing interest in the use of LNG for heavy-duty applications using a CI engine with diesel ignition [88]. These dual-fuel alternative powertrains are discussed further in Chapter 3.

Hydrogen can also be used be used as an alternative ICE fuel and this is discussed further in the following section. Many of the issues associated with hydrogen including infrastructure, storage and production relate both to hydrogen required for ICE and fuel cell vehicles.

2.5.4 Hydrogen and Fuel Cells

Hydrogen (H_2) can be produced from any primary energy source and can be used as a fuel in both ICE and fuel cell (FC) vehicles [89]. Short term hydrogen production is expected to progress from the current mainly fossil fuel production routes such as natural gas (NG) steam reforming, and coal gasification, to nuclear and hydropower electrolysis. Within 10 years hydrogen production is expected to include biomass feedstock along with electrolytic hydrogen from renewable resources such as wind and solar power. Longer term (20 years from now) carbon capture and storage (CCS) is expected to see emissions free hydrogen generation from fossil fuels as well as high-temperature electrolysis and photolysis [89; 90].

The delivery of hydrogen from production facilities to the point of sale presents major infrastructure challenges and requires a large investment. The global investment required to supply hydrogen to the transport sector is estimated to be between $0.1 to $1.0 trillion for pipelines and $0.2 to $0.7 trillion for filling stations[7] [91]. A co-ordinated roadmap is required if hydrogen is going to be successfully introduced. Currently the automotive industry finds itself in a ‘chicken and egg’ scenario where the lack of a hydrogen

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[7] Although this investment is substantial, it should be noted that existing energy supply systems will require an estimated investment of $25.6 trillion in order to meet the worlds 2030 predicted energy needs [7].

infrastructure means the public will not purchase hydrogen vehicles they cannot fuel, OEM's will not develop and manufacture vehicles which they cannot sell, and fuel providers will not provide fuel for a market that does not exist [92; 93].

There is likely to be three main phases in the introduction of the hydrogen infrastructure; the early implementation phase (2015-2020), transition phase (2015-2030) and the diffusion phase (2030-2050) [93; 94; 95]. The infrastructure is expected to begin in densely populated areas with high transport demand and for fleets where central refuelling is acceptable. Expansion of the infrastructure into more rural areas is likely to follow until a fully connected network is established.

Although an H_2ICE heavy-duty vehicle would allow the use of H_2 in the short term using current technology, storing enough hydrogen on-board the vehicle to achieve an acceptable driving range is a significant challenge. LH_2 offers 8MJ/litre compared to 31.2MJ/litre for gasoline, requiring four times the storage volume [96]. The storage of hydrogen in solid materials and liquids show the potential for increased volumetric density. Although these storage systems are currently being researched by the automotive manufacturers they have not yet being seen in prototype vehicles [97]. A major technological breakthrough would be required for these solutions to be used in practical applications [91]. Both the weight of the additional storage capacity, plus the lack of a suitable infrastructure for at least the next twenty years, means long-haul heavy-duty vehicles are unlikely candidates for conversion to H_2ICE.

FC vehicles face similar challenges for on-board storage but offer a far greater range than H_2ICE vehicles [94; 98]. In light-duty applications H_2ICE vehicles such as the BMW Hydrogen 7 H_2ICE's have been shown to offer a range of approximately 200km from 8kg of hydrogen while a fuel cell vehicle is expected to offer up to 500km from 4-5kg [99; 100].

Fuel cells still require significant technology development to make them a viable option for vehicle powertrains. The key issues relating to the use of fuel cells are similar to those already discussed for HEVs and include size, weight, cost, and long-term durability [98; 100]. Adoption of fuel cells is likely to begin in smaller niche markets, such as centralised distribution and public transport applications, before entering the mainstream. The European Commission's HyWays '*European Hydrogen roadmap'* does not predict significant market penetration of hydrogen technologies until 2050 [101]. One niche market for which fuel cells do show high potential is as a truck auxiliary power source on long-haul vehicles [102; 103]. The requirement for sustainable auxiliary power units (APUs) is being driven by regulations such as California's anti-idling regulation which aims to reduce emissions from the unnecessary idling of motor vehicles [104].

2.6 Low-Carbon Technology Review Conclusions

The internal combustion engine is expected to remain the focus of heavy-duty powertrain development for the foreseeable future, and certainly until beyond 2030. Development of low-carbon ICE based powertrains for heavy-duty applications is the focus of both the leading CV manufacturers and government CV roadmaps. Although the heavy-duty technologies discussed in current academic literature covers a much wider range, the focus is still on ICE improvements and alternative fuels. Investigations into hybrids and the other technologies currently being developed for use for light-duty applications are largely theoretical and based on modelling and simulation with their conclusions pointing to the requirement for a major technological breakthrough. Long-haul heavy-duty vehicles have quite different demands and characteristics to light-duty vehicles. Power requirements, annual mileage and life of the powertrain are all considerably higher in heavy-duty applications making the use of emerging light-duty technologies unacceptable. A summary of typical characteristics for light-duty (LD), medium-duty (MD) and heavy-duty (HD) CV applications is given in Table 6.

Characteristic	LD Commercial Vehicle	MD Commercial Vehicle	HD Commercial Vehicle
GVW	3.5t – 6t	>6t – 15t	>15t
Typical Drive cycle	Intermittent light duty	Continuous Daily Operation – Start-stop delivery	Continuous Daily Operation - Long Haul
Typical Engine Disp.	1.5 – 3 litres	4 – 7 litres	7 – 16 litres
Rated Power (kW)	~60-150kW	~80 - 260kw	~250 to 450kW+
Expected Lifetime Mileage	Up to ~150k	→	Up to ~1M

Table 6. Comparison of Commercial Vehicle Characteristics

Continued development of auxiliary components, to reduce parasitic losses, and waste heat recovery technologies are expected as the reduction of fuel consumption and CO_2 emissions becomes a legislative requirement. The integration of alternative fuels to reduce the reliance on fossil fuels, both for sustainability and fuel security reasons, is also high on the agenda.

The use of hybrid electric vehicles, without an unpredicted breakthrough in electric storage, will remain concentrated on buses and trucks operating in urban environments. Although an increase in electric auxiliary vehicle accessories is predicted due to focus on reducing engine losses. Fuel cells are expected to be used for auxiliary power generation but not as the primary powertrain source in heavy-duty vehicles. There are however likely to be exceptions to this rule in the case of high profile research based projects and public relations exercises. Hybrid electric and fuel cell vehicles are expected to continue to dominate the research programmes of automotive manufacturers and their suppliers with the technologies being seen increasingly in passenger and light-duty commercial vehicles which can accept lower energy density solutions. The future use of these technologies in heavy-duty vehicles will continue to be investigated as the technologies mature. Production volumes of heavy-duty vehicles are considerably less than that of the passenger car and light-duty CV markets (see Table 7), offering less opportunity for commonisation of components and component cost reduction. This makes the additional development costs required for such a transformational change more difficult to absorb by the manufacturers.

EU27 Registrations	2010
New Car Registrations	13,360,599
New LCV Registrations (1)	1,488,848
New Truck Registrations (2)	249,869
New Bus Registrations (3)	33,554
Total New Registrations	**15,132,870**

(1) Light Commercial Vehicles up to 3.5t (including light Buses & Coaches)
(2) Commercial Vehicles above 3.5t (excluding Buses & Coaches)
(3) Buses & Coaches above 3.5t

Table 7. Registrations of new motor vehicles in EU27

Source: ACEA [105]

There is no doubt that government initiatives have the ability to dictate which technologies succeed and which do not. Current heavy-duty emissions legislation is focused on tailpipe environmental pollutants whereas GHG based legislation should take into account the complete lifecycle emissions of the fuel. The correct technology will greatly depend on the final application and the US *Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles* regulations take a step in the right direction using a work based emissions metric for combination tractors. This moves away from the vehicle mass based metrics used for LD vehicles but is still based solely on the tailpipe emissions or fuel consumption figures. Short to medium term this is aimed at reducing the reliance of the US on imported fuels by reducing consumption but in the long term could divert effort from low-carbon alternative fuel programmes if the well-to-tank emissions are not taken into account. Governments need to avoid future technology forcing by basing legislation solely on tailpipe emissions. Taking into account well-to-wheel emissions is essential.

Chapters 3 and 4 evaluate the technical, economic and environmental influences of the potential heavy-duty ICE technologies identified in this chapter. Focus will be on technical improvements to existing ICE technology and alternative fuel ICE powertrains. The fuels investigated have been selected based on their ability to satisfy the requirements of heavy-duty drive cycles. This could be through their use as a straight alternative fuel, blended fuel with existing mineral diesel or as a fuel for dual-fuel powertrains. Also included in the review are fuels which featured prominently during the industry research. The technologies identified for evaluation in Chapter 3 and 4 are shown in Table 8.

Reduction of Parasitic Losses	Waste Heat Recovery	Alternative Fuels
Reduced Engine Loading of Auxiliary Components	Turbocompounding	First Generation Biodiesel
Electrification of Auxiliary Components	Bottoming Cycles	Second Generation Biodiesel and Syndiesel
		Third Generation Biodiesel
		LPG
		DME
		LNG and Biogas

Table 8. Potential heavy-duty powertrain technologies

3. A Technical Review of Potential Heavy-Duty Powertrain Options

This chapter presents a technical review of the key low-carbon powertrain solutions for future heavy-duty vehicles identified in Chapter 2.

3.1 Efficiency Improvements of Current ICE

There is an inherent link between fuel consumption and GHG emissions. The combustion of hydrocarbon fuels leads to the production of mainly CO_2 and H_2O, therefore any reduction of hydrocarbon combustion will reduce the amount of CO_2 produced. Current industry effort to increase engine efficiency, reduce parasitic losses, and develop energy recovery systems was identified in Section 2.1. An energy audit for a typical diesel engine is shown in Figure 18. With current trucks offering, on average, a peak of 42% thermal efficiency, the reduction of parasitic losses and recovery of waste heat energy has the potential to offer major fuel and therefore GHG emission savings [56; 106].

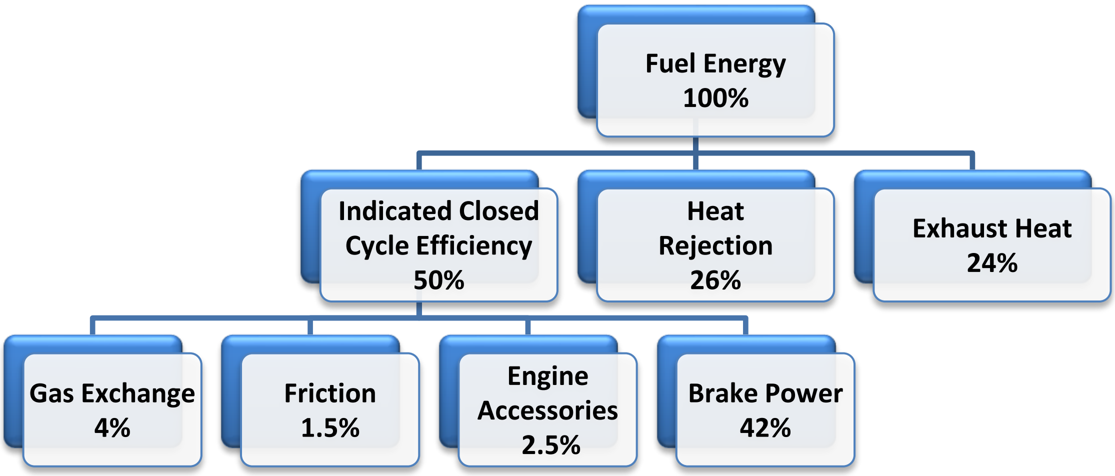

Figure 18. Typical diesel engine energy audit

Source: [56]

The conversion of parasitic gear or belt driven auxiliary components such as air-conditioning systems, water pumps, power-steering pumps and fans, to electric power is one option to increase engine efficiencies. These options are much more promising where sources of electric power are already available, such as hybrid vehicles, but are still estimated to offer at least a 2% efficiency improvement for long haul heavy-duty vehicles. Issues include the requirement of batteries, added weight and complexity if the system. Mechanical variable flow pumps as well as clutched air compressors are easier to integrate with the current technology and still offer CO_2 savings of between 0.5% and 4% [42].

Recovery of waste heat has the opportunity to offer considerable CO_2 savings, in the range of 3% to 6%, and also provide a source of power for the electrification of auxiliary components discussed above [107]. Turbocompounding and bottoming cycles can both be used to recover waste heat. Turbocompounding can either be mechanical or electrical. Mechanical turbocompounding technology is available from all of the major truck manufacturers. It uses an additional exhaust turbine to transfer recovered energy to the crankshaft to provide extra torque (see Figure 19). These systems are best suited to high load applications and therefore are well suited to long-haul heavy-duty drive cycles.

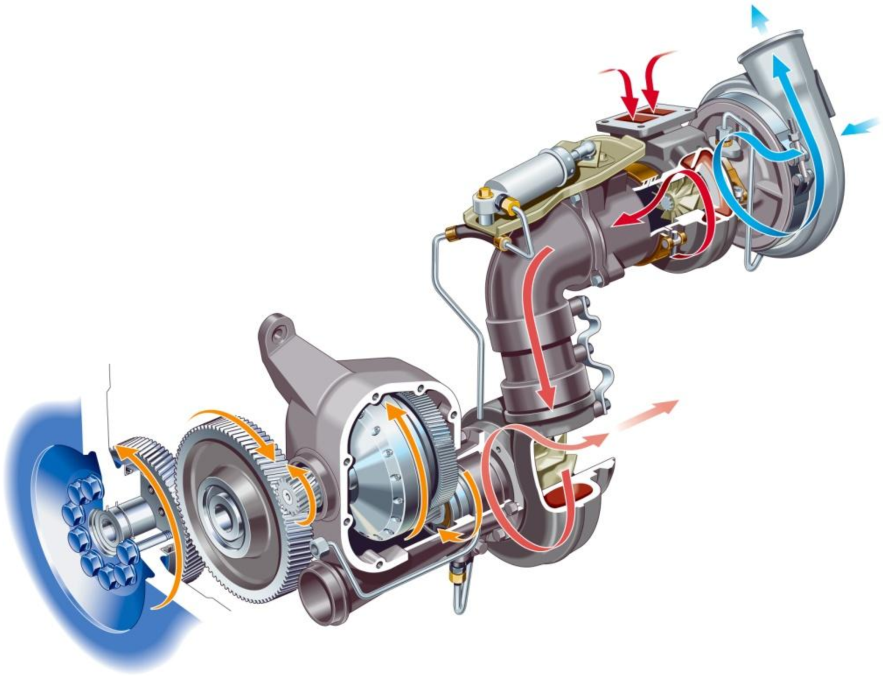

Figure 19. Scania turbocompounding principle

Source: Scania

In electrical systems the turbine is connected to an electric motor or generator for the recovered energy to be used by electrical components or stored in batteries for later use. These systems are currently in development and offer a source of power for the parasitic auxiliary items discussed previously. Once again the major issues are increased complexity, added weight and the requirement for batteries making the system much easier to integrate into new engine and vehicle designs which are already being designed to take advantage of the electrification of vehicle accessories and new mild-hybrid technology [42; 56].

Bottoming cycles, where waste exhaust heat energy is recovered using heat exchangers to drive a turbine to generate energy, are currently being investigated to improve heavy-duty truck engine efficiency. HGV's are expected to see the greatest benefits due to the engine spending long periods at high loads [42]. Both Rankine and Brayton bottoming cycles are currently part of the research and development programmes of CV engine manufacturers and are also part of the DOE Super Truck project [108; 109].

The Rankine cycle is a closed-loop thermodynamic cycle where water or an organic fluid is vaporised and condensed as it circulated between the low and high pressure side of the system. A schematic demonstrating the application and brake specific fuel consumption (BSFC) improvement of the Rankine cycle applied to the Caterpillar HECC (high efficiency clean combustion) HPL EGR (high-pressure loop EGR) waste heat recovery system can be seen in Figure 20. Heat is extracted by two heat exchangers (EV and SH) to evaporate the fluid and superheat the steam. The steam powers the turbine, generates energy through the use of a generator, and powers a pump which circulates the fluid around the system. The energy from the generator can be used to provide power directly to the crankshaft or an energy storage system. The recuperator (RC) and condenser return the steam to a liquid before beginning the cycle again. A radiator is also required to reject heat from the system.

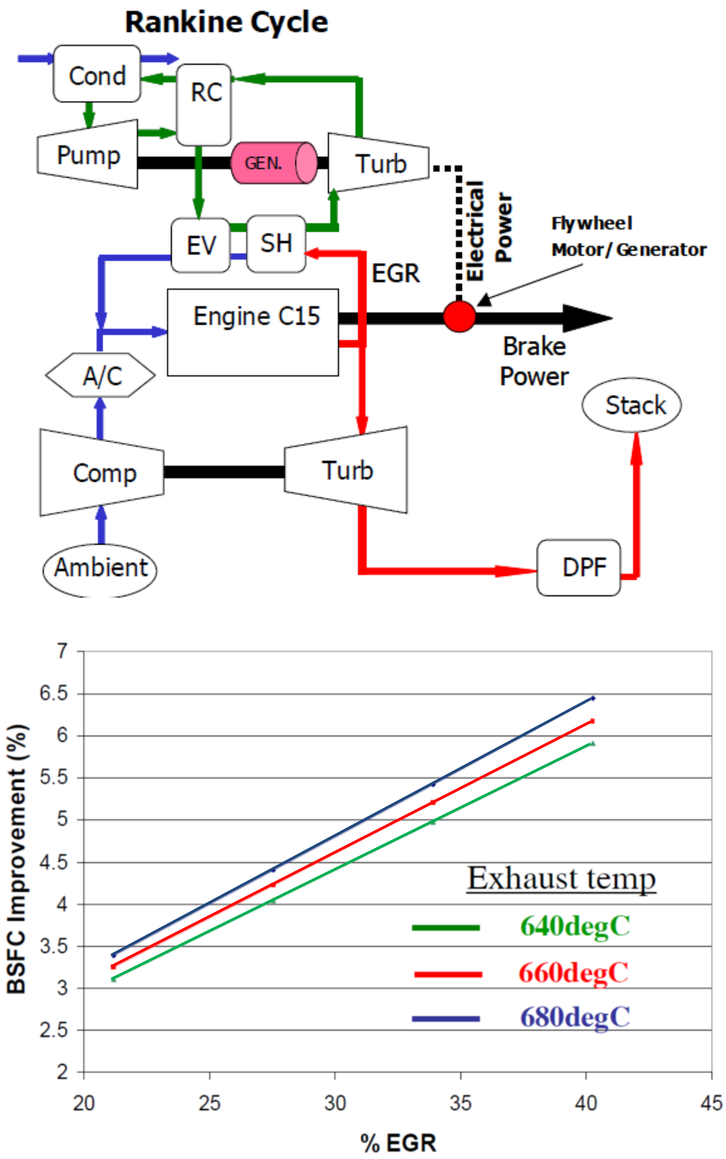

Figure 20. Rankine cycle application and BSFC improvement

Source: Caterpillar Inc. [110]

The Brayton cycle is an open-cycle system and is typically used to describe gas turbines. The heat exchanger (HE) extracts the EGR waste heat energy in place of the typical EGR cooler. The compressor draws in ambient air. The expansion of the air as it passes through the HE powers the turbine, which in turn powers the generator to produce energy. The energy from the generator can, once again provide power directly to the crankshaft or stored. The application and BSFC improvement of the Brayton cycle applied to the Caterpillar waste recovery system can be seen in Figure 21.

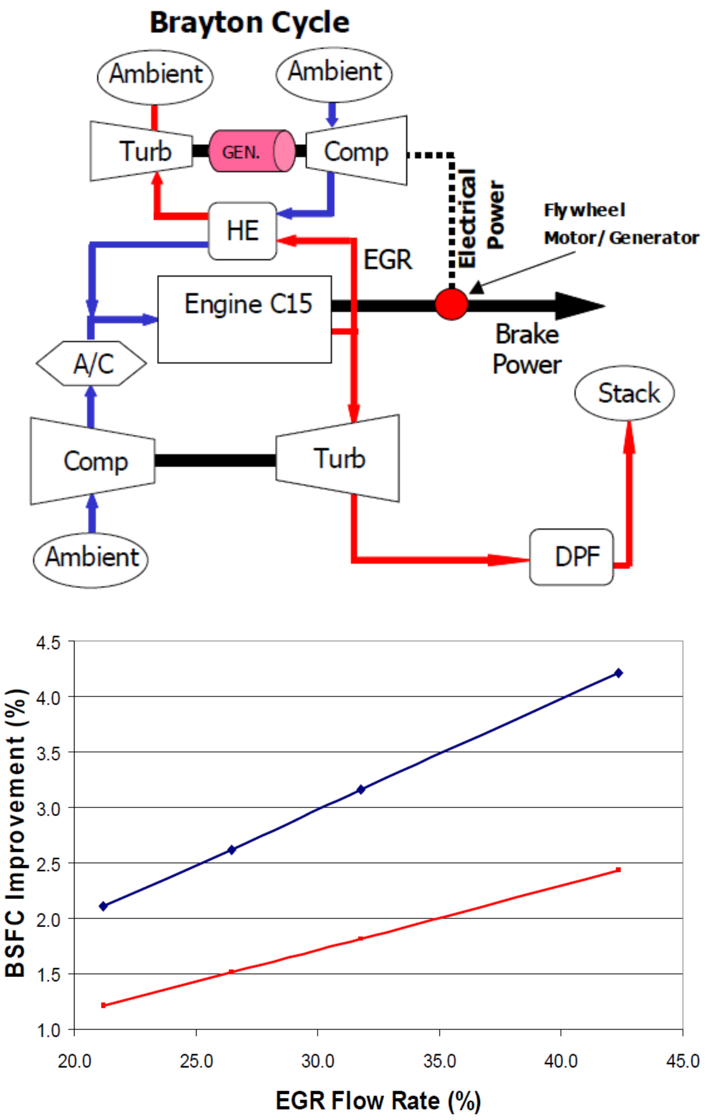

Figure 21. Brayton cycle application and BSFC improvement

Source: Caterpillar Inc. [110]

Although the Rankine cycle has been judged to offer increased cycle efficiencies over the Brayton cycle the additional fluid and increased cost, due to additional components, has divided opinions on which is best suited to use in future heavy-duty vehicles. Packaging and the additional weight of both systems are again fundamental challenges which must be addressed to gain market acceptance.

The technologies discussed in this section, although offering a reduction on fuel consumption and GHG emissions, do not change the basic power requirements of the heavy-duty engine. Therefore the base powertrain technology for long-haul applications, the internal combustion engine, does not change in a significant way. Downsizing is only possible for a small number of applications where the conditions specifically sit at the lower end of the heavy-duty drive cycle. The benefits of technologies such as cylinder deactivation, which vary the engine displacement under different engine loads, are also limited due to the reduced amount of time the engine spends at partial load during heavy-duty drive cycles. Cylinder deactivation has not yet seen a transfer from light to heavy-duty applications. BSFC improvements for each of the technologies discussed are shown in Table 9.

Technology	BSFC Reduction
Mechanical Variable Speed Pumps	0.5% - 1.5%
Clutched Air Compressors	Average saving 3.5% for long haul vehicles
Mechanical Turbocompounding	0.5% (low engine load – 80% turbine efficiency) 4.5% (full engine load – 80% turbine efficiency)
Electrical Turbocompounding	2% - 8% (standard T/C efficiency)
Rankine Cycle	3% - 6.5% (depending on EGR rate)
Brayton Cycle	1.5% - 4% (based on 80% T/C efficiency)

Table 9. BSFC reduction potential of reviewed technologies

Compiled from: [42; 107; 110; 111]

3.2 The Effects of Exhaust Emission Reduction Technology on Fuel Consumption

There is a potential conflict between the current heavy-duty environmental pollutant based emissions legislation and future GHG emissions regulations. The impact of additional powertrain components on the overall power demands of the system must be considered during the assessment of new technology. The use of emission control devices such as diesel particulate filters (DPF), used to control particulate matter (PM) emissions, exhaust gas recirculation (EGR) and selective catalytic reduction systems (SCR), used to reduce NO_x emissions, lead to an increase energy demand from the engine which could lead to an increase in fuel consumption. The change from Euro V to Euro VI emissions legislation has led to OEM's moving from SCR only or EGR plus DPF aftertreatment systems to systems using all three technologies. Ricardo expect the requirement of higher backpressures required for the EGR and DPF systems, plus the need for DPF regeneration, to increase fuel consumption by around 3% in early Euro VI vehicles [42]. For Euro V engines currently using EGR and DPF technologies, the addition of SCR should not increase fuel consumption further due to lower EGR rates being required.

3.3 Alternative Powertrains

The replacement of the traditional diesel powertrain with an alternative power source is another option for future low-carbon heavy-duty vehicles. As previously discussed the use of HEVs and FCVs is currently not viable mainly due to the energy density, cost and power-to-weight issues. Alternative powertrains are more likely to be an evolution of the traditional diesel ICE to allow the engine to run with a wider range of fuels. Dual-fuel powertrains which enable the engine to run on a mixture of diesel and other low-carbon fuels are seeing increased market interest. The primary choice for heavy-duty powertrains is diesel and natural gas (NG) although other gaseous fuels such as LPG and biogas can also be used.

There are two key dual-fuel approaches being seen for use in heavy-duty vehicles. The first introduces the gaseous fuel into the inlet manifold where it mixes with the air before being introduced to the cylinder. These systems are currently available both for installation by the OEMs or conversion of existing engines and are currently being marketed by Clean Air Power, Hardstaff and G-volution [112; 113; 114]. The G-volution system (shown in Figure 22) injects gas directly into the air intake tract prior to the turbocharger using two gas injectors to replace a calculated percentage of the diesel fuel. Although this system is currently marketed to take advantage of the widespread availability of LPG and the existing infrastructure, the system is able to be used with alternative fuels such as NG, biogas or hydrogen.

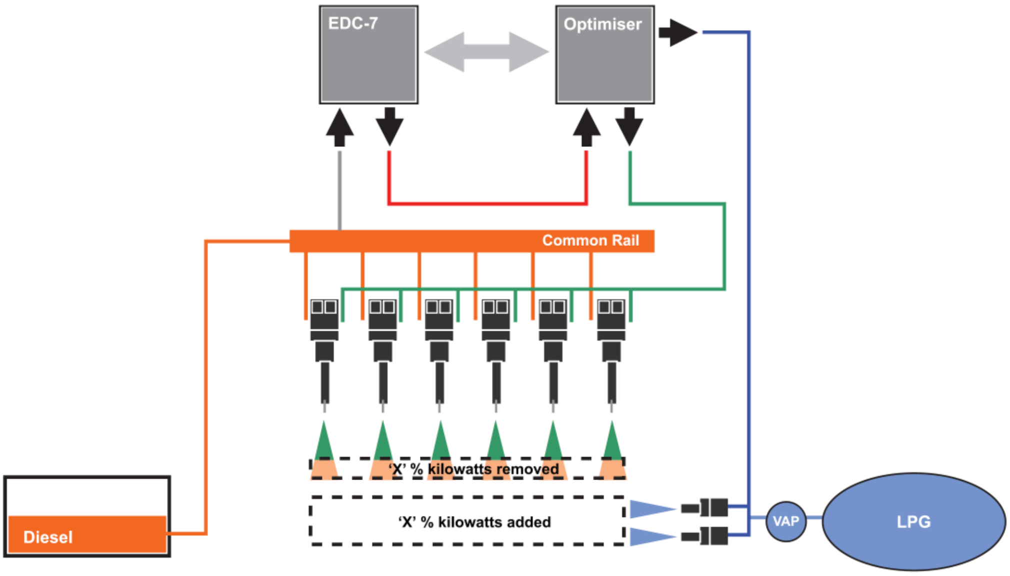

Figure 22. G-volution LPG dual-fuel system

Source: G-volution Ltd

The second approach, being marketed by Westport Innovations Inc, introduces the diesel and gas through a combined injector directly into the combustion chamber. The system injects a small amount of diesel as a liquid spark plug to ignite the main gas charge. Up to 95% of the diesel fuel energy is replaced with NG and CO_2 savings of up to 27% are promoted by Westport. An overview of the Westport high-pressure direct injection (HPDI) system can be seen in Figure 23. Westport currently have partnerships with Cummins, to produce HD NG engines, and with PACCAR to supply Westport HD branded engines for integration into Kenworth T800 and Peterbilt 386 / 387 class 8 trucks in the US [115].

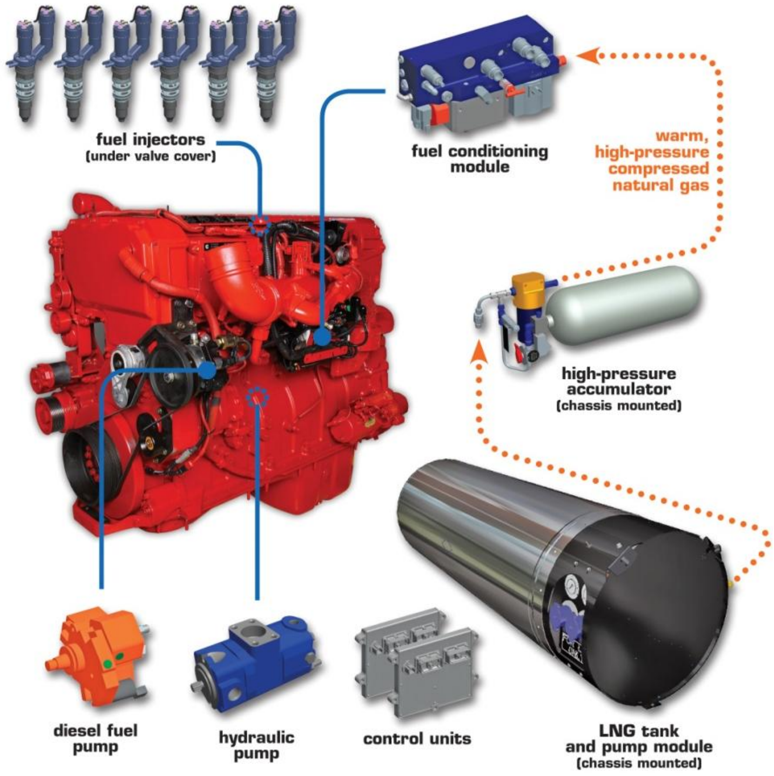

Figure 23. Westport LNG-diesel dual-fuel system

Source: Westport Innovations Inc

Currently 121 LNG trucks, utilising Westport dual-fuel powertrains, are in use as part of the South Coast Air Quality Management District's Drayage truck replacement programme for the ports of Los Angeles and Long Beach in the US [116]. All of the Top 7 Western European and North American truck manufacturers identified in Section 2.1 are currently developing heavy-duty NG dual-fuel vehicles. These vehicles also have the possibility of using biogas in the future further reducing well-to-wheel GHG emissions. The technical implications of these fuels are discussed further in Section 3.4.

3.4 Alternative ICE Fuels

This section discusses the technical issues related to the production, storage, transport and use of alternative fuels in internal combustion engines.

3.4.1 First Generation Biodiesel

The use of biodiesel as a diesel substitute is widely considered as the fastest and most viable way to incorporate sustainable fuel into the freight transport sector. This is due to the ease of integration with the current fuelling infrastructure and powertrain technology, and biodiesel's compatibility with mineral diesel allowing for fuel blending.

Biodiesel is mainly produced from the transesterification of vegetable oils and fats to methyl ester (see Figure 24). The feedstock can come from any oil rich crop such as rapeseed, palm oil or soybeans. Recovered waste oils and fats can also be used [72].

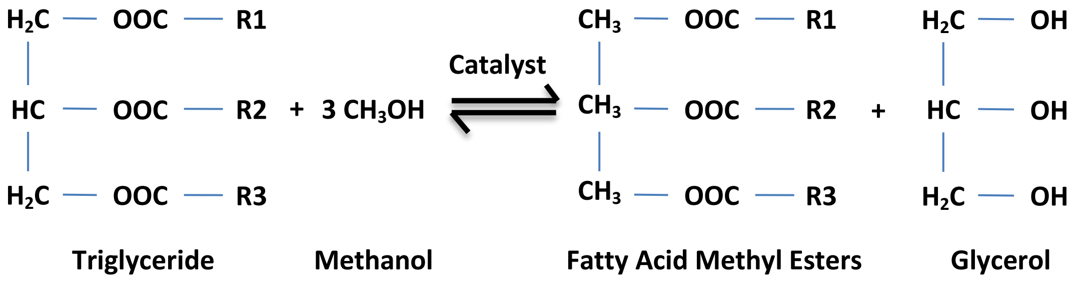

Figure 24. Transesterification chemistry

In the past FAME biodiesel has suffered from a lack of regulated specifications and quality standards. The fuel is also hydroscopic. This has led to concerns over fuel degradation within the fuel supply chain and vehicle fuel system [117; 118]. The products of this degradation such as formic, acetic and organic acids, water and methanol have been shown to be corrosive to both metallic and polymer products within the powertrain and can lead to engine damage. Over the past decades automotive manufactures have adapted to materials which are more resistant to corrosion from biodiesel. The choice of feedstock greatly affects the properties of the end product (see Table 10). With the right quality controls it is possible to produce first generation fuels which offer improved fuel properties such as higher cetane number, higher flash point, and better lubrication [119].

Fuel	Kin. viscosity (mm2/s, at 40 °C)	Density (g/cm3, at 21 °C)	Cetane number	Flash point (°C)	Cloud point (°C)	Pour point (°C)
Diesel	2.0–4.5	0.820–0.860	51.0	55	−18	−25
Soybean ME	4.08	0.884	50.9	131	−0.5	−4
Rapeseed ME	4.83	0.882	52.9	155	−4	−10.8
Palm ME	4.71	0.864	57.3	135	16	12
Sunflower ME	4.60	0.880	49.0	183	1	−7
Jatropha ME	4.4	0.875	57.1	163	4	–
Tallow ME	5.00	0.877	58.8	150	12	9
Soapstock ME	4.30	0.885	51.3	169	6	–

Table 10. Variation of diesel and biodiesel produced from different feedstock

Source: [119]

The lubricity of mineral diesel has been reduced due to the reduction of sulphur in the fuel, required to reduce exhaust emissions. The blending of FAME biodiesel increases the lubricity of the fuel offering reduced friction wear in engine components lubricated by the fuel [120]. High quality and purity biodiesel is now required to satisfy the American and European standards (ASTM 6751-3 and EN14214). The use of high quality feedstock reduces the issues historically connected to the use of FAME and makes it much more attractive for wide scale use [121]. The concerns over the hydroscopic properties, as well as variation of the fuel from different sources, means blending of the biodiesel is generally limited to 10%.

3.4.2 Second-Generation Fischer-Tropsch Diesel

Fischer-Tropsch (FT) synthesis is a well-established and commercialised process currently used in large scale gas-to-liquid (GTL) and coal-to-liquid (CTL) facilities. The FT process was developed by Prof Franz Fischer and Dr

Hanz Tropsch in 1920's Germany and was used during World War II to produce liquid fuels from coal reducing the country's reliance on foreign oil imports [122]. Today Shell and Sasol operate large GTL plants using the technology. Sasol has also operated a CTL plant, currently processing 1 million t/y of coal, in South Africa since 1955.

FT synthesis takes place by passing synthesis gas (CO + H_2) over specific catalysts such as iron (Fe) and cobalt (Co) converting the gas to liquid hydrocarbons. The process can be tuned to influence product selectivity. A high temperature process will lead to shorter hydrocarbon chains such as gasoline being produced while a lower temperature process will lead to longer hydrocarbon chains producing a higher yield of waxy products such as diesel. A number of process parameters affect the chain growth including temperature, catalyst and H_2/CO ratio. The waxes can be cracked catalytically with hydrogen to maximise diesel yield. Non-diesel products can be returned to the gasifier or used for other applications such as chemical feedstock [123; 124].

Biomass can also be used to generate Biomass-to-Liquid (BTL) FT Diesel. However, while elements of the process such as Gasification and Fischer-Tropsch synthesis are already well established other elements are still far from being commercialised. An overview of the FT BTL process can be seen in Figure 25. The biomass pre-treatment and biosyngas cleaning processes are a major challenge for BTL implementation [72]. The BTL process remains in the development phase and still requires substantial research and development to both reduce the cost and increase energy efficiency [75].

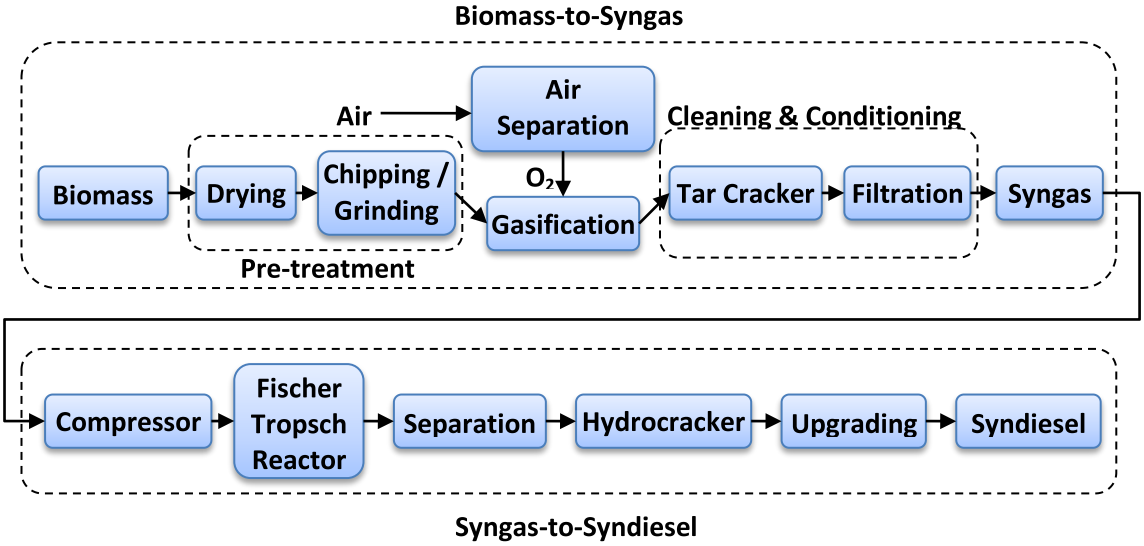

Figure 25. Thermal-chemical (FT) conversion for syndiesel production

Compiled from: [72; 74; 125]

The FT process produces high quality diesel with low sulphur content which can be used in existing diesel engines without the need for engine modification or fuel blending. The fuel offers improved engine performance compared to mineral diesel due to the higher cetane number, and comparable fuel consumption due to its higher energy density. A summary of alternative fuel energy density and cetane / octane properties can be seen in Table 11.

Property	Mineral Diesel	Gasoline	Liquid H_2	FT Diesel	FAME	LNG	LPG	HVO	DME
Energy Density by Volume (MJ/Litre)	35.3 – 36.0	31.2 – 33.2	8.9	33.1 - 34.4	33.9	25	25.4	34.4	18.2-19.3
Cetane	45-53			70-80	51-62			75-99	55 - 60
Octane		90-95	106			120	92		

Table 11. Alternative Fuel Properties

Compiled from: [72; 126; 127]

3.4.3 Upgraded Pyrolysis Oil

Upgraded pyrolysis oil can potentially be used to produce synthetic diesel and petrol using crude oil type refineries. It can also be used as a feedstock for other BTL processes. Pyrolysis oil (also known as bio-oil) is created by heating biomass to around 500°C in the absence of oxygen [72]. The potential to covert the biomass to pyrolysis oil at decentralised pyrolysis plants, before being converted to fuel at a centralised processing plant, offers reduced transport costs compared to biomass [77]. Although the technology for producing pyrolysis oil is currently available, the refinery upgrading process still requires substantial research and development [128].

3.4.4 Hydrogenation of Vegetable Oils (HVO)

Synthetic diesel can also be produced from the catalytic hydrogenation of vegetable oils and animal fats by a process known as HVO (see Figure 26) [129]. The high temperature (up to 450°C) and pressure (up to 152 bar) catalytic reaction of the hydrogen with the triglycerides in the oils and fats produces and a hydrocarbon synthetic diesel similar to that produced by Fischer-Tropsch synthesis [130].

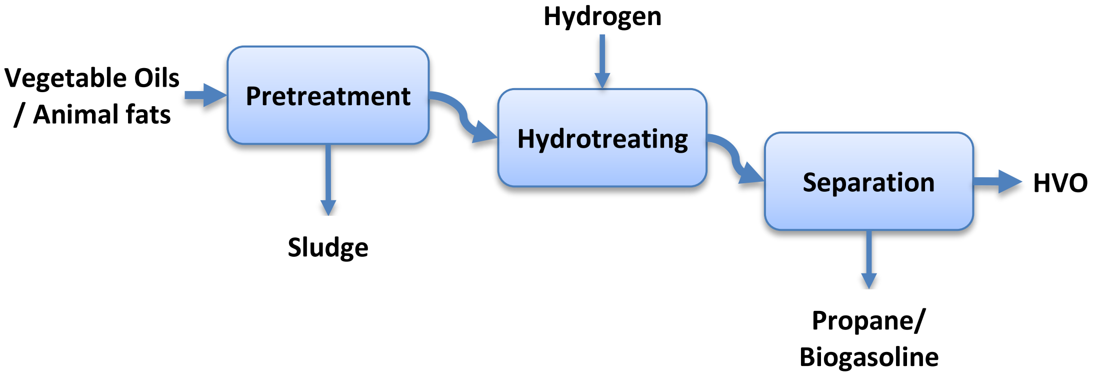

Figure 26. Production of HVO

As with FT fuel, the diesel can be used directly in existing diesel engines without engine modifications and offers improved engine performance due to the high cetane number.

This process has been commercially available in Finland since 2007. Neste Oil currently has the capacity to produce 2 million tons annually of renewable NExBTL diesel [131].

3.4.5 Third-generation Biodiesel from Algae Feedstock

Third-generation microalgae offer high potential as a future biofuel source. They are currently at a very early stage of development and commercialisation is not expected before 2020 [76; 132; 133]. Over 50% of their weight is oil and the rapid growth-rate of algae offers high yields. Algae are predicted to produce between 20,000 and 80,000 l/acre pa, 7 to 31 times that of palm oil. Many incremental R&D steps will be required to find strains which provide both high levels of lipid yield and high productivity.

Algae farms can use several methods to cultivate and grow algae although currently only photoautotrophic production has been demonstrated for large scale algae production [134]. Figure 27 shows a typical open pond system. These systems have been available since the 1950s and therefore are the most established. The paddle wheel circulates the mixture of algal cells and nutrients. Fresh feed is added in front of the paddlewheel and the algae are harvested after a complete a loop of the system [133]. This technology has already been productionised, not for biofuel production but for the production of Spirulina (a dietary supplement). Earthrise Nutritionals currently have 30 Spirulina ponds, each over an acre in size in California.

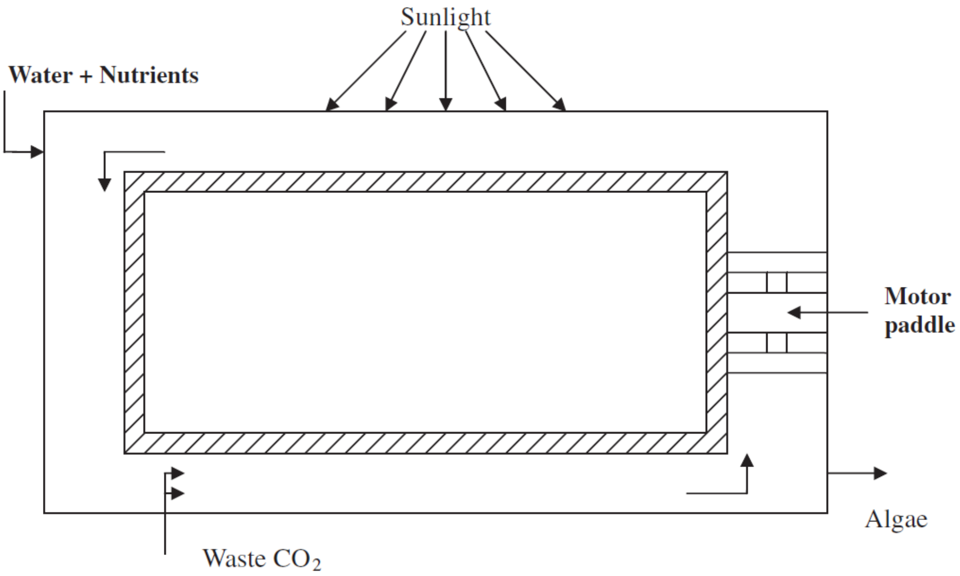

Figure 27. Open pond algae farm system

Source: Demirbas [133]

A major concern over these open pool systems is contamination by external sources including other algae types and algae eating bacteria. Photobioreactors offer a closed system in which the algal mixture is typically circulated through glass or plastic tubes (see Figure 28). A typical photobioreactor is 10 -100m^3 in size and requires its own control, piping and valve system incurring considerable costs compared to open ponds for high volume scenarios such as biofuel production. These systems nevertheless are still widely studied in the literature mainly due to the potential increase in productivity and ability to capture GHG emissions such as CO_2 which would be released in open pond systems.

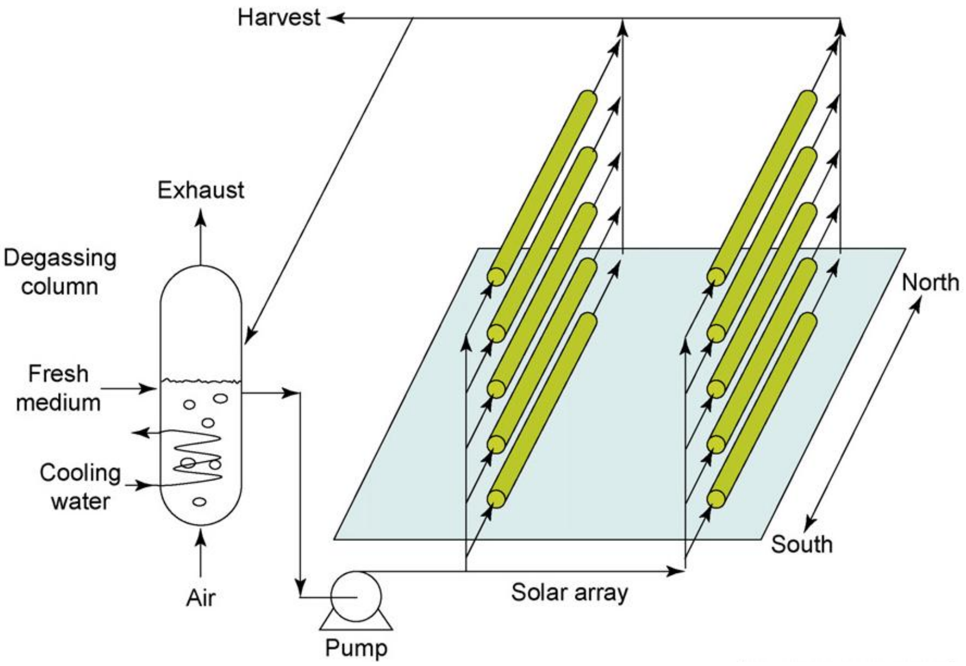

Figure 28. Algae photobioreactor system

Source: Yusuf [135]

Light is a crucial element in the algae growth process. Economical production systems are likely to depend on freely available sunlight, limiting the use of the technology to climates with abundant sunshine [128].

Heterotrophic algae cultivation which removes the requirement for sunlight is currently in development. Instead of sunlight the algae are fed feedstock such as lignocellulosic sugars. The fermentation technology is already well known and high biomass yields have been achieved. The availability of sustainable low-cost feedstock which does not compete with other technologies is a major challenge. Hybrid systems which use both sunlight and lignocellulosic feedstock are also being developed to maximise the benefits and minimise the negatives of each cultivation method. The selection and development of algae with high lipid productivity, the ability to endure the stresses of bioreactors, and dominate wild algae strains in open pond systems will be key to maximising production yields [134].

Conversion of algae to biofuel can be achieved through the use of thermo-chemical, chemical and biochemical processes. Current research is mainly based on the conversion of algal-oil to biodiesel using the transesterification processes used for the production of first-generation biofuels. Other uses being investigated for algae are anaerobic biomethane and biohydrogen production although once again these processes are a long way from commercialisation [133].

3.4.6 Liquefied Petroleum Gas (LPG)

LPG (also known as autogas) is produced as part of natural gas processing and crude oil refining and consists primarily of a mix of propane (C_3H_8) and butane (C_4H_{10}). For storage the LPG is pressurised to around 10 bar, which transforms the gas to a liquid state and the liquid is contained in a composite or steel tank [127].

LPG autogas currently fuels over 7 million vehicles in Europe (accounting for 3% of passenger cars) and 16 million vehicles worldwide, according to data published by the European LPG Association [136; 137]. Typically LPG is used in light-duty SI engines where the fuels can be used in bi-fuel systems alongside gasoline. The additional purchase price off these vehicles is around €1000-€1500 [127]. With the cost of LPG around half the price of gasoline break-even for a passenger vehicle is around 2 to 3 years for the average driver.

The fuel can also be used in CI engines with the addition of a cetane improver, for example di-tertiary-butyl peroxide (DTBP), or in a dual-fuel powertrain such as those discussed in Section 3.3 [112; 138]. Although the use of cetane improver with LPG leads to thermal efficiencies comparable to diesel the lower energy density limits range of the vehicle. For long-haul transportation this means the requirement of additional storage tanks, compared to that required for diesel, reducing the available payload and limiting acceptance. The engine and fuelling strategy also require modification adding to cost and the loss of the ability of the powertrain to use more widely available diesel fuel. Dual-fuel powertrains provide the opportunity to benefit from the lower cost and tailpipe emissions of LPG while maintaining the efficiencies of the CI engine [112]. This provides the most viable use of LPG for heavy-duty vehicles and provides an opportunity to develop technology which can in the future be used on NG and biogas vehicles. Acceptance however is likely to rely on the introduction of such systems by the OEMs as third-party modification of a new vehicle engine is likely to affect warranty validity.

3.4.7 Dimethyl Ether (DME)

Dimethyl ether (DME) can be produced from a diverse range of feedstock, for example NG, crude oil, coal, and biomass. It is suitable as a substitute for both diesel and LPG. The production of DME is a two-step process. Firstly synthesis gas is produced in the same way as for BTL, CTL, and GTL processes discussed in Section 3.4.2. Then the DME is produced via a methanol synthesis and dehydration process [139]. DME is a gas at atmospheric pressure but becomes a liquid at relatively low pressures (similar to LPG). DME can be used in modified diesel engines and is generally stored on the vehicle in a pressurised tank as a liquid.

Due to high oxygen content DME burns cleaner and produces lower NO_x and PM emissions than conventional diesel [140]. DME has a low boiling point which leads to quick evaporation in the engine and the high cetane number results in a low auto ignition temperature reducing ignition delay [79]. Torque, power and brake specific energy consumption (BSEC) at full load are comparable to those of diesel at high engine speeds. While considerable improvements in both torque and power are possible at lower speeds [140]. Results can be seen in Figures 29 and 30.

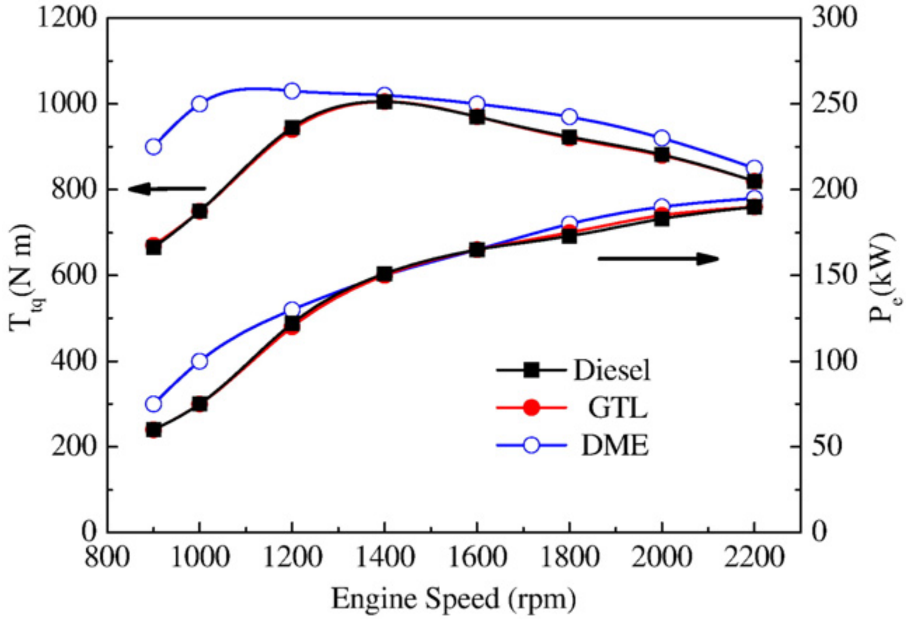

Figure 29. Comparison of torque and power for Diesel and DME fuels

Source: Xinling [140]

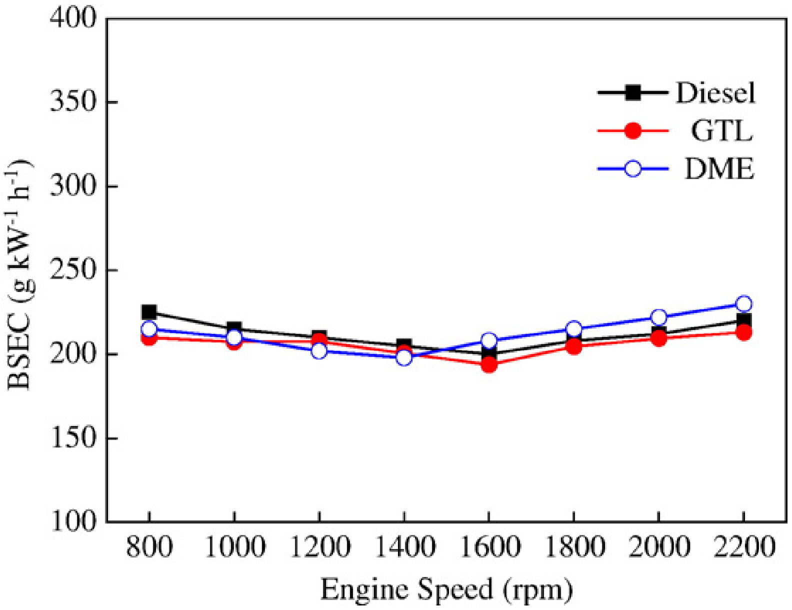

Figure 30. Comparison of BSEC for Diesel and DME fuels

Source: Xinling [140]

Disadvantages of DME include its low viscosity which requires tighter clearances to reduce leakage in the fuel injection system, and leads to the increased wear of fuel system components. The corrosiveness of DME is another concern for FIE manufacturers. DME is not compatible with most elastomers. Inert materials such as polytetrafluoroethylene (PTFE) need to be used to avoid deterioration of seals [79]. The low combustion enthalpy of DME (calorific value is around half to two thirds that of diesel) means the storage of the required volume of DME for long range transportation is a major challenge [141]. DME therefore has much more potential for captive fleets than for long-haul freight transportation. Wide-scale distribution of DME could be carried out through the existing LPG infrastructure with small modifications to ensure pumps, pipes and seals are resistant to the corrosion properties.

Volvo trucks are currently carrying out customer field trials of bio-DME trucks using modified D13 engines (6 cylinder 12.8l) in Sweden [142]. These trucks, for the reason discussed above, are operating in regional networks so that a central refuelling location can be used. The bio-DME is produced using black liquor as a bio-feedstock. Black liquor is a by-product of the pulp and paper industry and is a valuable source of bioenergy in countries such as Sweden where large paper and pulp industries exist [143]. As the biomass has already been partially processed into a liquid form it is easier, and more efficient due to its higher energy density compared to wood biomass, to transport to the final processing plant for conversion into automotive fuel. The DME for the Volvo field trials is produced by Chemrec in northern Sweden. The production facility is built alongside their pulp-production plant and is able to produce five tonnes of bio-DME per day.

3.4.8 Natural and Biogas

Natural gas is primarily composed of Methane (CH_4) and can be used in a gaseous (CNG) or liquefied (LNG) form in internal combustion engines with very little modification to the base engine. CI dual-fuel LNG / Diesel engines (discussed in Section 3.2) are most applicable to heavy-duty applications. This technology maintains the higher compression ratio and efficiencies of the diesel combustion cycle, injecting the gas into the combustion chamber late in the compression stroke, while benefiting from the reduced gas combustion emissions. Typically the NG is stored on the vehicle at -160°C in a double-wall, vacuum-insulated pressure tank as LNG [144]. Conversion of NG to LNG reduces the volume of the gas by 600 times benefiting both bulk gas transportation and on-board storage on the end use vehicle.

Biogas is produced by the anaerobic digestion (AD) of organic matter and can be used, compressed or liquefied, in the same way as NG. Biogas has the potential to offer the same tank to wheel benefits of NG but with much lower well to tank emissions (this is discussed further in Chapter 4). Anaerobic digestion takes place when organic matter is digested by micro-organisms in the absence of air, releasing methane (CH_4) and carbon dioxide (CO_2) (approximately 60% and 40% respectively). Large scale digesters are mainly found in industrialised countries but small scale digesters used to generate biogas for cooking, localised heating and power generation can be found worldwide. The actual yield and final composition of biogas is dependent on the feedstock used. The gas is likely to contain contaminates such as water, hydrogen sulphide, nitrogen, oxygen, ammonia, siloxanes and particles [145]. As well as removing these contaminants the biogas needs to be upgraded to biomethane, increasing the CH_4 content to improve the energy density, to make it suitable for wide-scale automotive use. This is a major technical challenge which is both financially demanding and energy intensive. Further development of these processes is required to allow biogas to compete with NG and take advantage of the existing NG infrastructure.

3.5 Technical Review Summary and Conclusions

The inherent link between fuel consumption and GHG emissions means increased ICE efficiency remains a key priority whatever fuel is being used. Reduction of parasitic losses by reducing the load on the engine from auxiliary components is already being implemented by the OEMs and engine manufacturers. The use of turbocompounding is also being used to recover waste heat energy.

There is a potential conflict between existing tailpipe and GHG emissions regulations. The impact of additional powertrain components implemented to reduce exhaust emissions such as NO_x, CO, HC and PM need to be carefully assessed to determine their effect on the overall power demands of the system.

The lack of electrical hybridisation viable for long-haul vehicles makes the use of electric auxiliary components more difficult to integrate, therefore mechanical systems are expected to take priority in the short to medium term. The mechanical technologies reviewed offer BSFC improvements of up to 4.5% therefore the ICE for long-haul applications does not change in a significant way. Downsizing is only possible for a small number of applications where the conditions specifically sit at the lower end of the heavy-duty duty cycle.

Biodiesel and synthetic diesel are the easiest alternative fuels to integrate with current ICE technology and diesel infrastructure. They also have an energy density close to that of mineral diesel, therefore offering a comparable vehicle range (see figure 31).

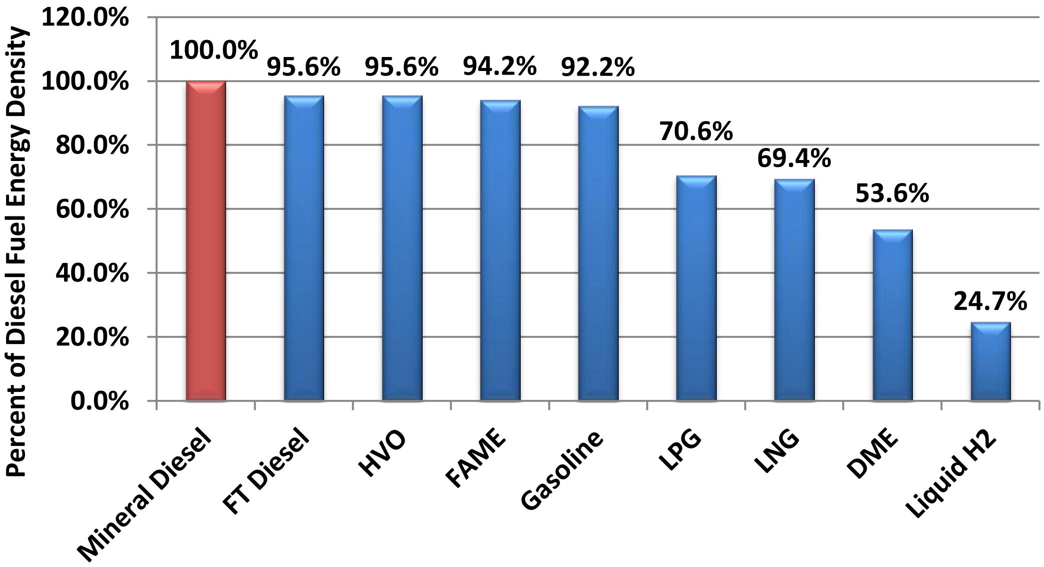

Figure 31. Energy density of fuels

Regulated specifications and quality standards for FAME are now in place in most markets ensuring a higher quality fuel than in previous years. The hydroscopic properties and variation of properties from different feedstock however means concerns remain over fuel degradation leading to fuel system and engine corrosion. First-generation FAME biodiesel fuel blending limits are typically limited to 10%. The properties of second-generation syndiesel allow the blend of sustainable diesel to mineral diesel to be increased. Commercial processes still require process development and optimisation with biomass pre-treatment and biosyngas cleaning processes both remaining a considerable challenge. Third-generation biodiesel also faces considerable challenges. Although the rapid growth-rate of algae offers the potential of high biodiesel yields the process technology is a long way from commercialisation.

An increase in the availability of alternative fuel and dual-fuel powertrains is expected over the next 20 years. Fuels such as LNG and DME remain high on the priorities of both OEM and government research agendas. Although the energy density of these fuels are much lower than that of diesel and its substitutes, the opportunity of greater fuel security and diversity based on geographic location make these fuels attractive alternatives to diesel in some applications. The environment and economic impacts of these fuels is discussed further in Chapter 4.

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4. The Environmental and Economic Impact of Alternative Powertrains and Fuels

This chapter reviews the environmental and economic impact of the technologies reviewed on Chapter 3. The environmental impact is assessed by reviewing published lifecycle studies, sustainability reports and land use data. The economic review takes into account the financial cost of fuel production, engine modification and establishing a suitable infrastructure.

It should be noted that although the focus is on CO_2, as this is currently the main contributor to GHG emissions, during the study of alternative fuels and well-to-wheel analysis it is important that all sources of GHG emissions are taken into account. The measurement of GHG emissions from these studies are therefore often reported as CO_2-equivalent. Each GHG is given a global warming potential (GWP) number based on its atmospheric lifetime and heat retaining potential. This GWP is relative to CO_2 which has a GWP of 1. The increased use of alternative fuels such as natural gas, which is primarily composed of methane (CH_4), makes the consideration of these other emissions even more critical. The GWP of selected alternative fuel related emissions are shown in Table 12.

Name	Chemical Formula	Global Warming Potential (GWP)
Carbon Dioxide	CO_2	1
Methane	CH_4	25
Nitrous Oxide	N_2O	298

Table 12. GWP of Selected Green House Gases

Source: Intergovernmental Panel on Climate Change [146]

Currently the biofuels industry is heavily supported by government subsidies, especially in developed areas such as the EU and the US. In 2007 OECD member countries provided approximately US$15bn in biofuel subsidies

[147]. Without these subsidies, realising a profit is a major challenge and therefore the move from fossil to biofuels is not financially attractive for the energy and petrochemical industry. However, CO_2 reduction along with the continually increasing oil price and future fuel security concerns continue to make the alternative sourcing of transport fuel an essential component in the future strategy of both government and energy companies.

4.1 The CO_2 Reduction Potential and Financial Implications of ICE Efficiency Improvements

With current diesel engines offering around 42% thermal efficiency there is a focus on the reduction of powertrain losses to reduce fuel consumption and GHG emissions. Future ICE technologies being developed and their BSFC improvement potential are discussed in detail in Section 3.1. As there is an inherent link between fuel consumption and GHG emissions the reductions in BSFC quoted can be converted directly into the GHG emissions savings shown in Table 13.

Technology	CO_2 Reduction Potential
Mechanical Variable Speed Pumps	0.5% - 1.5%
Clutched Air Compressors	3.5% Ave
Mechanical Turbocompounding	0.5% - 4.5%
Electrical Turbocompounding	2% - 8%
Rankine Cycle	3% - 6.5%
Brayton Cycle	1.5% - 4%

Table 13. CO_2 reduction potential of ICE technologies

While some of the savings might appear small, with heavy-duty truck fuel economy currently around 6 mpg and average vehicles covering in the region of 120,000 miles per year, one heavy-duty truck has the potential to use as much fuel per year as around 50 cars. Therefore even a small reduction in fuel consumption offers the potential of a large reduction in global GHG emissions.

The financial implications of each technology are shown in Table 14. The base powertrain assumption is a 2010 model year Euro V diesel ICE. The payback time varies for the same technologies due to different fuel costs and drive cycles being considered in Cooper's and Hill's analyses. A three year payback period is typically demanded by the industry. Further incentives will therefore be required to encourage adoption of electrical compounding and bottoming cycles for long-haul heavy-duty vehicles. The cost of electric turbocompounding varies depending on the electrical components attributed to it. Therefore in applications where additional electrical or hybrid components are being integrated the cost for the power electronics, motor-generator, and electrical accessories could be further reduced.

Technology	**Estimated Vehicle Cost Increase (€1 = US$1.3)**	**Payback Time (Years)**	
		Hill (2011) [42]	**Cooper (2008)** [111]
Clutched Air Compressors	€140	0.3	-
Mechanical Turbocompounding	€2,000 - €2,500	-	2.0
Electrical Turbocompounding	€5,000 - €7,000	5.87	3.5
Bottoming Cycle	€11,500	5.8	5.2

Table 14. Financial implications of ICE technologies

Compiled from: [42; 56; 111]

4.2 The Environmental and Economic Impact of Dual-fuel Powertrains

As discussed in Section 3.3, heavy-duty CI dual-fuel systems are currently being marketed for both LPG and LNG fuels with advertised CO_2 savings of up to 27%. The cost for aftermarket conversion of existing engines is estimated at between €11,000 and €30,000 for the inlet manifold type systems [148; 149].

The cost for dual-fuel DI LNG/diesel engines has, in the past, been considerably more, the additional cost for the Cummins-Westport ISX-G engine being in the region of €75,000 compared to a traditional diesel powertrain [150]. These costs are predicted to reduce dramatically as the technology begins to benefit from economies of scale. The additional cost for a Westport HPDI LNG/diesel engine is expected to be between €27,000 and €31,000 [151]. An overview of the system costs can be seen in Table 15.

Technology	System Cost (€1 = US$1.3 / €1 = £0.85)
G-volution	€11,000 (System Purchase Cost)
Clean Air Power	€26,000 (Vehicle Conversion Cost)
Hardstaff	€15,000 – €30,000 (Vehicle Conversion Cost)
Westport HPDI	€27,000 – €31,000 (Increased Vehicle Cost)

Table 15. LNG system costs

Although there is an increased capital cost for these vehicles, with the low cost of NG compared to diesel payback for all the systems reviewed is expected within the typically assessed 3 year period. The current lack of an adequate infrastructure for LNG refuelling is the main roadblock to mainstream uptake of the technology, rather than powertrain costs. The future potential of both LPG and LNG for use in heavy-duty powertrains is discussed further in the following sections.

4.2.1 LPG

As LPG is a by-product of the natural gas processing and crude oil refining industries, supply is limited based on global gas and oil demand. Globally 47% of LPG is used for cooking and heating and therefore increased demand on LPG for transport could have wide reaching side effects, not only by limiting availability of LPG but also increasing LPG prices. The most detrimental effects are likely to be felt by those isolated from the natural gas grid, for example developing countries. The Asia-Pacific region is the leading market and in 2009 there was an increase in demand of 6.4% in India and 7.8% increase in demand in China [152].

Although there are concerns over the long-term sustainability of LPG as an automotive fuel, it does offer a potential stepping stone between current liquid fuels and the future use of natural or biogas for dual-fuel CI engines. LPG is currently half the price of diesel and there is already a global distribution network in place with more than 54,000 autogas fueling stations available worldwide (compared to around 19,000 natural gas fueling stations). An overview of the European fueling station network can be seen in Figure 32.

Figure 32. European LPG filling station network – 2007

Source: AEGPL [136]

The well-to-wheel (WTW) analysis results presented in Figures 33 and 34 show that LPG GHG emissions are comparable to those of diesel. NO_x and

PM emissions are greatly reduced, while HC emissions are increased (although still lower than those of gasoline) [153; 154].

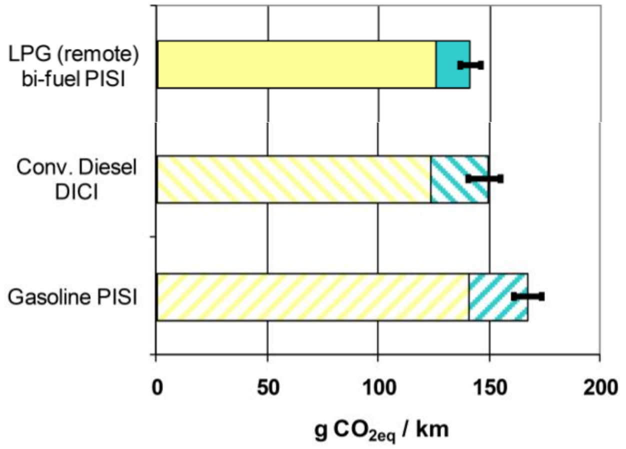


Figure 33. WTW GHG emissions from LPG

Source: JRC [153]

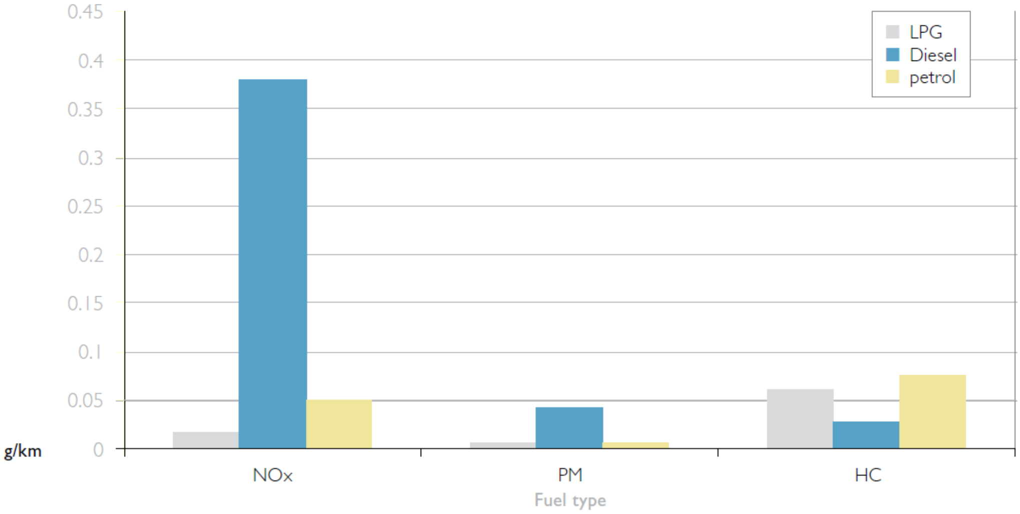


Figure 34. Environmental tailpipe LPG emissions

Source: Atlantic Consulting / AEGPL [154]

Even though the cost of LPG is lower than diesel, with GHG emissions close to those of diesel, limited LPG infrastructure in some countries, additional system weight reducing vehicle payload, and concerns over long-term sustainability, the widespread use of LPG as a primary fuel for long-haul vehicles is not expected.

4.2.2 Natural Gas

Natural gas is the only fossil fuel predicted to see increased consumption during the next 20 years [155]. Although the dominance of fossil fuels in the global energy mix is set to decline, natural gas consumption is set to increase on average by 1.6% per year from 2008 to 2035. Global NG consumption is expected to reach 169 trillion cubic feet by 2035 (see Figure 35) [156]. 80% of this increased demand comes from the growth of non-OECD countries, in Europe and the Americas use is expected to increase by 0.7% and 0.9% respectively (see Figure 36).

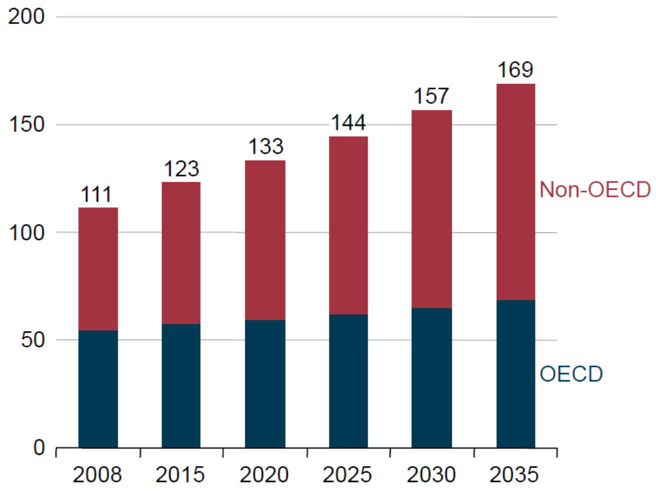


Figure 35. World NG consumption 2008-2035 (trillion cubic feet)

Source: EIA [156]

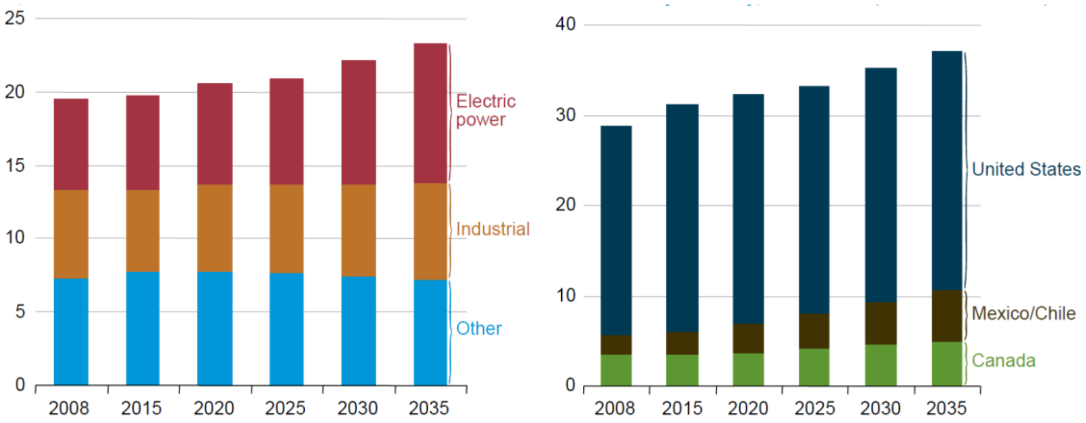


Figure 36. NG Consumption in OECD Europe (Left) and Americas (Right)

Source: EIA [156]

There has been an increase in reported NG reserves over the last decade mainly due to the development of gas extraction technologies allowing the use of unconventional gas resources such as tight gas, shale gas, and coalbed methane. Half of the estimated gas resource now comes from unconventional gas. This also offers the benefit of increased energy security as the resources are more widely spread across different geographical locations than conventional gas. The increase in unconventional gas production in China, Canada, and the US can been seen in Figure 37. Estimated global NG reserves have increased from 2,500 trillion cubic feet in 1980 to 6,675 trillion cubic feet in 2011.

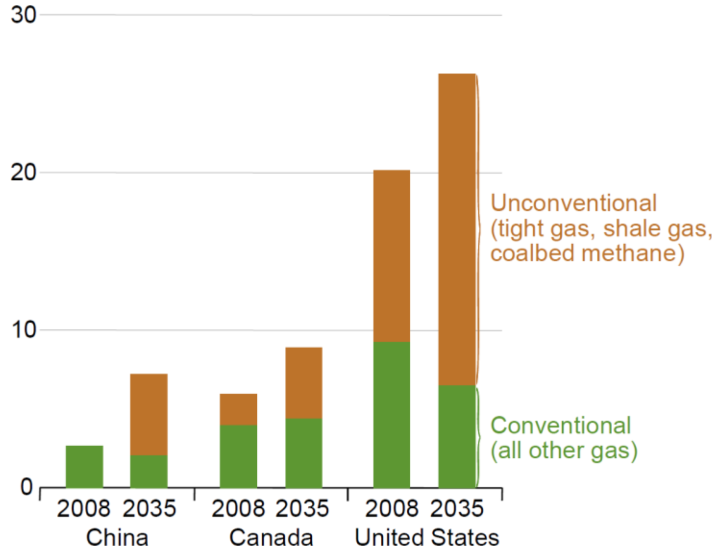


Figure 37. NG production in China, Canada, and the US (trillion cubic feet)

Source: EIA [156]

NG is the cleanest fossil fuel, producing fewer pollutants than other hydrocarbon fuels. Exhaust emissions are greatly reduced compared to both diesel and LPG. PM, HC, NOx and CO emissions compared to LPG and diesel can be seen in Figure 38.

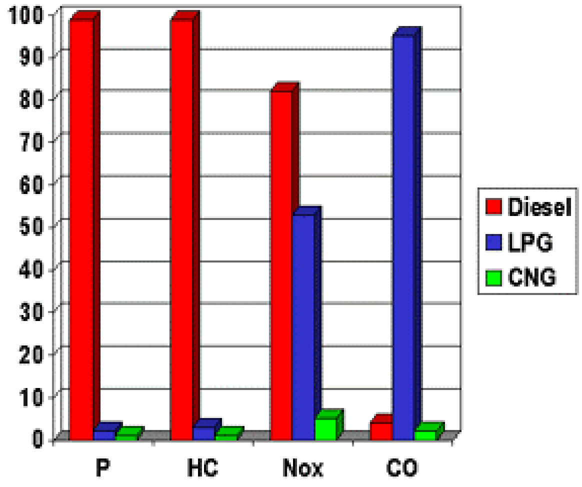


Figure 38. Tailpipe emissions of diesel, LPG and NG

Source: Clean Air Power [114]

The lower carbon-energy ratio of NG also leads to reduced CO_2 emissions compared to diesel. Reported CO_2 savings are up to 27% are advertised by Westport [115]. LNG does however produce higher CH_4 and N_2O emissions than diesel although in a study carried out using a converted Cummins ISX450 engine with Westport LNG system still produced 13% lower CO_2-equivalent GHG tailpipe emissions [157]. WTW lifecycle emissions for both large scale regasification terminals (TER) and small scale liquefaction plants (SSL) have been studied in the literature. Results from Arteconi et al. can be seen in Figure 39. Although the overall emissions for the SSL conversion route are comparable with diesel emissions, as LNG gains further market penetration it is expected that the liquefaction efficiencies will improve and infrastructure improvement will reduce distribution related emissions.

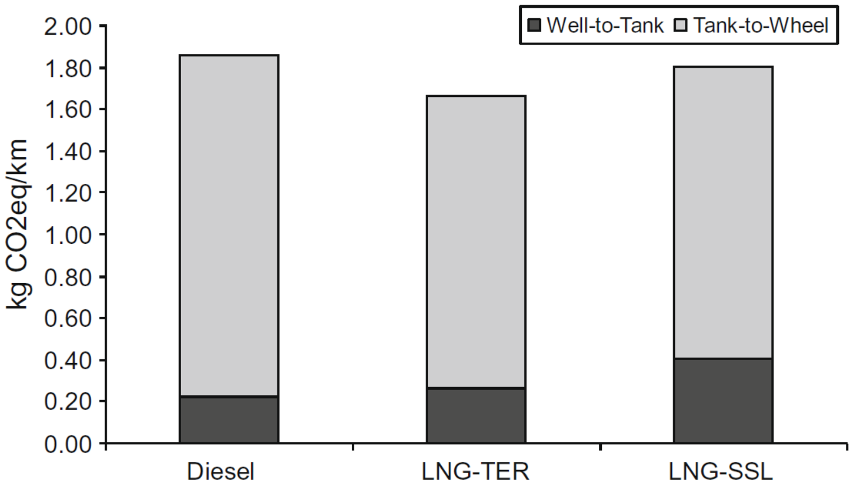


Figure 39. Well to wheel Diesel and LNG CO_2 equivalent emissions

Source: Arteconi et al. [85]

The use of biogas shows the greatest potential for the reduction of WTW GHG emissions. Figure 40 shows the results of a study carried out by TIAX on behalf of Westport. Automotive biogas (biomethane) is discussed further in Section 4.3.5.

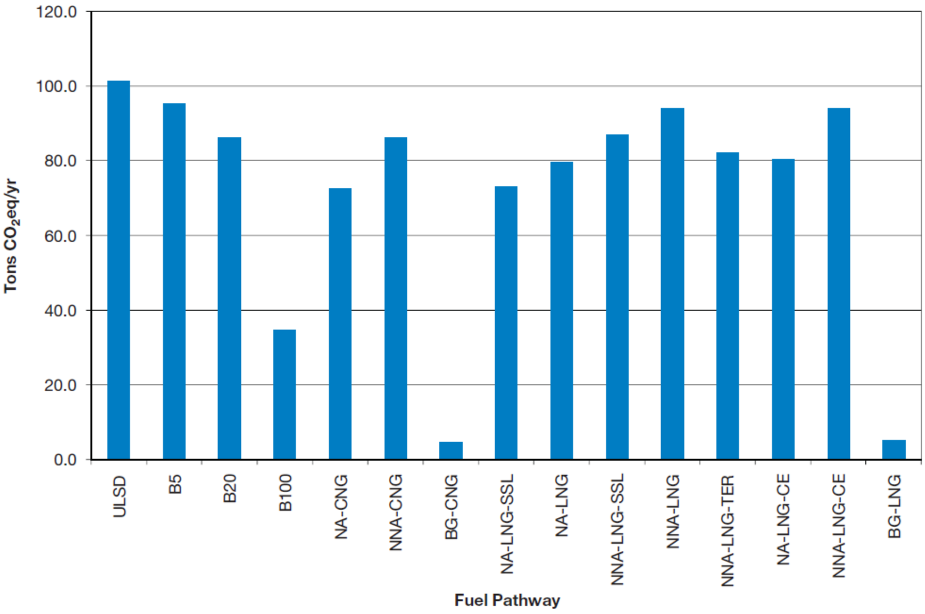


Figure 40. Well to wheels GHG emissions for gas pathways

Source: TIAX LLC [158]

The distribution infrastructure does not currently exist to support the use of LNG in road vehicles and this lack of infrastructure will continue to limit acceptability of NG vehicles. Globally only 56 of the current 19,679 natural gas fueling stations supply LNG and additional investment will be required to allow widespread LNG refuelling [159]. The industry is currently in a ‘chicken and egg’ scenario similar to that already discussed for hydrogen. The liquefaction process is energy intensive and accounts for the bulk of LNG costs. The cost of a liquefaction plant based on establishing a greenfield LNG terminal is estimated at US$ 3–5 billion [160]. Fuel providers are unlikely to invest in an infrastructure for a market that does not exist, which in turn limits the ability of the market to be established. One solution is the establishment of localised refuelling stations although the cost of these is substantial. A LCNG refuelling station capable of supplying between 20 and 30 dual-fuel vehicles is estimated at between £300,000 and £500,000 [161].

4.3 Environmental Impacts of the Global Biofuel Industry

Fuels derived from biomass are considered as ‘carbon neutral’ as the CO_2 released during combustion of the fuel is absorbed during crop growth. A comparison of fossil fuel and biomass carbon flow can be seen in Figure 41.

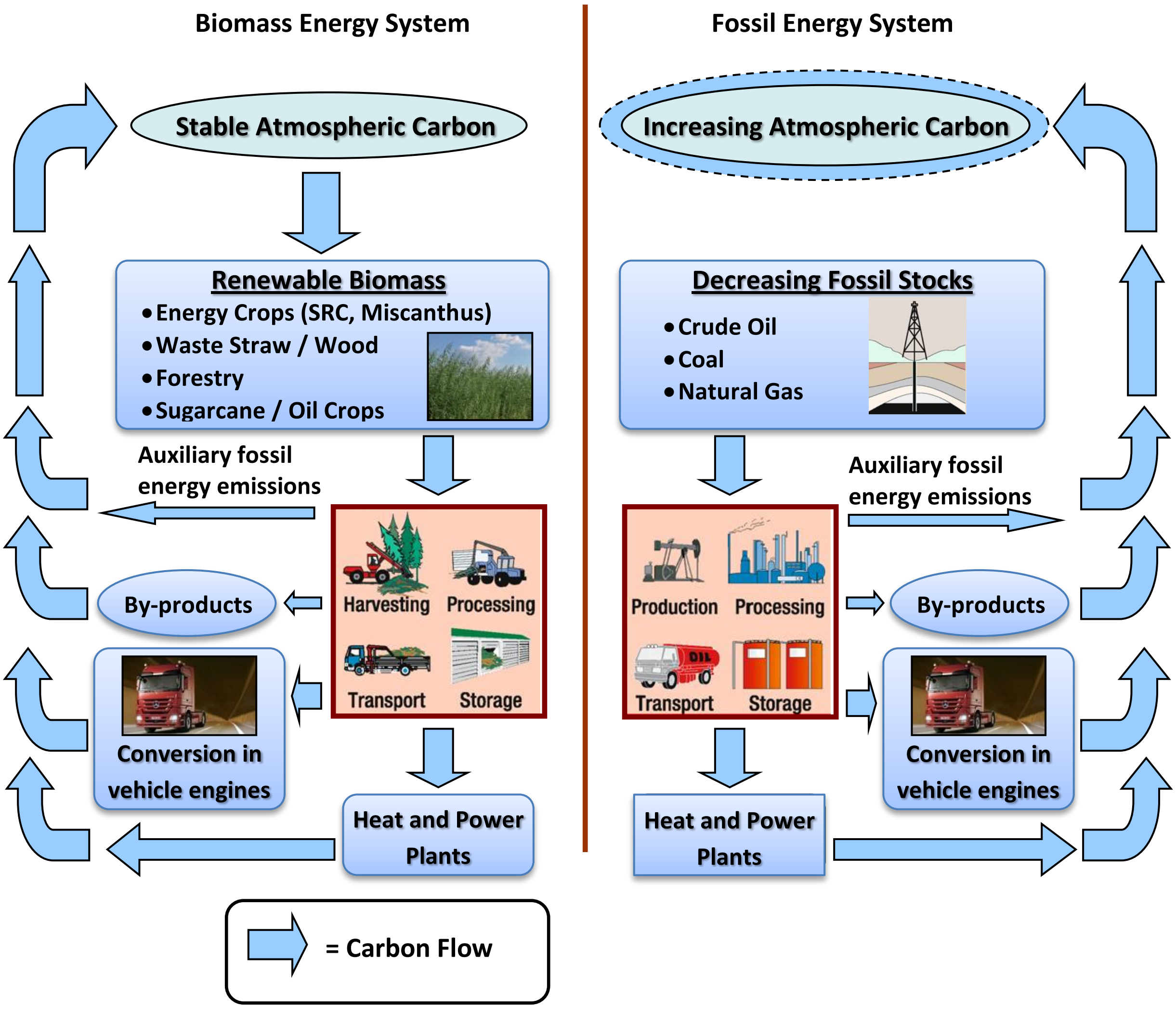


Figure 41. Comparison of fossil and biomass carbon flow

Adapted from: [162]

This is a simplified model and there is currently still significant fossil fuel energy used during harvesting, processing and transportation in many pathways. Even when the fossil energy is incorporated into the assessment the potential for GHG emission reduction as well as improving local air quality is substantial [163; 164]. Potential GHG improvements, compared to gasoline and diesel, for different pathways can be seen in Figure 42. The data was collected by the OECD from 60 published life-cycle studies [164]. The uncertainty of the ability of final processes, and therefore GHG saving, can be seen in the range for each of the pathways. Sugarcane ethanol shows the most consistent results between studies due to the fact it has been well established for years in Brazil. It is clear however that of the current and emerging biofuels, second-generation biofuels have the potential to offer the greatest GHG benefits over the complete life-cycle.

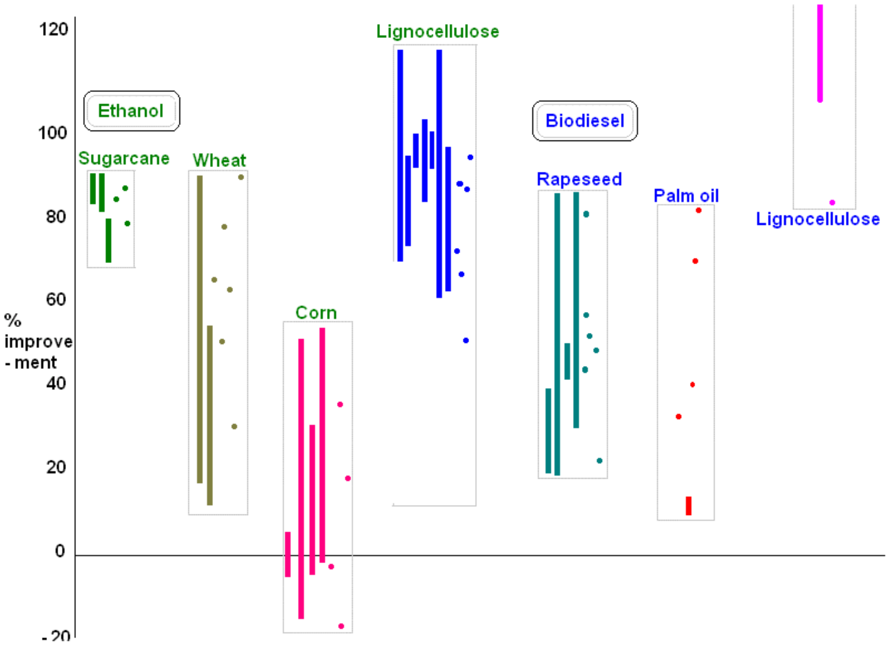


Figure 42. Net GHG emission improvement of biofuel pathways compared to gasoline and diesel

Source: OECD [164]

It should be noted that all the figures exclude the effects of land use change which could dramatically affect the carbon balance. Carbon is stored in three main pools; soil, litter (forest residues) and vegetation. Soil contains 50-300 t C/ha compared to 2-20 t C/ha in biomass crop. The farming of biomass and increased use of forest waste will reduce the amount of carbon storage in both forest litter and soil pools. The effect will vary widely depending on location, soil composition and other geographical factors and may not always be detrimental [165]. Well managed farming of Miscanthus on set-aside land in some regions has been shown to increase carbon sequestration [162].

The indirect annual emissions such as those generated from agricultural fuel and fertiliser also need to be considered. Nitrous oxide (N_2O) emissions are generated from the use of nitrogen fertiliser and released N_2O captured within the soil. The global warming potential of N_2O is 298 therefore even small quantities can have a huge impact on the overall GHG balance [166]. The farming of these crops is also very water intensive and may lead to a shortage of water for food crop irrigation, cooking and drinking in developing countries [119]. Although research is on-going to estimate the size of these effects, the results are currently not available for use in life-cycle studies [167]. The effects however must be considered before a decision can be taken on which feedstock is best suited to each region.

4.3.1 First Generation Biodiesel

Although biodiesel was developed as a sustainable alternative to crude oil based diesel, there are questions over the sustainability of first generation biofuel feedstock. Among the concerns are the levels of nitrous oxide (N_2O) emissions produced during biofuel crop production and competition for prime agricultural land between biofuel and food crops leading to increased food prices [72; 168]. Production of first-generation biofuel is also unprofitable in almost all countries outside of Brazil. The OECD found the production costs for rapeseed biodiesel in the EU to be three times greater than mineral diesel [164].

In 2010 there was 4.6 million hectares of arable land in the UK [169]. 25,084 million litres of diesel were consumed in 2009 [170]. 20% of the arable land in the UK would be required just to provide the 5% required to satisfy the 2013 RTFO target (based on the data shown in Table 16). In the United States 24% of existing crop land would be required to grow oil palm in order to replace 50% of US transportation fuel [171].

Fuel	Crop	Average Crop Yield for U.K. (t/ha)	Volume of Fuel Generated (L/ha)	Energy Density (MJ/L)	Gross Energy Output (MJ/ha)
Biodiesel	Oilseed Rape	3.3	1455	34.45	50,125

Table 16. Biodiesel Fuel Yield from Oilseed Rape

Source: [172]

These concerns led to the government commissioned “Gallagher Review of the Indirect Effects of Biofuels Production” [70]. The report recommendations forced the government to reduce the RTFO targets to decrease the risk of unintended indirect effects. It is now generally accepted that alternative feedstocks are required to produce sustainable fuels which do not compete with food production.

The main contributor to first-generation biofuel production costs is feedstock and therefore production costs are not expected to fall sufficiently to make them more competitive. Currently ethanol production in Brazil is the only competitive biofuel pathway (see Figure 43). Average production costs are estimated at between US$0.23 and US$0.37 making ethanol production competitive at between US$30 to US$42 per barrel [173]. The low cost of Brazilian feedstock is due to a number of unique elements which are extremely difficult, if not impossible to replicate in the majority of other regions. These include government incentives offering large government subsidies and tax rebates for sugarcane producers and distilleries, plus legislation requiring the mandatory inclusion of high volumes of ethanol added to gasoline (22%) [37]. The unique environment also ensures a low feedstock cost due to the Brazilian climate allowing two natural yields of sugarcane per year. This example highlights the need for future biofuel solutions to be selected based on the suitability of the region. There will not be a ‘one size fits all’ solution.

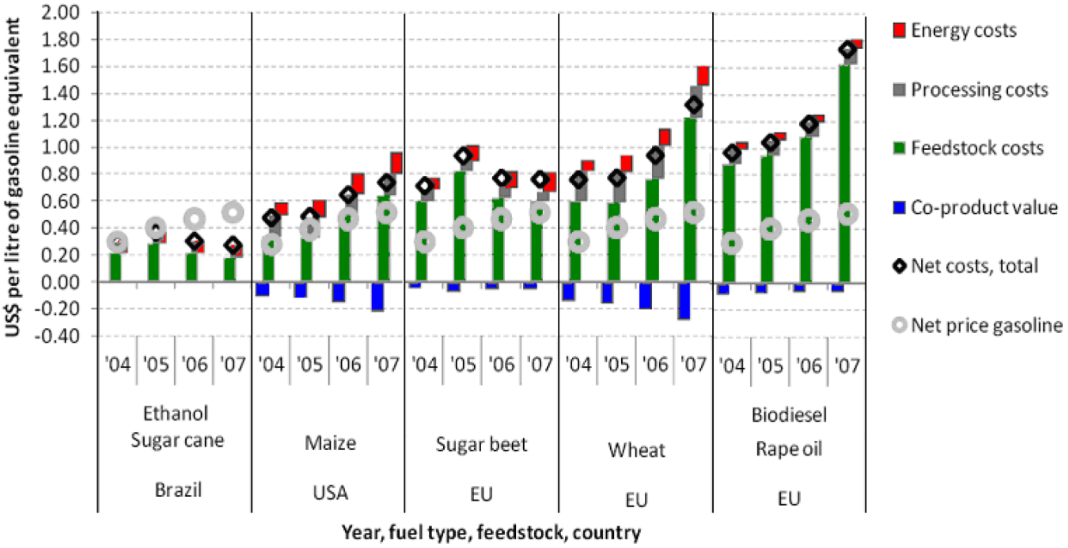


Figure 43. Production costs of first-generation biofuels

Source: [72]

The highly ambitious targets set by the developed countries for sustainable transport fuel use mean that imported fuels and biomass will be required. In the EU around 58% of biofuel crops will need to be imported in order to achieve the 10% target for renewable transport fuels by 2020. This level of import demand is highly likely to lead to worldwide biofuel and biofuel crop prices being influenced by the policies of the developed countries [174]. It should, for example, be considered how an increase in prices for sugar cane due to increase demand in other parts of the world could affect the competitiveness and profitability of ethanol in Brazil.

Demand for food and water will continue to grow along with energy demand and there is increasing correlation between the growth of the biofuel sector and the increase in food prices. This link is expected to grow stronger with future fluctuations in energy costs leading to corresponding changes to food prices. While the increase in prices has had positive outcomes in some areas, boosting both employment and incomes, in other areas the switch of land use to the more profitable biofuel feedstock has led to concerns over food security [119].

4.3.2 Second Generation Biofuels

The feedstock for second-generation biofuels itself can originate from any lignocellulosic biomass (see Figure 44). This reduces the reliance on food sources and allows crops to be grown on marginal land. Feedstock can also be sourced from commercial, municipal and forestry waste [175]. Lignocellulosic fuels also have the potential to provide a much higher energy return (MJ of energy released from the fuel compared to the MJ of energy required to produce it) of between 4.4 and 6.6 MJ per litre. Current first-generation processes provide a return of 1.3 to 1.65 MJ per litre [72].

Short Rotation Coppice such as Willow and Poplar
Energy Crops such as Miscanthus
Straw from agriculture such as Wheat Straw, Barley Straw and Oilseed Rape Straw

Broadleaf Forestry
Coniferous Forestry
SRF (Whole Tree)
SRF (Small Round Wood)

Waste Wood from construction, demolition, municipal solid waste, commercial and industrial sources

Figure 44. Lignocellulosic biomass sources

Source: [175; 176].

WTW GHG emissions are greatly reduced compared to diesel, NG, and LPG when using sustainable feedstock. Results from the European Commission Joint Research Centre WTW analysis can be seen in Figure 45.

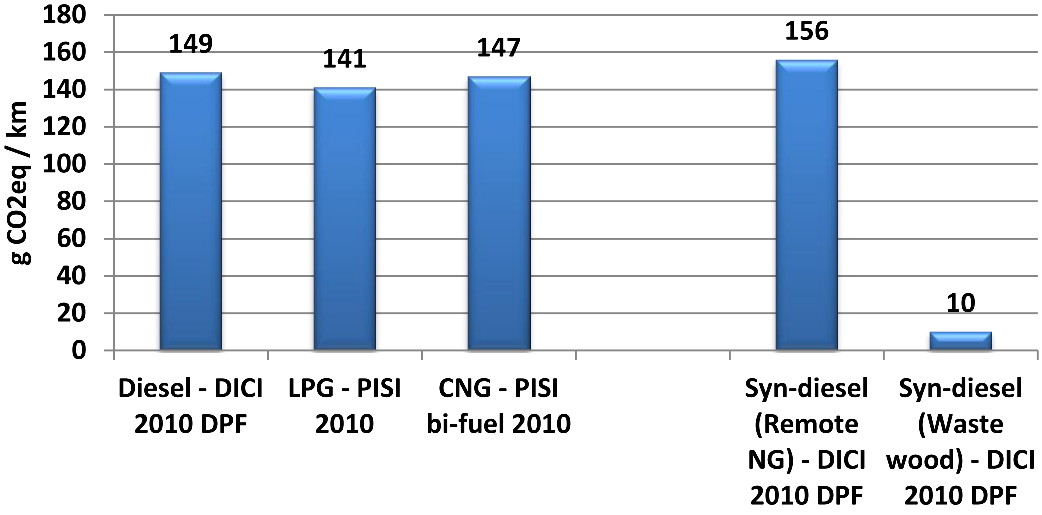
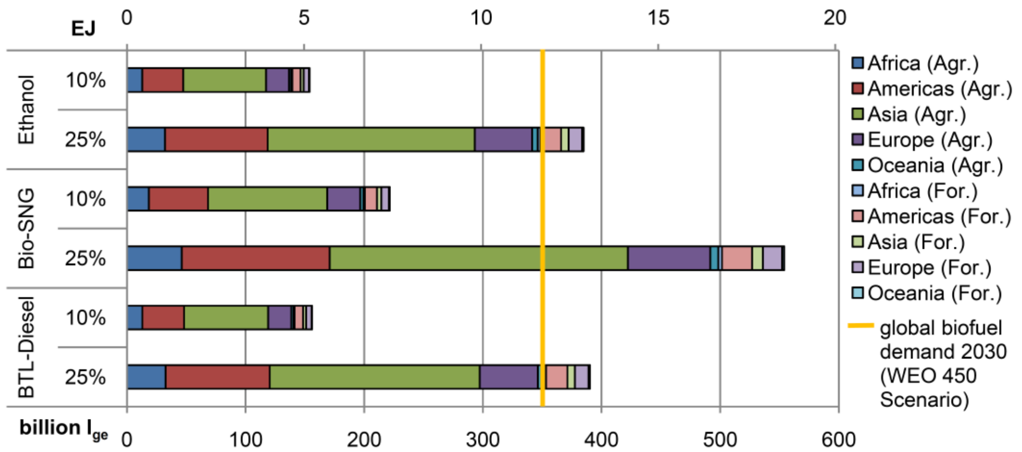


Figure 45. WTW GHG emissions for second generation FT biodiesel

Source: JRC [153]

The IEA has investigated the available biofuel from second-generation processes, based on predicted feedstock availability in 2030. Results show that 25% of agricultural and forestry residues would be required to satisfy the biofuel demand in the WEO 450 scenario (see Figure 46). It should be noted that the Bio-SNG is synthetic natural gas created via the gasification process not biogas created by anaerobic digestion.



Amounts cannot be summed up. Each bar indicates biofuel yields using all available residues. "25%" and "10%" assume respective shares of agricultural and forestry residues to be available for biofuel production.
Assumed conversion factors: BTL-Diesel – 217 lge/t_{DM}, Ethanol - 214 lge/t_{DM}, Bio-SNG – 307 lge/t_{DM}

Figure 46. Theoretical biofuel production from residues in 2030

Source: IEA [81]

Studies of these second generation fuels have also seen major reductions in exhaust emissions compared to mineral diesel, improving local air quality [163]. Figure 47 shows the results of trials conducted by Volkswagen AG using FT diesel in VW Golf TDI cars. It shows significant reductions in particulates, NO_X, CO and hydrocarbons. FT fuels blended with mineral diesel have also shown better than linear emissions benefits for PM, NO_X, HC and CO. An example of CO emissions reduction for blended fuels can be seen in Figure 48.

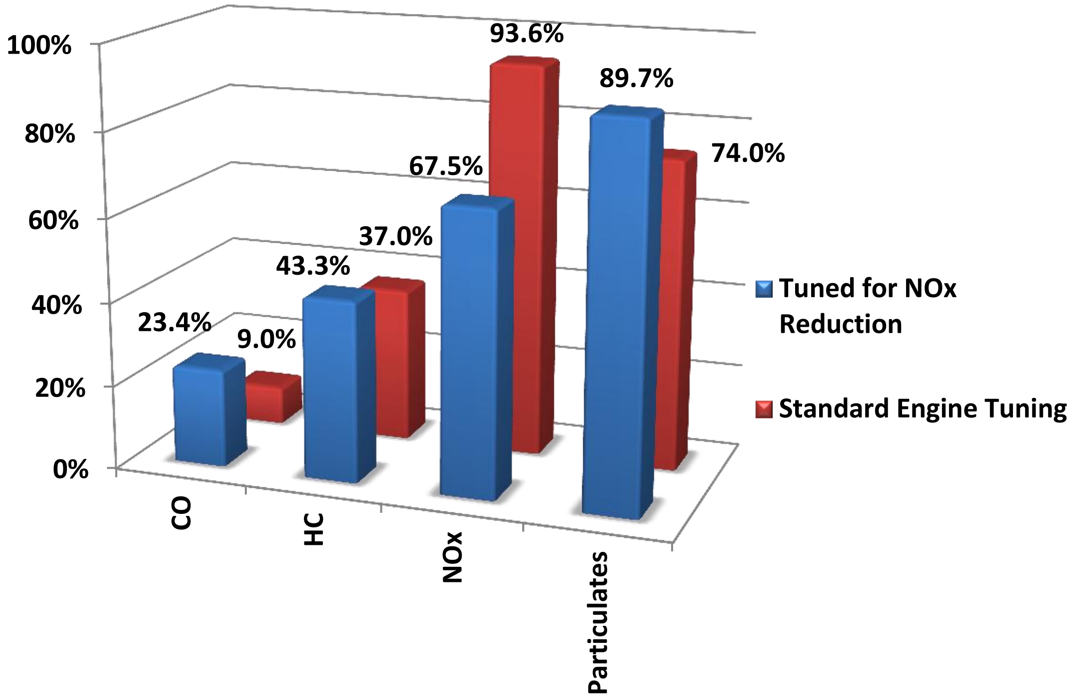


Figure 47. Exhaust emissions from FT diesel relative to mineral diesel

Source: Volkswagen AG [163]

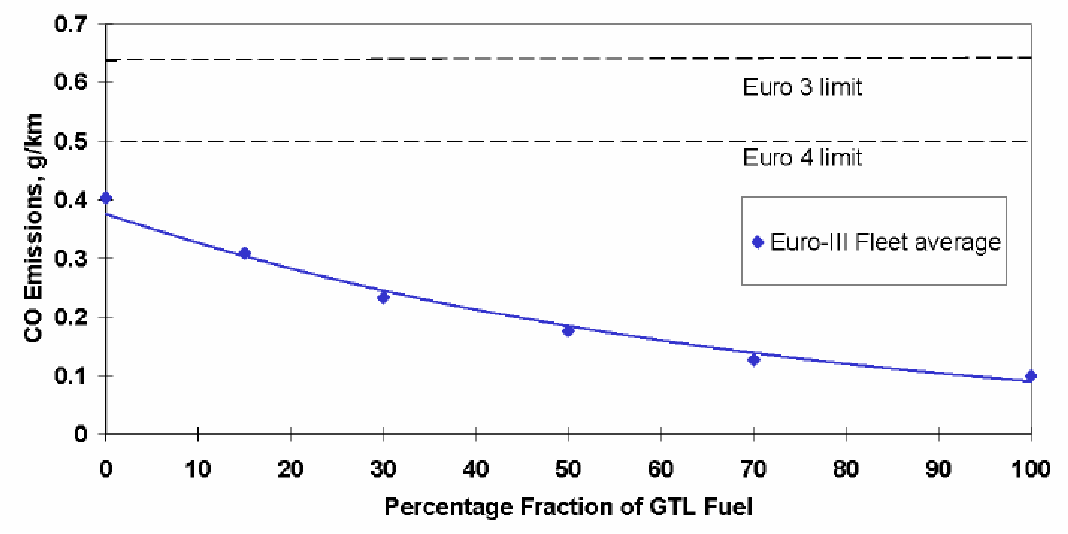


Figure 48. Impact of FT diesel blend concentration on CO emissions

Source: [163]

Second-generation fuels provide an opportunity to reduce the effect of biomass demand on food crop feedstock prices due to their reduced reliance on prime agricultural land. The establishment of the production facilities however requires a substantially higher investment than first-generation biofuel production technology. The estimated cost for a 640MW BTL plant planned by Choren and capable of producing 270 million litres pa (200,000 tonnes pa) is around €800m [177]. This investment is likely to mean that developing countries will struggle to justify the funds required especially in cases where first generation feedstock costs are already low, or domestic energy supply is currently lacking. For comparison, the cost of a FAME biodiesel plant capable of producing 250,000 tonnes pa is estimated at between €50m and €100m [126]. The skilled engineers required for installation of second generation conversion facilities are also unlikely to be available in countries other than the major and larger emerging economies.

Predicted production costs, compiled by the International Energy Agency (IEA), can be seen in Table 17. They conclude that production costs would need to be at 0.80 US$/lge (excluding subsidies) to be competitive with crude oil at US$100 per barrel [72].

Fuel	Assumption	Production cost 2010 US$/lge	Production cost by 2030 US$/lge	Production cost by 2050 US$/lge
Bio-chemical Ethanol	Optimistic	0.80	0.55	0.55
	Pessimistic	0.90	0.65	0.60
BTL Diesel	Optimistic	1.00	0.60	0.55
	Pessimistic	1.20	0.70	0.65

Table 17. Second-generation biofuel cost assumptions

Source: [72]

Although these targets may be achievable the plant investment is likely to be out of the range of developing countries and will require large scale foreign investment. The main local benefits of second-generation fuels for developing countries therefore are likely to be job creation and local growth from the need of the agricultural skills required for cultivation of feedstock. The use of existing farm labour for the harvesting of residue lignocellulosic biomass could extend the typical seasonal duration of employment. Other areas of the value-chain which are likely to benefit the local economy are transportation and labour for infrastructure development [178].

4.3.3 DME

Although the GHG emissions for NG derived DME are comparable to those of mineral diesel, DME produced for renewable feedstock offers GHG reductions of between 83% and 95% (see Figures 49 and 50).

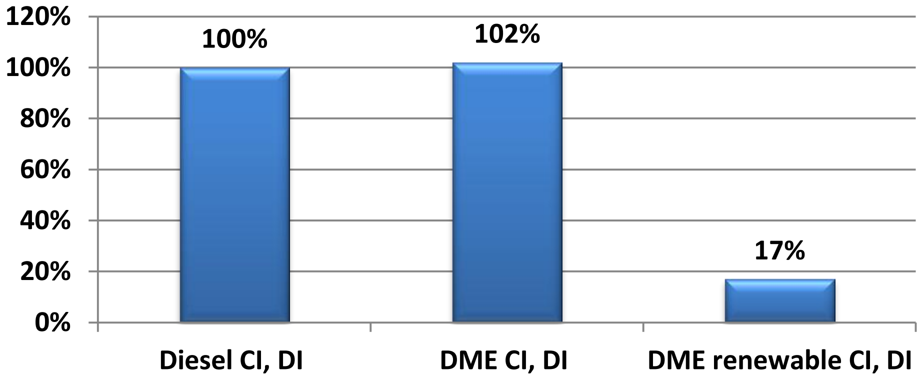


Figure 49. DME WTW GHG emissions relative to mineral diesel

Source: [79]

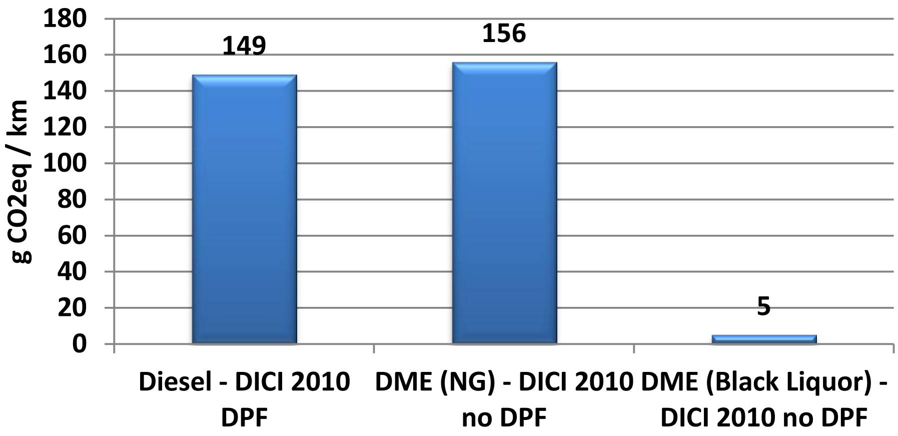


Figure 50. DME WTW GHG emissions - JRC analysis

Source: JRC [153]

Exhaust emissions are also greatly improved over those from diesel. HC emission reductions of 40.1% and reduction NOx reduction of 48.2% are presented in the literature. DME has also been shown to be virtually smoke free [140].

The low energy density of DME would require an extensive refuelling infrastructure which currently does not exist. As the properties of DME are similar to LPG, initial distribution costs could be reduced by utilising the existing LPG infrastructure. This would allow initial market penetration and additional fuelling stations could then be built as demand increases. Although any lignocellulosic biomass can be used as a feedstock black liquor offers the lowest WTW GHG emissions. The integration of the DME facility with an existing pulp production plant also allows a reduction in transport costs for the feedstock and reduces plant capital costs. The cost of a co-located 100,000 tonne bioDME plant is estimated at €330m [179]. Uptake of DME is therefore expected to be closely linked to economies with an established pulp and paper industry where the black liquor, as a by-product is freely available.

4.3.4 HVO

HVO produces synthetic diesel with similar properties to FT fuels and therefore also offers reduced tailpipe emissions. Emissions results from a turbocharged 8.4 litre 6-cylinder DICI engine without EGR or exhaust aftertreatment can be seen in Figure 51 [130]. The results used default injection timings and optimisation of the powertrain, as well as the use of aftertreatment technologies, would expect a reduction in emissions comparable with those discussed for BTL fuels.

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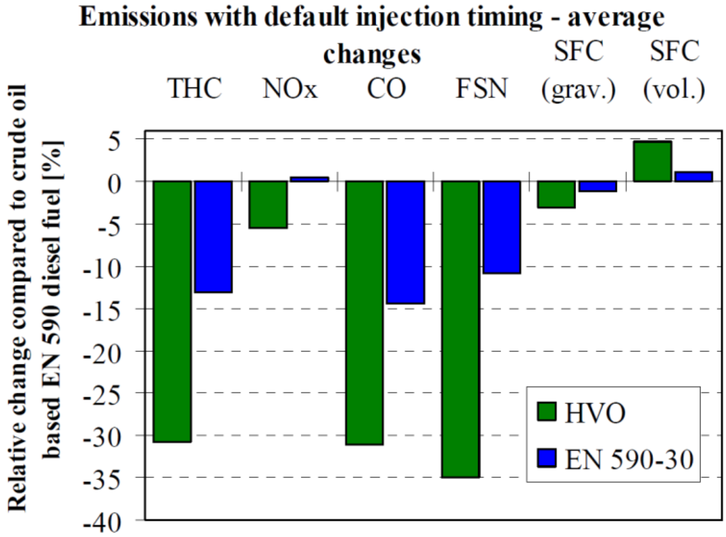

Figure 51. Comparison of emissions of HVO and EN 590-30 diesel

(FSN = filter smoke number SFC = specific fuel consumption)

Source: [130]

GHG emissions are higher than those for other BTL pathways as the hydrogen production, required for the HVO process, is energy and GHG intensive (see Figure 52). The assumption made in the JRC analysis is that hydrogen is generated by the steam reforming of natural gas [153].

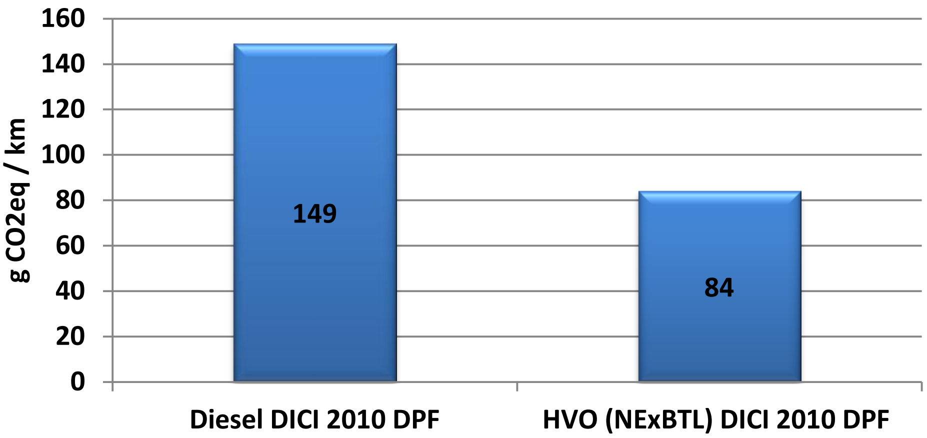

Figure 52. HVO WTW GHG emissions

Source: JRC [153]

HVO still requires oil feedstock grown on prime agricultural land and therefore is not considered a full second-generation solution [72]. The process however becomes more attractive when we consider its use for the conversion of third-generation algae feedstock.

4.3.5 Biomethane (Biogas)

Biomethane is the name given to upgraded biogas suitable for transport applications. Upgrading of the biogas is required to remove CO_2 and increase the CH_4 content. Although it is possible to fuel an engine with unprocessed biogas, removal of CO_2 from the biogas is carried out in order to increase the energy density of the gas and to achieve a constant gas quality between biomethane and NG [180].

The upgrading of the biogas is both financially demanding, energy intensive and remains a major technical challenge. The investment required for plant capable of treating 200 Nm^3 of gas per hour is estimated to be €1m [181]. This does not include the cost of plant operation.

The tailpipe emissions benefits of biomethane are similar to those already presented for NG. Biomethane however offers major reductions in WTW emissions due to the fact that it is produced from sustainable organic material. Even with upgrading emissions taken into account the use of biomethane offers GHG savings of up to 77% compared to diesel (see Figure 53) [153]. Future process improvements are expected to reduce WTW emissions even further. Efficiency improvements could also been seen by pre-treating the feedstock and the addition of micronutrients to increase gas yields [182].

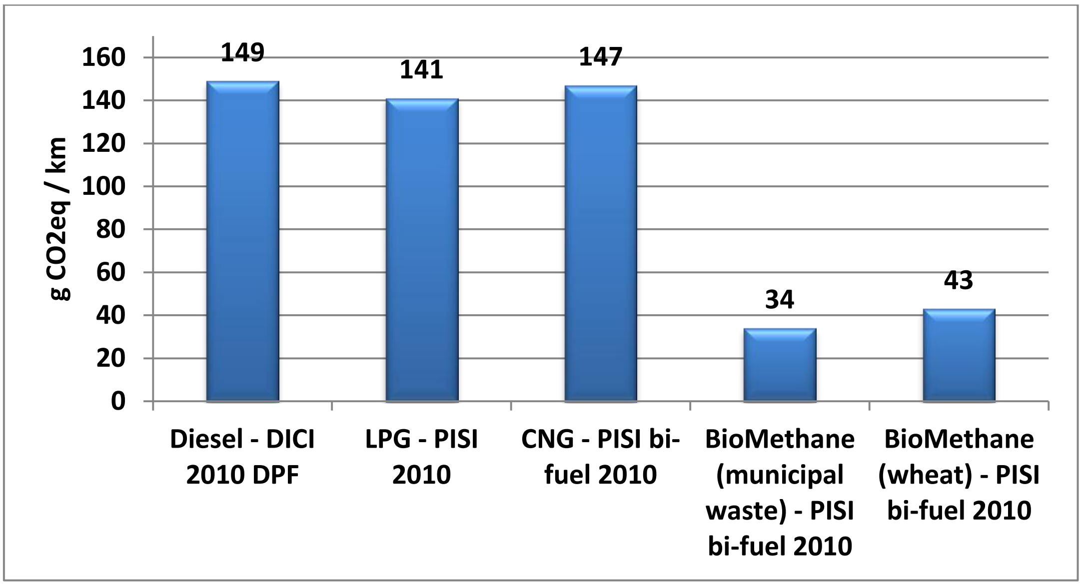

Figure 53. Biomethane WTW GHG emissions

Source: JRC [153]

Biogas faces the same distribution infrastructure challenges as those discussed in Section 4.4.2 for LNG. Until the upgrading process can be proven to provide consistent and acceptable gas quality, use of the established NG pipelines cannot be considered. This means that initially localised supply for captive fleets is the most realistic and lowest cost option for the short term.

4.3.6 Third-generation Biofuels

The primary issue with algal biofuels is that the production of microalgae feedstock with the technology currently available is not economical. Current estimates predict the cost of algal biofuel manufactured in large scale production would be around twice that of those produced from soybean oil today. Major advances in production technology and algal biology are required in order to make the fuel competitive with mineral diesel. The production of the biomass alone will need to decline by a factor of 9 to make the algal biofuel competitive with crude oil at $100 per barrel [135]. It is expected that development of an economical production method will take between 5 and 10 years of concerted, coordinated research and development. Future costs of algae biodiesel production are estimated to be as low as $0.26 per litre (equivalent to crude oil at $60 per barrel) [183]. Commercialisation is not expected before 2020.

The use of the high oil yield algae alongside the low-cost and easier to establish first-generation conversion technologies offers developing countries the opportunity to benefit from the lower costs of processing and also detach the effect of fuel prices from those of food.

4.4 Environmental and Economic Review Summary and Conclusions

The review of future internal combustion engine efficiency improvements found that the mechanical systems for parasitic loss reduction and waste heat recovery are expected to take priority for heavy-duty powertrains, not only because of the ease of integration identified in Chapter 3 but also due to their lower cost compared to electrical systems. While CO_2 savings of 4.5% for the mechanical systems might appear small, the high fuel consumption levels of heavy-duty trucks combined with their high mileage offer the potential of a large reduction in global GHG emissions. Electrical technologies are likely to be limited in uptake due to the payback period extending beyond the typical three years used by haulage companies. Both electrical turbocompounding and bottoming cycles show unacceptable payback periods of over 5 years. Although it could be argued that due the potentially large environmental benefits on offer these payback periods should be reviewed by the haulage companies themselves, remaining competitive in the market place is crucial to the future survival of these companies. If the technology is not widely adopted the pioneering companies are likely to find themselves at a commercial disadvantage. A legislation based requirement for the recovery of waste exhaust heat, or financial incentives to offset the increase in capital cost, would help early adopters of the technology remain competitive as well as promote the uptake and further development of these high potential technologies.

LPG and NG dual-fuel compression ignition powertrains offer well-to-wheel CO_2 savings of up to 27%. Based on the system cost estimates presented and the low cost of LPG and NG they also offer viable payback periods of less than 3 years. LPG is unlikely to be used widely as a heavy-duty fuel due to additional system weight, future sustainability concerns, and a varying refuelling infrastructure across different countries. NG is the cleanest fossil fuel and continually increasing resource potential across various geographic locations has led to increased interest both due to sustainability and fuel security benefits. Biomethane offers the greatest potential of GHG emissions saving for dual-fuel diesel / gas powertrains although technology development is required to optimise the biogas upgrading process to increase efficiency. Currently the LNG refuelling infrastructure required for road transport does not exist and this is likely to limit uptake of diesel/NG vehicles. Dual-fuel heavy-duty vehicles are likely to be limited to localised fleets which are able to use central fuelling stations. LPG could be used in areas where an acceptable exists as a stepping stone to the use of NG and biomethane in the future.

Fuels derived from biomass are considered as ‘carbon neutral’ as CO_2 released during combustion of the fuel is absorbed during crop growth. These biofuels offer a low-carbon sustainable alternative to current fossil fuels.

Although biodiesel was initially hailed as a sustainable alternative to mineral diesel, there are now questions over the sustainability of first generation biofuel feedstock. Among the concerns are the levels of nitrous oxide (N_2O) emissions from crop production and competition for prime agricultural land leading to increased food prices. The majority of biofuels are also unable to compete with fossil fuels without financial subsidies. As the main contributor to first-generation biofuel production costs is feedstock production costs are not expected to fall sufficiently to make them competitive. Currently ethanol production in Brazil is the only competitive biofuel pathway. The ambitious targets set by the EU for sustainable transport fuel means that around 58% of biofuel crops will need to be imported in order to achieve the 10% target for renewable transport fuels by 2020.

Second-generation biofuels offer the potential to provide greater GHG benefits over the complete life-cycle. A comparison of the well-to-wheel GHG emissions of mineral diesel and the reviewed alternative fuels can be seen in Figure 54. There is a high level of uncertainty around the capability of final processes and further research and development is required to optimise production of these fuels. Synthetic diesel is expected to become the prime biofuel for compression ignition internal combustion engines due to the ease at which it can be distributed using the current infrastructure, and utilised in existing engine technologies. Renewable bio-DME offers favourable GHG and tailpipe emissions but the low energy density of the fuel and lack of refuelling infrastructure limits the use of DME to localised fleets where central refuelling is possible.

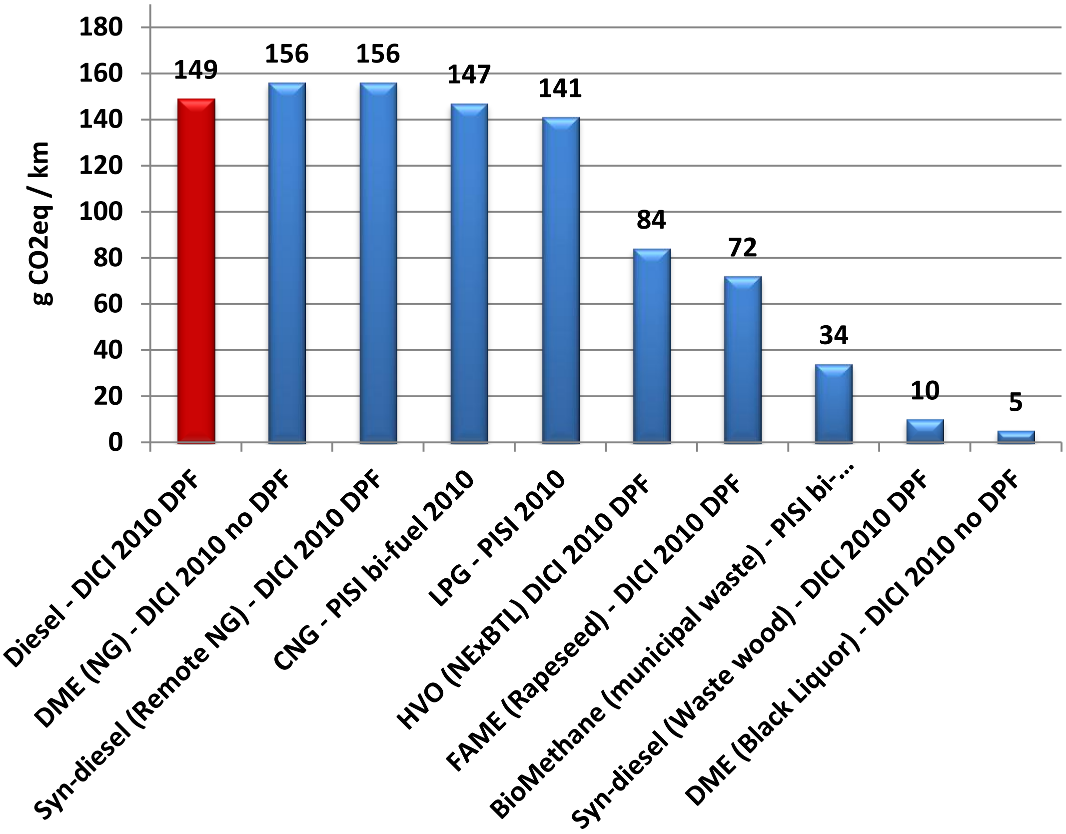

Figure 54. WTW GHG emissions of alternative fuels compared to mineral diesel

The feedstock for second-generation fuels can originate from any lignocellulosic biomass, reducing the reliance on food sources and prime agricultural land. Feedstock can also be sourced from commercial, municipal and forestry waste. The IEA has calculated that 25% of agricultural and forestry residues would be required to satisfy the biofuel demand in the WEO 450 scenario using second-generation processes.

Job creation, local growth from the cultivation of feedstock, transportation requirements and the labour for infrastructure development of the new processes are likely to benefit local economies. The establishment of second-generation production facilities however require a substantially higher investment and technical knowledge than first-generation biofuel production technology, therefore limiting their availability to developing countries without the aid of foreign investment and knowledge transfer. A summary of first and second-generation production plant capital costs can be seen in Table 18.

Technology	Plant size (tonnes pa)	Approximate Cost (€)
FAME Biodiesel	250,000	50m – 100m
HVO	170,000	100m
FT Synthetic Diesel	200,000	800m
DME	100,000	330m

Table 18. First and second-generation biofuel plant capital costs

Compiled from: [126; 177; 179]

Third-generation algae fuels offer the opportunity to reduce production costs and improve well-to-wheel energy efficiency for all pathways due to the greater biomass yields. The use of algae oil alongside the low-cost first-generation conversion technologies offers developing countries, unable to establish second-generation processes, the opportunity to detach biofuel feedstock costs from those of food. HVO processing of algae oils would offer synthetic diesel from sustainable oil feedstock. Commercialisation of an economical production method for algae is not expected before 2020.

5. The Implications of Sustainable Low-carbon Powertrains on the Automotive Industry

The internal combustion engine is expected to remain the primary choice for heavy-duty powertrains until beyond 2030, offering some technology security to both the OEMs and suppliers. Any move away from the internal combustion engine to electric or hydraulic hybrids is likely to be limited to minority applications such as urban refuse and delivery. Existing core competencies, strategic assets, capital equipment, technical expertise and brand value means the established manufacturers are in a good position to maintain their market dominance and the threat of new entrants remains low. However, the increase in electric auxiliary components and fuel cell development for auxiliary power is already being seen and the increase in technology mix is expected to continue. As powertrain technologies continue to diversify, the development of knowledge and competence in these new technology areas is crucial in order for companies to maintain a competitive advantage in the future.

With global fuel prices increasing and CO_2 emissions targets expected to be in place for most of the major commercial vehicle markets by 2020, truck manufacturers in the established markets, with strong fuel consumption and emission reduction R&D programmes, are also likely to gain competitive advantage in emerging markets as they aim to implement stricter emissions legislation.

Medium-duty drive cycle applications hold far greater technological risk than those for heavy-duty as the final technology is likely to be far more diverse depending on the application. These market conditions offer opportunities to companies with innovative cultures and strong R&D competences. With the light-duty and passenger car markets already heavily focused on the development of electric and hybrid electric vehicles, manufacturers with in-house experience of these technologies, or partnerships with companies involved in their development, are ensuring that they are in a good position to profit from opportunities for alternative powertrain technologies. Partnerships, mergers, and acquisitions continue throughout the automotive industry and these are expected to increase as manufacturers compete to offer a more complete product portfolio. Barriers for new entrants to the market remain high for OEMs, powertrain, and component manufacturers, as existing technology is still required in most scenarios.

Fuel options are expected to diversify over the next 20 years as governments look to switch to more secure sources of automotive fuels. For example, with the growth in US NG resource, funding and support for dual-fuel CI and NG SI engines is expected to stimulate the NG infrastructure in the US. This in turn is expected to lead to an increase in NG vehicles. As the majority of the alternative fuels discussed are yet to become cost competitive with mineral diesel, legislation, subsidies, and local feedstock availability are all likely to have a large influence on which technologies succeed and which do not.

In the future OEMs, engine manufacturers, and component suppliers will require the ability to accommodate a greater range of products within their manufacturing systems to remain competitive. Currently alternative powertrains and fuels are being manufactured in limited quantities and higher costs are being tolerated. Flexibility of future component production lines will be essential to ensure the business can adapt quickly to the uncertain requirements of rapidly changing powertrain technologies. Process efficiency must be improved as economies of scale reduce to enable the industry to offer low-carbon solutions at an acceptable cost.

6. Conclusion

The compression ignition internal combustion engine is expected to remain the focus of heavy-duty powertrain development for the foreseeable future, certainly beyond 2030. Although increased electrification is expected to be seen on heavy-duty vehicles (for example, APUs to reduce idling), the demands of heavy-duty drive cycles prohibit the use of the current electric and hybrid electric powertrain technologies being developed for light-duty applications.

Existing core competencies, strategic assets, and technical expertise puts established manufacturers in a good position to maintain their market dominance. Manufacturers with strong emission based R&D programmes are also likely to gain competitive advantage in emerging markets as they aim to implement stricter emissions legislation. An increase in electric auxiliary components is currently being seen and continued powertrain diversification is expected. The development of knowledge and competence in these new technology areas is crucial in order for companies to maintain their competitive advantage in the future.

Increasing combustion engine efficiency is expected to remain a key technological focus of truck and engine manufacturers as the reduction of fuel consumption and CO_2 emissions becomes a legislative requirement. With current trucks offering a peak thermal efficiency of around 42%, waste heat recovery and parasitic loss reduction technologies are expected to be seen on the majority of new truck models. Initial implementation is predicted to be via mechanical systems, with widespread use of electrical technologies not expected until an increased level of electrification is seen on long-haul vehicles. Concerns such as technology payback time, packaging, increased weight, and the added complications of installing electrical systems solely for auxiliary components, are expected to limit their uptake. An overview of the technologies assessed for parasitic loss reduction and waste heat recovery can be seen in Table 19.

Technology	CO_2 Saving Potential	Technology Readiness	Investment Required Based on Payback Period (1 low - 5 high)	Current Status
Mechanical Variable Speed Pumps	1.50%	Ready	1	Currently being implemented by OEMs.
Clutched Air Compressors	3.5% Ave	Ready	1	Currently being implemented by OEMs.
Mechanical Turbocompounding	4.50%	Ready	3	Currently being implemented by OEMs.
Electrical Turbocompounding	8%	Ready	4	Requires greater uptake of vehicle electrification.
Bottoming Cycle	6.50%	Further R&D Required	5	Requires greater uptake of vehicle electrification and packaging development to reduce weight.

Table 19. Comparison of ICE loss reduction technologies

The use of alternative fuels in the existing diesel powertrain offers the fastest route to reducing both GHG and exhaust emissions. Although the greatest reductions are seen when the fuels are used neat, biofuels blended with existing mineral diesel also offer significant emission improvements.

FAME biodiesel is currently the most established biofuel for use in CI engines. The low cost, the simplicity of feedstock processing, as well as ease of integration with current ICE technology and the diesel refuelling infrastructure, has led to a 3 fold increase in production since 2005. Sustainability concerns around first-generation biofuels, concerns over fuel degradation, and the high cost of oil crop feedstock, is expected to see widespread transition to second-generation fuels over the next 5 years as the process technology matures. The high quality synthetic diesel produced by second-generation processes allows its use in current ICE powertrains without engine modification or fuel blending. GHG and exhaust emissions are both significantly improved. The large capital investment required for installation of second-generation production plants is expected to limit their availability in developing countries until capital costs decrease. Third-generation algae fuels offer the opportunity to reduce production costs and improve WTW energy efficiency for all pathways, although process commercialisation is not expected until beyond 2020. Microalgae feedstock offers oil yields up to 31 times greater than that of traditional oil crops. The use of first-generation, and HVO, processes with economical and sustainable algae feedstock offers the opportunity to greatly reduce fuel costs and detach biofuel feedstock costs from those of food.

Over the next 5 to 10 years the choice of automotive fuels is expected to diversify as countries move to utilise local biomass resource and increase their own energy security. The use of fuels such as bio-DME and biomethane, which cannot easily be integrated into the existing fuelling infrastructure but offer greatly reduced GHG and exhaust emissions, are expected to be seen for localised fleets where suitable bio-feedstock is available.

The growth in recoverable NG reserves has seen increased interest in dual-fuel heavy-duty diesel/LNG powertrains. NG produces less GHG emissions and fewer pollutants than other hydrocarbon fuels, plus the use of unconventional gas resources offers the opportunity of greater energy security. NG vehicles are also able to move to biomethane when it becomes more widely available in the future to further reduce GHG emissions. Lack of an adequate refuelling infrastructure in the short to medium-term will impede wide-scale acceptance, and dual-fuel vehicles expected to be limited to localised fleets which are able to use central fuelling stations. An overview of the alternative fuels investigated in this report can be seen in Table 20.

OEMs, engine manufacturers, and component suppliers will require the ability to accommodate a greater range of products in order to remain competitive. The flexibility of future component production lines is essential to ensure businesses can adapt quickly to the uncertain requirements of rapidly changing powertrain technologies.

The powertrain is only one area where low-carbon benefits can be achieved and there is also considerable focus on other vehicle improvements. Technologies such as intelligent transport systems (ITS), tyre pressure monitoring and adjustment, improved cab, chassis and trailer aerodynamics, and the use of lightweight materials, all have their part to play in reducing both fuel consumption and GHG emissions.

Fuel	GHG Reduction Potential (1 low - 5 high)	Compatibility with current ICE technology (1 low - 5 high)	Compatibility with current refuelling infrastructure (1 low - 5 high)	Expected date of technology commercialisation [126; 183; 184]	Current Status
FAME Biodiesel	3	4	4	Established	Blending generally limited to 10% due to concerns over fuel properties. Concerns over long-term sustainability.
FT Synthetic Diesel	5	5	5	2015 - 2016	Pilot plants already established. Efficiency improvements and technology cost reduction required
DME	5	4	2	2014 – 2015	Pilot plants are already established. Lack of refuelling infrastructure and energy density limits wide-scale use.
HVO	3	5	5	Established	Produces high quality synthetic diesel but currently uses first-generation feedstock.
Aglae Biodiesel	5	4-5	4 -5	Beyond 2020	Major advances in production technology and algal biology are required to make algae biodiesel economical.
LPG	1	3	2	Established	Dual-fuel systems can be fitted to current CI ICE powertrains. LPG refuelling infrastructure is limited.
LNG	1	3	1	Established	Dual-fuel systems can be fitted to current CI ICE powertrains. Lack of LNG refuelling infrastructure.
Biomethane	4	3	1	2016	Pilot plants already established. Upgrading technology needs further research and development.

Table 20. Comparison of alternative automotive fuels

6.1 Further Work

The technologies in this Thesis have largely been investigated as isolated solutions. Further work should assess the ability of combining low-carbon technologies to offer benefits greater than their individual sums. For example, the integration of electrical heat recovery systems to power electrical auxiliary components. This not only offers the opportunity to reduced fuel consumption, by fully isolating parasitic components from the powertrain, but also the potential to reduce the overall cost of component integration due to the use shared electrical components. This could lead to increased uptake of the technology due to shorter payback periods.

This study has also been mainly focused on the direction being taken by manufacturers in the established markets such as Western Europe, North America and Japan. The influence of manufacturers in emerging markets, as CO_2 regulations become more widespread, requires further investigation. Further work should focus on the ability of manufacturers in these high volume markets to influence the acceptance of specific low-carbon powertrain technologies. Innovative manufacturers in the emerging markets who focus on developing new powertrain technologies are also likely to target a larger market share in the future. An additional investigation into the effect of these emerging markets on the future business strategies of OEMs and suppliers in the established markets is also recommended.

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Appendices

Appendix 1 - Truck Market Segmentation

Market	Typical Characteristics
Heavy-duty Truck **(Class 8 in North America)**	• >15 tonnes GVW. • >215 hp. • Equipped with engines of >8 litres capacity. • 6 cylinders (and small number of V8).
Medium-duty Truck **(Classes 4-7 in North America)**	• 6 - 15 tonnes GVW. • 100 - 350 hp. • Equipped with engines of 4 - 7 litres capacity. • 4 & 6 cylinders.
Light-duty Truck	• 3.5 - 6 tonnes GVW. • 80 - 120 hp (up to 300 hp in US). • Equipped with engines of 2.7 - 6 litres capacity. • 4 & 6 cylinders (and 8 cylinders in US).

Appendix 2 – Current CV Hybrid Development

Company	Year	Technology Introduction
Daimler [185]	2004	Fuso Aero Star Eco series hybrid urban bus developed. The latest model is driven by a lithium-ion battery and two electric wheel hub motors.
	2009	Fuso Canter Eco Hybrid is first series-produced parallel hybrid truck to be sold in Europe.
	2009	Atego BlueTec parallel Hybrid undergoes Deutsche Post fleet test.
	2009	More than 1700 Orion VII HybriDrive urban buses are on the roads in North America.
	2010	Atego BlueTec Hybrid innovation fleet to be introduced at end of 2010.
	2010	4,000 Daimler hybrid trucks and buses are on the road worldwide in day-to-day service.
Volvo [186; 187]	2006	Volvo announces a parallel heavy-duty hybrid solution based on the I-SAM (Integrated Starter Alternator Motor) concept.
	2009	A diesel-electric hybrid refuse truck developed by Mack trucks is trialed by the city of New York.
	2009	Hybrid bus field tests were carried out in Gothenburg, Stockholm and London.
	2009	First commercially sold hybrid bus (Volvo 7700) delivered to Sales-Lentz in Luxemburg.
	2010	Nettbuss (Norway) orders 12 hybrid buses from Volvo.
	2011	Volvo group currently have currently developed 20 different hybrid vehicles based on the I-SAM concept. These include wheel loaders, buses and refuse collection trucks.
PACCAR [188; 189]	2006	DAF presents a prototype LF parallel hybrid at IAA Nutzfahrzeuge in Hanover.
	2007	Kenworth introduce the T270 medium duty hybrid-electric truck.
	2007	Freightliner introduce a medium duty (class 6/7) hybrid utility truck.
	2008	Peterbilt medium duty Model 330 (class 6) and Model 335 (class 7) Hybrid Electric vehicles enter full production.
	2010	Peterbilt launch the Model 386 heavy-duty (class 8) electric hybrid tractor.
	2010	DAF begins production of its LF Hybrid Distribution Truck at Leyland in the UK.

CV Hybrid Development at Daimler, Volvo and PACCAR

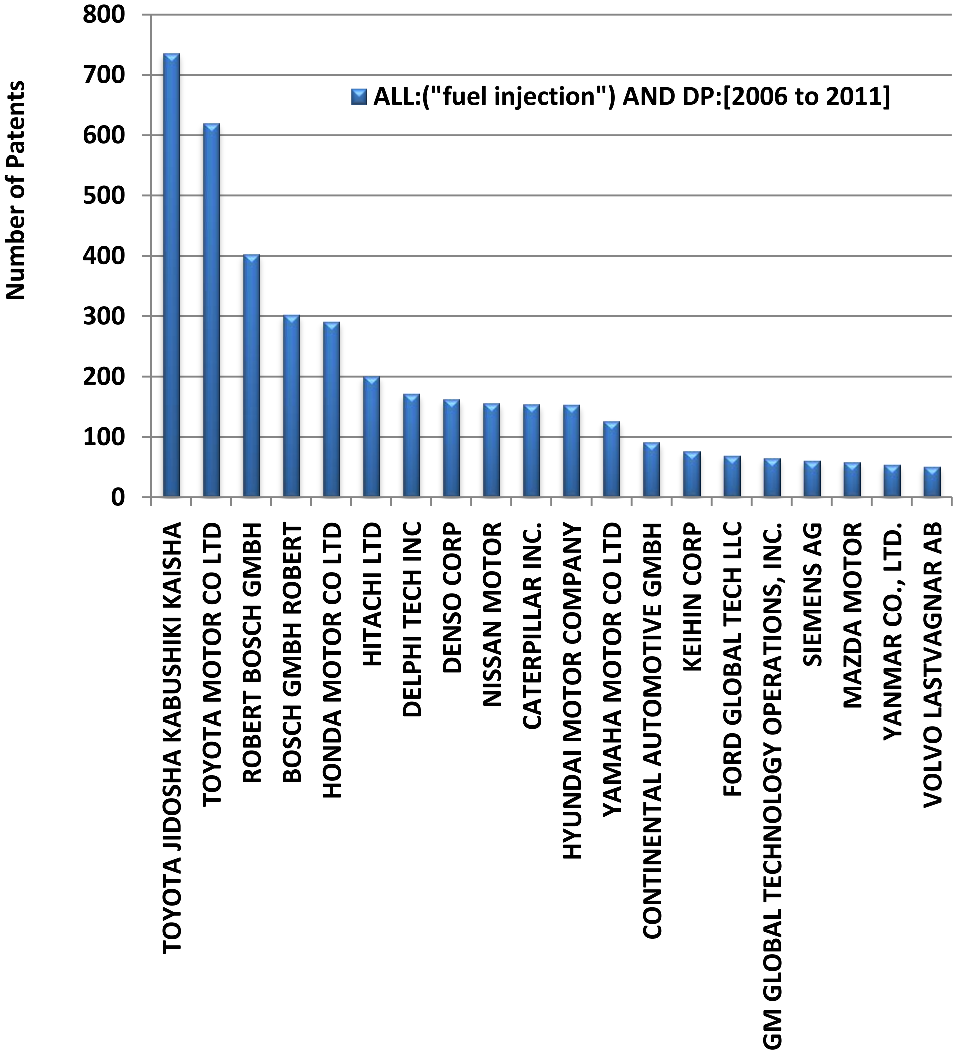
Appendix 3 – Patent Search Methodology

The patent search was carried out in stages as to gradually narrow in on the technologies being developed. Searches were also carried out both with and without the patent classification class defined. This was deemed by the author to be the most effective way of ensuring that patent applicants unknown by the author as well as classifications not primarily associated with the technology were not excluded. The table below shows the search criteria used for each stage of the patent search.

Stage	Search Terms	Description
Stage 1	ALL:(“fuel injection”) AND DP:[2006 to 2011]	Searches the complete database for the phrase “fuel injection” between the years 2006 and 2011
	ALL:("fuel injection") AND DP:[2006 to 2011] AND ICF:"F02"	Searches within the F02 classification (combustion Engines) for the phrase “fuel injection” between the years 2006 and 2011
	ALL:("fuel injection" OR "fuel delivery" OR "alternative fuel") AND DP:[2006 to 2011]	Searches the complete database for the phrase “fuel injection”, “fuel delivery” or “alternative fuel” between the years 2006 and 2011
Stage 2	ALL:("fuel injection" OR "fuel delivery" OR "alternative fuel" OR "fuel injector") AND DP:[2006 to 2011] AND PA:*	Searches the complete database for the phrase “fuel injection”, “fuel delivery” or “alternative fuel” between the years 2006 and 2011 PLUS the applicant named. *The applicant name is stated here e.g. TOYOTA or Daimler

Patent Search Terms

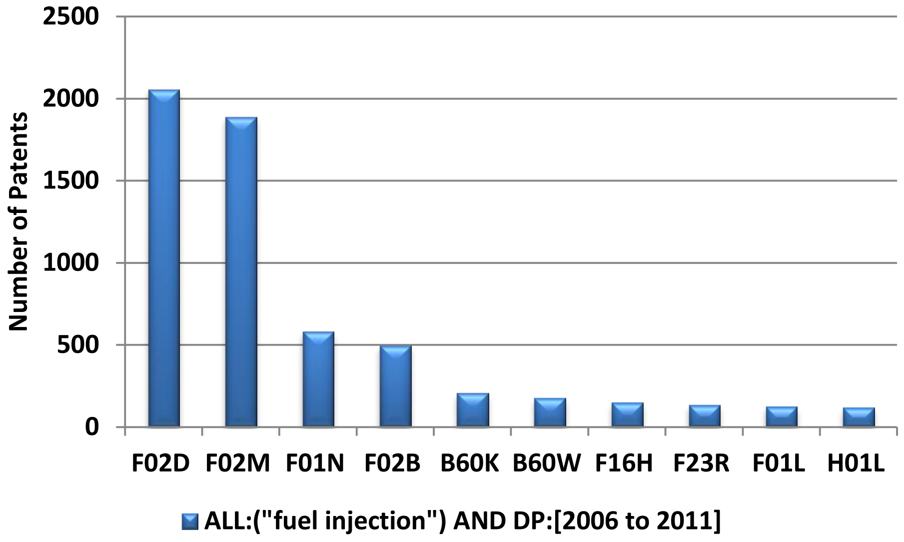
The graph below shows the result of a search for patents between 2006 and 2011 using the search terms "fuel injection". The search returned 8,029 results, the majority from applicants outside of the CV manufacturers identified in Section 2.1. In fact only Toyota and Volvo appear in the top twenty applicants. The major FIE manufacturers such as Bosch, Continental, Delphi, Denso, Hitachi and Siemens appear as expected. Further limiting the results to the internal combustion engine classification (F02) reduces the number of patents to 4,214. The top ten applicants remain the same.



Fuel Injection Patent Applications by Applicant between 2006 and 2011

Source: WIPO

The largest sets of patents in both of these searches are found within F02D (controlling combustion engines) and F02M (supplying combustion engines in general with combustible mixtures) classifications (see the graph *'Patent Applications by Classification'* below). Other classifications identified within the initial search such as F01N (exhaust apparatus for internal combustion engines) and B60 (relating to engine subsystems) were judged to be valuable to the study and therefore further searches were not limited by classification.

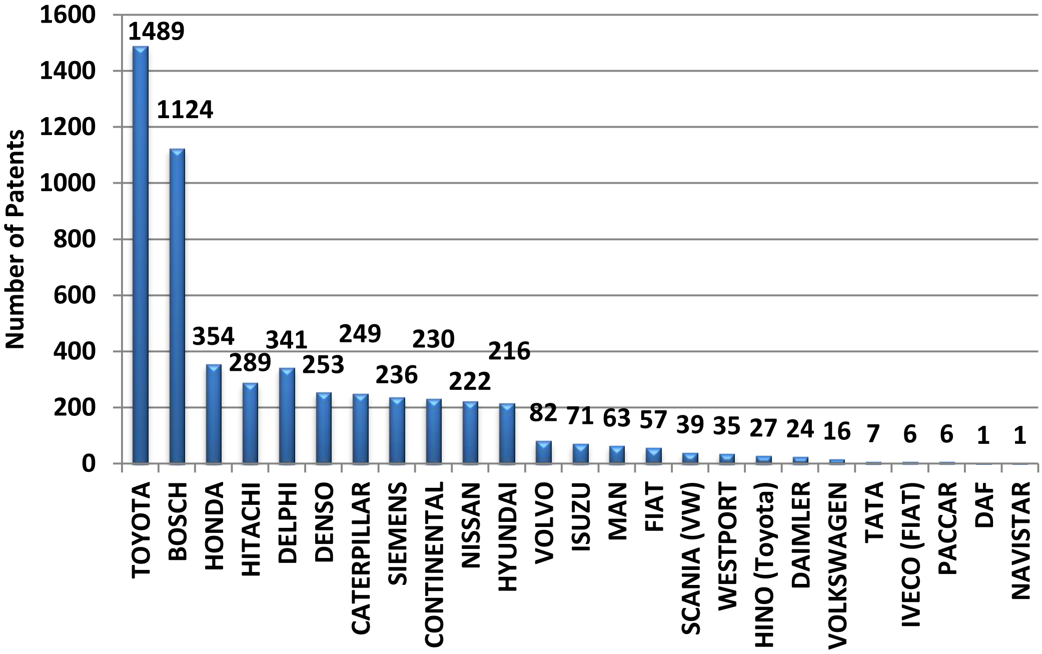


Patent Applications by Classification

Source: WIPO

Based on the descriptions of reviewed patents from the first searches the additional search terms "fuel delivery" and "alternative fuel" were added along with the OR Boolean operator to further extend the search results. Further searches were then carried out specifying the applicant to identify the technology trends for each company. This reduced the number of patents to 5,438. The total number of patents raised by each of the specified applicants can be seen in the graph *'Number of Patents by Specified Applicants'* below.

On investigation a large number of these patents were not directly to CV applications however, attempting to limit the search further using additional keywords such as "truck", "commercial vehicle", or "compression ignition" emitted far too many patents as the final application of the invention is not commonly expressed.



Number of Patents by Specified Applicants

Source: WIPO

The search term was further refined to include the names of the CV manufacturers identified in Section 2.1 and leading FIE manufacturers in the applicant field.